AN OVERVIEW OF VANADIUM REDOX FLOW BATTERY FOR COMMERCIAL APPLICATIONS WITH RENEWABLE ENERGY

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Certification

This is to certify that this project and thesis entitled **“An overview of vanadium redox flow battery for commercial applications with renewable energy”** is done by the following students under my direct supervision and this work has been carried out by them of the Department of Electrical and Electronic Engineering under the Faculty of Engineering of Daffodil International University in partial fulfillment of the requirements for the degree of Bachelor of Science in Electrical and Electronic Engineering.

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Abstract

The vanadium Redox Flow Battery (VRFB) is a promising electrochemical energy storage device that retains electrical energy by adjusting the oxidation numbers of anolyte and catholyte via a redox reaction. It is suitable for a wide variety of renewable energy for commercial applications. The operating theory of a vanadium redox flow battery is discussed in this article. Technology, features, and performance of component technologies, as well as traditional implementations. This research examines various different kinds of batteries, as well as their benefits and drawbacks. Furthermore, this thesis focuses on clean energy industrial applications. The aim of this research is to make a distinction between the current available energy storage systems and the most viable and effective energy storage system. It has been discovered by observation and analysis that a vanadium redox battery can be commercialized using renewable energies. Furthermore, there are a few shortcomings that have been identified by recent researchers, including the fact that using the VRFB for commercial purposes is not feasible.

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Chapter 1

Introduction

1.1 Introduction

Renewable energy sources, such as solar and wind power, are increasingly being promoted around the world in order to achieve a low-carbon society. Solar and wind power generators face a number of challenges, including production variability. Problems such as voltage rises, frequency fluctuations, and surplus produced power are expected if they are added in large numbers to the power system. Energy storage systems, in which energy storage batteries are expected to become essential for use, are gaining interest as a solution to these problems. Flow batteries can compensate for losses and provide power backup, potentially reducing the effect of a power outage. Energy storage has the ability to be a critical component of the grid, allowing for more effective capacity use and seamless integration with existing power plants and transmission lines. It's also a good way to use arbitrage since it allows individual power producers to store surplus energy during off-peak hours. Due to the high demand for electricity, an energy storage system was built, and this energy was distributed to all electrical appliances, especially large-scale energy users. The world's population and industrial growth have risen significantly over time. The clean energy storage system is a solution to the world's intermittent energy issues while also providing a positive environmental perspective. This renewable energy source will take the place of non-renewable energy, which has become the most common global energy resource in recent years, including in Bangladesh. This was the driving force behind all of the researchers' efforts to create a sustainable energy storage device, as non-renewable energy sources contribute to global warming through the release of harmful gases. Renewable energy is energy derived from natural resources that can be replenished on a regular basis. Due to the rising demand for power, the previously mentioned renewable energy would experience volatility and dispersal. As a result, it is the primary impetus for bolstering the energy storage technology initiative. Energy storage is the act of reserving a certain amount of energy for later use. The vanadium redox flow battery is one of several types of redox flow batteries. The vanadium redox battery (VRFB) is the most advanced, the only commercially viable, and the most commonly used RFB among the RFBs suggested. In comparison to other RFBs. The vanadium electrolyte technologies are described in this review from the perspectives of VRFB design, cost analysis, and future prospects.

1.2 Objectives

The objectives of this thesis are,

I. To study energy systems and energy storage systems.
II. To learn the distinctions between the capacitor and battery of energy storage system.
III. To describe various types of battery systems and make a difference among them.
IV. To learn more about the vanadium redox flow battery's theory and configuration.
V. To look at the characteristics and results of VRFB.
VI. To study the traditional and industrial uses of vanadium redox flow batteries.
VII. To create a VRFB vs. other traditional batteries comparison.

1.3 Research Methodology

This is a thesis analysis article. The energy system, energy storage system, energy system assessment, and advanced technology of vanadium redox battery system have all been discussed in this paper. The features, phenomena, and configuration were also discussed. We've distinguished between various battery systems and compared vanadium batteries to other types of batteries. Finally, we addressed the commercial implementation of vanadium redox flow battery energy storage systems as well as an overview of their investment costs. Since this is a review article, all data were gathered from a variety of online sources in order to evaluate and link to previous related works on vanadium redox flow batteries and energy storage systems.

Chapter 2

Energy Storage System

2.1 Introduction

To meet the rising global population's energy demands, the world's current energy output will be doubled by 2050. Our world is more mindful of environmental issues than it has ever been. Due to dwindling fossil fuel supplies and global climate change, an increase in energy must be accomplished without causing significant CO_2 emissions. Renewable energy technologies have been a hot topic in recent decades as part of this target. Wind, solar, and tidal energy are all scattered and inherently intermittent renewable energy sources. Due to the volatile nature of renewable energy, advanced large-scale energy storage systems are needed to get the most out of these resources, and the current trend appears to be requiring more energy storage devices at the grid-scale to increase renewable energy penetration. Rechargeable batteries are a cost-effective way of storing electricity. Lithium-ion, nickel-metal hydride (Ni-MH), lead-acid, redox flow, and the sodium-sulfur (Na-S) device are among the battery technologies available [1].

The redox flow battery (RFB) is one of them, and it's a promising energy-storage solution that's ideal for stationary applications thanks to its modular nature, good scalability, flexible operation, and low maintenance costs. RFB systems have a distinct design that consists of three components: a stacked cell, energy storage tanks, and a flow system. Redox flow batteries (RFB) are made up of an electrochemical cell that uses two chemical components dissolved in liquids within the battery and separated by a membrane to provide chemical energy. They've emerged as one of the most exciting large-scale energy storage solutions. Due to its decoupling of power output and energy storage capability, the redox flow battery (RFB) is a promising technology for this application, and it has been demonstrated in multiple large-scale energy storage projects [2].

2.2 The Need for Energy Storage

Manufacturing, service industries, future renewable energy industries, and all the portable devices with which we have become obsessed all depend on energy storage. The tablet, iPad, and iPod era would not have advanced as quickly if modern energy storage, such as lithium-ion (Li-ion) batteries, had not been invented [3]. Aside from entertainment, energy storage is important in high-tech manufacturing, where an uninterruptible power source with a constant frequency is needed. According to reports, the US industry loses $80 billion per year as a result of mostly brief power outages [4]. High-tech, high-cost industries, such as chip fabs, have massive power storage backups, such as lead-acid batteries, as well as frequency smoothing, to mitigate this. Grid frequency control is a crucial application for flywheels and ultracapacitors, as utilities usually change the frequency to smooth the power output. In the event of a power outage, some critical service sectors, such as the telecommunications industry, depend heavily on large batteries. A 40-MW Ni/Cd battery system is used in remote areas, such as Fairbanks, Alaska, to ensure continuous power availability.

Electrification of the transportation sector has received renewed attention in the last decade; electric vehicles dominated transportation for a brief time at the turn of the twentieth century. The all-electric Nissan Leaf and the plug-in GM-Volt have joined the market, spurred on by the popularity of the Toyota Prius hybrid electric vehicle. With well over 25 million miles powered on Li-ion batteries, the electric bus has joined the fleet. The GM Volt and the buses are both powered entirely by electricity, with the internal combustion engine acting as a generator. Both of these vehicles improve their performance by recovering energy during braking. Capturing the energy usually lost when a dock crane lowers a crate is a similar application; capturing this energy by capacitors saves about 40% of overall energy consumption. Subways, with their frequent stops and starts, can also absorb the braking energy for later use. Low cost and long life are critical for commercial performance in both of these transportation applications.

Renewable energy sources, such as wind and solar, cannot serve as the primary source of energy unless they are accompanied by an energy storage system. Also, when connected to the grid, a storage unit is needed to smooth the output; one example is a new wind farm in West Virginia that includes a 20-MW battery storage facility [5]. Furthermore, energy storage would be expected as the percentage of renewable energy production into the grid reaches around 10%. Furthermore, wind energy is most abundant during the nighttime hours, when demand for electricity is lowest.

A large storage facility may reduce the need for intermittent power generation to meet peak demand. If a low-cost energy storage facility is available, the primary power generator could operate all night to fill the storage device, which could then be released during high-demand hours, obviating the need for peak-only power plants [6].

2.3 What Are Batteries and Capacitor

Batteries and capacitors are the two most common types of electrochemical energy storage. Electrical energy is stored as chemical energy in batteries, while energy is stored as a surface charge in capacitors. As a result, the materials' properties must be very different. Since chemical reactions occur within the bulk of the solid in batteries, the material must be engineered to enable the reacting species to infiltrate the material and then be removed. To make a commercially viable rechargeable battery, this must happen thousands of times. A capacitor, on the other hand, necessitates a considerable number of surface areas, since the storage capacity is proportional to the surface area. Since the structural integrity of a capacitor material is not compromised, pure capacitors can be charged and discharged millions of times without any material deterioration, whereas chemical reactions in batteries are not always easily reversed due to structural changes. Supercapacitors are a mix of the two, involving surface charge as well as certain Faradaic reactions in the bulk of the material. As shown schematically in Fig. 1, batteries and capacitors have two electrodes, the anode, and the cathode.

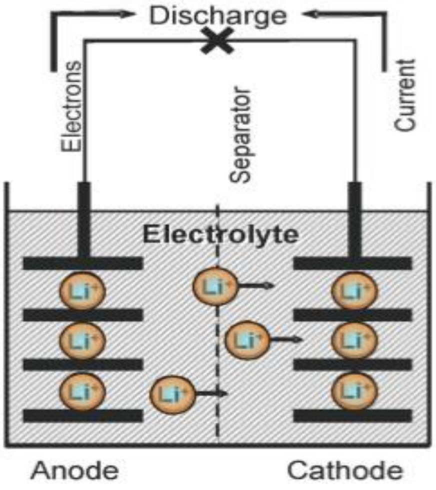


Figure 1: Schematic of a battery.

The anode is that the positive conductor, from that the electrons flow on discharge; the cathode is that the negative conductor to that the electrons flow through the external circuit doing work. Cations usually flow from the anode to the cathode through the electrolyte in the battery to balance this flow of electrons. Only ions, not electrons, can pass through this electrolyte, which can be a liquid or a solid. In the case of the popular Zn/MnO_2 dry cell, it's usually an aqueous solution, such as sulfuric acid in the Pb-acid battery or potassium hydroxide in water. A porous separator is positioned between the two electrodes to prevent them from touching. Regardless of whether the device is being charged or discharged, the more electropositive electrode in the charged state is referred to as the anode in the battery/capacitor industry. In the second-age time, the reaction mechanism of a modern battery and the complexity of a real electrode will be addressed.

2.4 Basic Principle of Advance Energy Storage

Environmental worries over the continued use of nonrenewable resources and the growing difficulty of power delivery networks have spurred the urgent use of alternative and clean energy sources such as wind and solar energy. In terms of non-constant power generation, the efficient use of these new energy sources is critical. As a result, developing advanced energy storage systems for delivering energy on demand is a successful technique. Energy storage devices are currently available for a variety of large-scale applications and are divided into four categories, as seen in Figure 2: mechanical, chemical, electrical, and electrochemical.

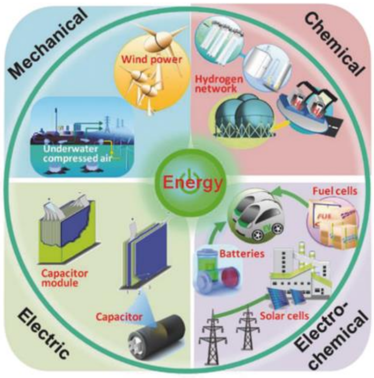


Figure 2: Different types of energy technology.

Currently, mechanical energy storage through pumped hydroelectricity is the most common form of energy storage. Electrochemical energy storage (EES) systems, such as electrochemical capacitors (ECs) and batteries, have shown great promise in powering portable electronics and electrifying transportation because of their advantages of high round-trip performance, long cycle life, and the ability to be implemented with a variety of chemistries based on cheap, sustainable alumina [7]. Electric energy is generally deposited in EES in one of two ways: directly by a non-faradaic process or indirectly through a faradaic process. Non-faradaic systems use electrostatic storage to store energy. Electric double-layer capacitors (EDLCs) are typically highly efficient and ideal for power storage (e.g., frequency regulation), but they have a poor energy density and a short discharge period. Electrical energy can also be retained by converting it to chemical energy, which requires faradaic oxidation and reduction of electrochemically active reagents and then releasing it on demand. Pseudo capacitors and assorted batteries are common examples of faradaic devices. Figure 3(a) shows a Rag one plot that contrasts the power and energy relationships of different EES structures. Grid-scale stationary EES device sales are expected to rise from $1.5 billion in 2010 to $25.3 billion in the next ten years, according to Pike Research, with EES technologies seeing the most dramatic increase.

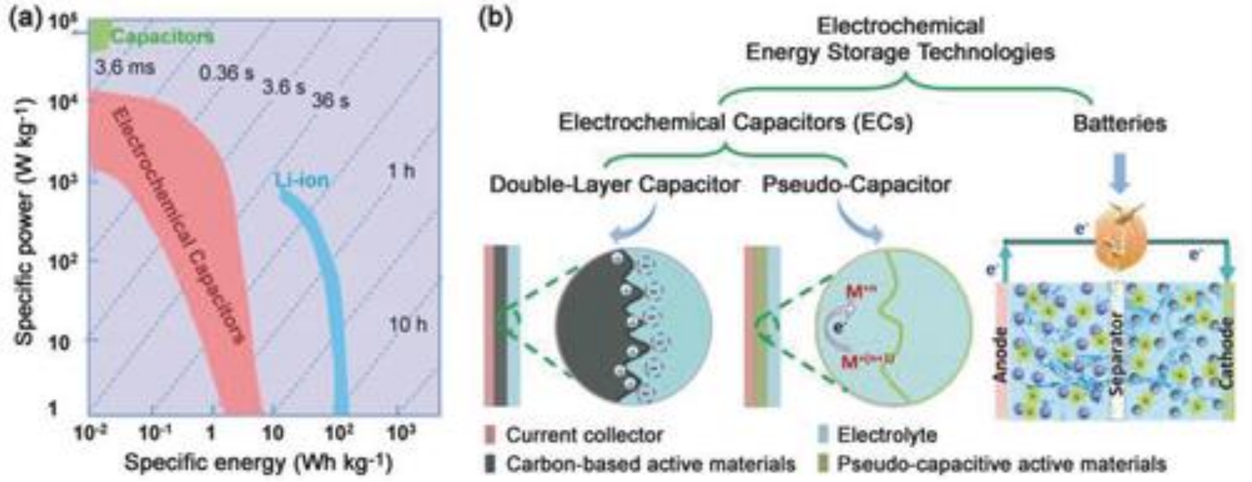


Figure 3: (a) Rag one plot comparing the power-energy characteristics and charge/discharge times of different energy storage devices. b) Schematic diagram comparing the fundamental mechanisms of electrochemical energy storage in double-layer capacitors, pseudo-capacity.

Although EES solutions have a lot of scope for use, their operational efficiency is still lagging behind the industry's extremely stringent requirements. Identification of suitable electrode materials that meet the specifications of high energy/power densities and long cycles is a major challenge. Reduced particle size, morphology modulation, and composite materials have all been suggested as possible solutions. Because of the popular movement toward increasing the reciprocal penetration of nanostructured materials, certain novel electrode materials close the gap in electrochemical activity between ECs and batteries (combining the high-energy-density of batteries with the high-power density of pseudo capacitors). Depending on its composition, morphology, particle size, and intercalation ion (i.e., Li^+ or Na^+), the same electrode material can exhibit pseudocapacitive or battery-like activity. Furthermore, the fabrication of hybrid materials, which incorporate two or more electroactive materials in a single-electrode configuration, increases the electrochemical behavior's complexity. To prevent any misunderstanding and incorrect assumptions in the field of electrochemical energy storage, detailed comparisons of EES systems using accurate dimensions and tests would be beneficial. Furthermore, such research will advance fundamental knowledge and provide fundamental guidelines for material selection and electrode design for high-performance energy storage systems.

The fundamental electrochemistry principles and the simple research techniques used to classify capacitive features are first introduced in this article. We'll go through some examples of how pseudo capacitive and battery-type materials are differentiated and categorized using these general properties. The latest materials and electrode design techniques for high-performance energy storage are then discussed. Pseudo capacitive materials with intrinsic properties are described, extrinsic pseudo capacitive materials are debated, and novel hybrid architectures for high-performance energy storage systems are suggested. This study can help to improve basic electrochemistry knowledge as well as functional research methods for characterizing different nanostructured electrode materials for advanced electrochemical energy storage technologies.

Due to their rapid charge-discharge rate and long-life span, EC devices have gained a lot of attention in recent decades. ECs have greater power densities than other energy storage systems, such as lithium, and can charge and discharge in a matter of seconds (Figure 3a). Since the first patent on ECs was issued by General Electric in 1957, these devices have been used in a variety of areas, including power capture and delivery, power quality applications, and backup power. Based on their energy storage systems, ECs are divided into two categories: EDLCs and pseudo capacitors (Figure 3b). Energy is deposited in EDLCs by electrostatic charge accumulation at the electrode-electrolyte interface. Electro sorption and/or reversible redox reactions at or near the surface of the electrode substrate, typically a conducting polymer or transition metal oxide, store energy in pseudo capacitors. All of these functions are present in a supercapacitor system in general.

EDLCs store energy through charge adsorption at the electrode's surface, rather than through faradaic reactions. The configuration of the charges in the Helmholtz double-layer results in a displacement current during the charge/discharge phases. EDLCs can produce energy rapidly because the materials can respond quickly to changes in potential and physical reactions in nature, as seen in the Rag one plot in Figure 3a. The amount of stored energy is small and much smaller than that of pseudo capacitors and batteries due to the confinement of the electrode surface. The following is a summary of the EDL capacitance,

$$C_{dl} = \frac{Q}{V} = \frac{\Sigma r \Sigma 0 A}{d} \qquad (1)$$

Where C_{dl} is the EDL capacitance of a person anode, Q is the entire charge exchanged at potential V, εr is the dielectric settled of the electrolyte, εo is the dielectric consistent of a vacuum, d is the charge break remove, and A is the cathode raise area. When Cdl is consistent for EDLCs, the taking after condition depicting the reaction current, I can be inferred from Condition 1

$$I = \frac{dQ}{dt} = C_{dl}\frac{dV}{dt} \qquad (2)$$

where t is the charge time. If the applied voltage V varies with time t in a linear way, that is, $V = V_0 + vt$ (where V_0 is the initial voltage and v is the sweep rate (V s^{-1} or mV s^{-1})), the relationship can be described as,

$$I = C_{dl}\nu \qquad (3)$$

The current responses straightly with a clear rate, as appeared in Condition 3. This interprets into a well-defined rectangular current (I)–voltage (V) plot or cyclic voltammogram for distinctive clear rates Figure 4(a). Conceivably, on the off chance that the capacitor is charged or released beneath a settled current, the voltage will raise (charging) or decrease (releasing) with a settled rate, as calculated by Condition 3. In this way, a triangular charge/discharge bend is anticipated, as appeared in Figure 4(b).

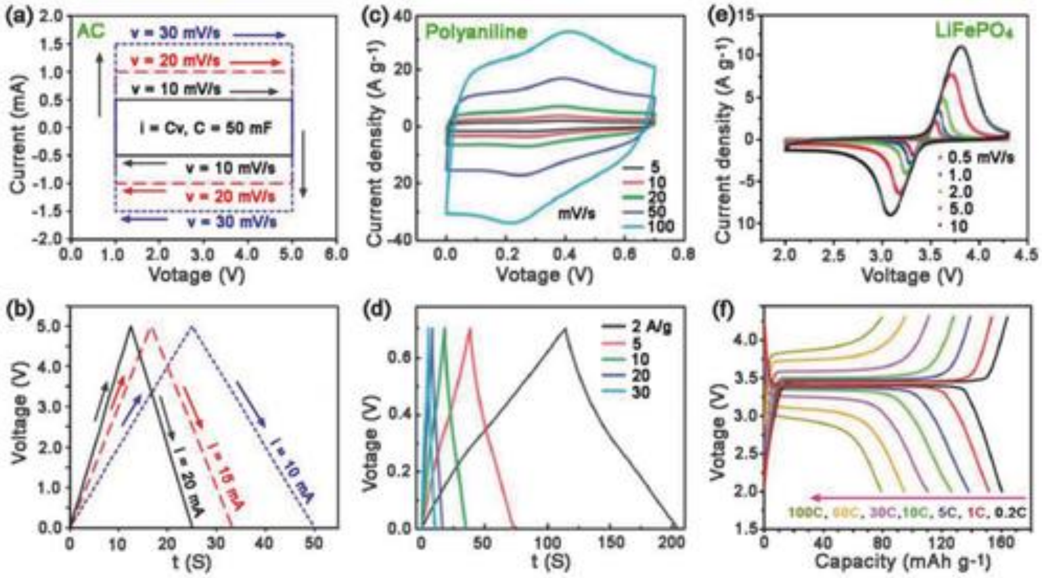


Figure 4: Cyclic voltammograms (top) and galvanostatic charge/discharge curves for different types of electrode materials.

This arrangement appears a wide run of clear rates and current densities, highlighting the special electrochemical highlights of each fabric. A move from (a, b) ordinary capacitive behavior to (e, f) normal battery behavior has been well outlined with (c, d) pseudocapacitive behavior as a middle-of-the-road case.

Over the final decades, vital progress made in fundamental understanding and plan of terminal materials for vitality capacity gadgets. Carbon-based materials, such as energized carbons (ACs), carbon nanotubes (CNTs), and graphene, are thought of as EDLC supercapacitors, where their anode surface region and surface state, pore arrangement and pore measure allotment, and the number of carbon layers, are basic parameters. To date, the gigantic endeavor has been made to upgrade the vitality thickness of EDLCs, considering coordinating carbon pore sizes with the electrolyte particle estimate, oxygen functionalizing the carbon surface or fitting the oxygen substance, adjusting carbon with heteroatom (N, S, F, etc.) doping or co-doping, receiving redox dynamic species-based electrolytes, and planning ionic fluids with tall working voltage and a mass temperature run in any case, EDLC supercapacitors can still not pay a visit to the unbending requirement for high-energy thickness gadgets due to inherent disadvantages, constraining their large-scale application [8].

2.5 Various Types of The Battery System

2.5.1 Lead Acid Battery

Normally,12 volts lead-acid battery has six isolate 2-volt cells linked in series. Fig 5(a) describes a single cell. The anode formed a lead plate that roofed with spongy lead. The cathode build lead (2) oxide accumulates on a lead plate. Two electrodes are sunk in an electrolyte near 4.5 M sulfuric acid. The lead-acid battery tasks as a galvanic cell to serve current to the exotic load when its battery discharge. The spongy lead anode is oxidized to lead (2) ions, which next respond with sulfuric acid to build infusible lead (2) sulfate.

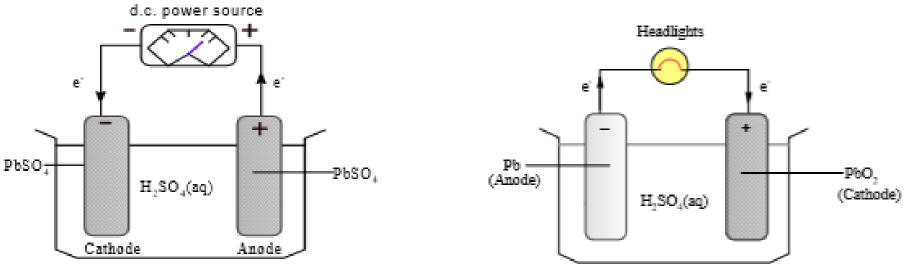


Figure 5: (a) A discharging Lead-acid battery, (b) A recharging Lead-acid battery.

The Lead anode makes electrons because it bears a negative charge, that footstep by exotic circuit and repeat drives the lead (4) oxide cathodes. The Lead (4) oxide is decreased by lead (2) sulfate. The cathode has a positive charge that causes electrons are eroded. Bothe releasing electrons are metallic lead and accepting electrons is lead (4) oxide are responsible for chemical reaction. The two half-reaction during discharge,

$$\text{Anode: } Pb(s) + H_2SO_4(aq) \rightarrow PbSO_4(s) + 2H(aq) + 2e \qquad (4)$$

$$\text{Cath: } PbO_2(s) + 2H(aq) + H_2SO_4(aq) + H_2SO_4(aq) + 2e \rightarrow PbSO_4(S) + 2H_2O(l) \qquad (5)$$

The upstairs two half-reaction omit both electrodes roofed infusible lead (2) sulfate. The overall discharge reaction,

$$Pb(s) + PbO_2(s) + H_2SO_4(aq) \rightarrow 2PbSO_4(s)+2H_2O(l) \qquad (6)$$

Here sulfuric acid vanishes and water is produced. In time discharge assembly and solidity of aqueous sulfuric acid drop calmly. By surveying the fixed gravity of its aqueous sulfuric acid, the situation of charge of the battery can be ascertained. Here Fig 5(b) indicates that how a full discharge lead-acid battery can be recharged by conquering a straight current through it [9]. The two half-reaction in time recharge,

$$\text{Cathode: } PbSO_4(s) +2H(aq) +2e \rightarrow Pb(s) +H_2SO_4(aq) \qquad (7)$$

$$\text{Anode: } PbSO_4(s) +2H_2O(l) \rightarrow PbO_2(s) +2H(aq) +H_2SO_4(aq)+2e \qquad (8)$$

And the overall recharge reaction,

$$2PbSO_4(s) +2H_2O(l) \rightarrow Pb(s)+PbO_2(s)+2H_2SO_4(aq) \qquad (9)$$

2.5.2 Lithium-Ion Battery

The Lithium-ion battery is more plight energy storage processing gainable and extensively used in portable electronics. It is now valued at the rest of the world and 10 billion dollars per year growing. The main cause behind this quick growth is its high energy thickness and also recycling. Execution which has no alternative energy storage devices can compare. At present demand for energy and green energy increasing day by day. This battery (lithium-ion) system for vehicle and grid load leveling alongside encomiastic energy storage for renewable energy such as solar and wind power system of lithium-ion battery is just directly lithium-ion batteries reserve electrical energy in electrodes produced intercalation with buddy oxidation and wane method happening at the two electrodes. Normally Lithium-ion battery shaped a graphite negative electrode(anode), a nonaqueous fluid electrolyte, and a laminar $LiCO_2$ positive electrode which show in Fig 6(a) that charging Li+ ions.

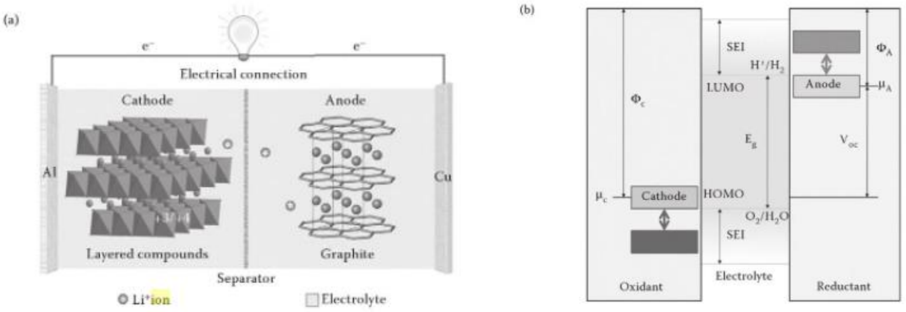


Figure 6: (a) A traditional Lithium-ion battery, (b) Open circuit energy diagram.

Generally, consecutive Lithium-ion battery cell in that, in time discharge Li+ ions drive away by the electrolyte and electrons flux per the exotic circuit, both passing from the anode (negative) to the cathode(positive). Fig 6(b) open circuit energy diagram of an aqueous electrolyte, anode, and cathode work functions (Φ_A an Φ_C) where Eg is the electrolyte potential window for thermodynamic stability [10]. The chemical reaction here,

$$\text{Cathode: } Li_{1-x}CoO_2 + XLi^+ + Xe \rightarrow LiCoO_2 \quad (10)$$

$$\text{Anode: } Li_x C_6 \rightarrow XLi^+ + xe^- + C_6 \quad (11)$$

Full cell reaction,

$$LiC_6 + CoO_2 \rightarrow C_6 + LiCoO_2 \quad (12)$$

2.5.3 Sodium-Sulfur Battery

Sodium-sulfur (Na-S) batteries are a sort of high-temperature, fluid metal battery that was displayed inside the 1970s. They have a put to a family of batteries known as sodium beta batteries; the negative terminal is made of liquid sodium while a solid ceramic texture of beta-alumina (a sort of aluminum oxide) serves as the electrolyte (Figure 7). In a sodium-sulfur battery, the positive anode is made from liquid sulfur. In arrange that the cathodes be kept in their liquid state, and to empower the response component whereby sodium particles are passed through the electrolyte to combine with the sulfur, these batteries must be worked and directed at a tall temperature, regularly 300°C. Usually not as restrictive because it sounds; on the off chance that the batteries are cooled at that point self-discharge is made irrelevant as a chemical response cannot take put, and keeping up the tall temperature amid operation is effectively accomplished by collecting the normal warming impact from tall current conduction amid operation.

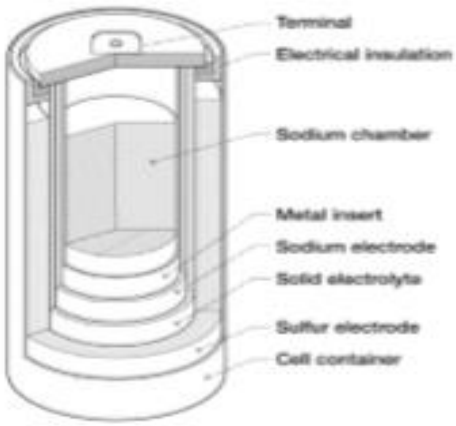


Figure 7: Cut-away sodium sulfur.

2.5.4 Redox Flow Battery

In an RFB, the cathode and anode materials are made by electrolyte solutions (i.e. catholyte and anolyte) in where the energy is stored. The electrolyte at the anode and cathode sides is pushed through porous electrodes located at each side in a cell stack, to prevent mixing, where they are separated by an ion-exchange porous separator or membrane. Electrochemical redox occurs a reaction on the electrode surfaces. This standard model of RFBs allows independent scaling of the power and/or energy. The power is dependent on the size and design of the electrochemical cell

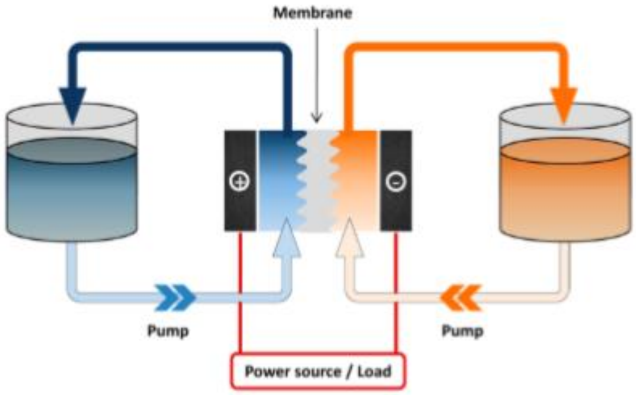


Figure 8: Schematic illustration of a redox flow battery. Active species are stored externally in the storage tanks, while the conversion between electrical and chemical energy occurs in the cell unit.

(the stack) whereas the energy is defined by the number of stored electrolytes. The energy to power ratio (E/P) can be widened over a high range. A high E/P ratio can reduce the cost of the entire system by more than 50% on an energy basis. On the other hand, since they are particularly well suited for small and medium-scale applications and for a short-term duration and fast response times, Li-ion batteries are well suitable for the electronics and automobile industries applications. However, scaling up Li-ion batteries is difficult so requires additional management systems for small-format battery cells [11].

Redox flow batteries have been examined for nearly 40 a long time, ever since the primary concept detailed by Thaller in 1976. NASA-Lewis Research Middle created the primary total redox vitality capacity framework based on the Fe (III)/Fe (II) and Cr (III)/Cr (II) redox couples as the positive and negative dynamic species, individually. Since at that point, redox stream batteries have been altogether created, driving to different systems. By and large, two major standards can classify RFBs [12].

Characteristics of RF batteries:

1. RF batteries have some characteristics and can be used in various applications.
2. 1. The battery reaction principle of RF batteries is simply the change in the valence of the metal ions in the electrolyte, realizing a long charge/discharge cycle service life.
3. 2. The yield segment (cells) and capacity area (tanks) are autonomous of each other, and those can be ideally planned concurring to application needs.
4. 3. Maintenance is simple since the same electrolyte is provided to individual cells and thus the state of charge (SOC) in each cell does not ought to be observed, as a result, heat can be controlled effectively by the flowing electrolyte. While the SOC can be effectively checked by measuring the potential of the electrolyte, the SOC can be observed persistently during operation.
5. 4. In positive and negative tanks, the electrolytes are stored separately, so that no self-discharge occurs during standby and stoppage, except in the cell section.
6. 5. RF batteries are effective to absorb irregular and short-cycle output fluctuations, such as in natural energy generation because of the characteristic of instantaneous response in an order of milliseconds and that can charge and discharge at an output rate a few times larger than the designed rating for a short period of time.

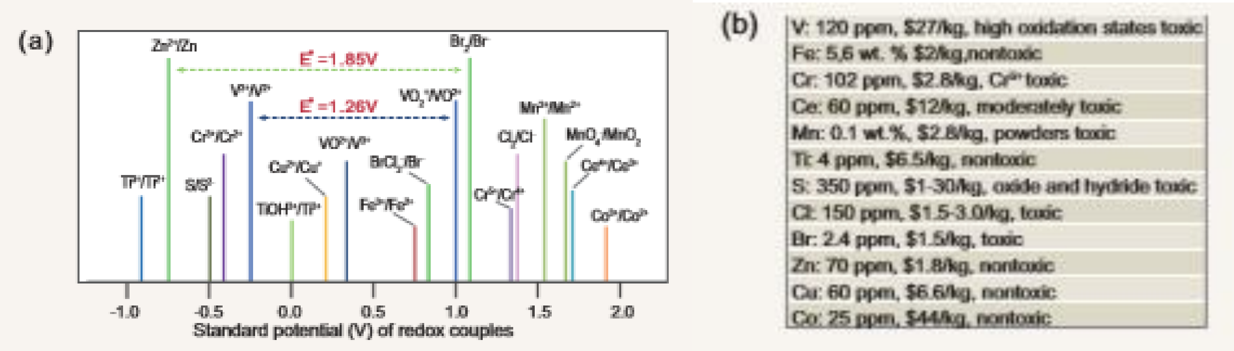
7. 6. The electrolyte is friendly for the environment because it just changes during normal operation except for changes in ion valance, and it can be used virtually permanently and reused.

The disadvantages of RF batteries are as follows:

1. Because an RF battery uses metal ions that solved in a solution whereas its active material, solubility is limited, and hence the volume of the tank section is filled by necessity large, and the energy density is comparatively small compared with other energy storage batteries.
2. To circulate an electrolyte to the cells, pumping power is badly needed.
3. Shunt-current losses may take place through electrolytes.

2.5.4.1 Aqueous Redox-Flow Batteries

Due to the great safety characteristics and high control densities (e.g. VRBs and hydrogen/bromine RFBs), aqueous systems have attracted broad interest. It has one drawback, which's the lower energy density. Figure 9(a) appears the potentials of conventional redox couples, which made of inorganic materials. The availabilities, toxicities, and approximate costs of the materials have appeared in Fig. 9(b) [13].



V: 120 ppm, \$27/kg, high oxidation states toxic
Fe: 5,6 wt. % \$2/kg,nontoxic
Cr: 102 ppm, \$2.8/kg, Cr^{6+} toxic
Ce: 60 ppm, \$12/kg, moderately toxic
Mn: 0.1 wt.%, \$2.8/kg, powders toxic
Ti: 4 ppm, \$6.5/kg, nontoxic
S: 350 ppm, \$1-30/kg, oxide and hydride toxic
Cl: 150 ppm, \$1.5-3.0/kg, toxic
Br: 2.4 ppm, \$1.5/kg, toxic
Zn: 70 ppm, \$1.8/kg, nontoxic
Cu: 60 ppm, \$6.6/kg, nontoxic
Co: 25 ppm, \$44/kg, nontoxic

Figure 9: (a) Redox potential of various inorganic redox couples (b) The cost of active species displayed in.

2.5.4.2 Non-Aqueous Redox-Flow Batteries

The utilize of non-aqueous electrolytes in RFB configurations has been considered since of the higher cell possibilities that are conceivable when one isn't concerned by the breakdown of the watery electrolyte. In expansion, numerous couples and reactants are much more solvent in non-aqueous solvents. In any case, the challenges of low electrolyte conductivities, soundness, and taken a high to constrain the improvement of nonaqueous RFB frameworks.

As an illustration, the zinc/cerium cell has been worked on by Plurion Constrained. As with the zinc/bromine cell, the negative cathode breaks up and plates zinc, Eq 13,

$$Zn \rightleftharpoons Zn^{2+} + 2e^{-},\ E^{0} = -0.75V \text{ vs. RHE} \qquad (13)$$

and at the positive cathode, cerium is carried between Ce (III) and Ce (IV)

$$Ce^{3+} \rightleftharpoons Ce^{4+} + e^{-},\ E^{0} = 1.75V \text{ vs. RHE} \qquad (14)$$

The designers claim a cell potential of roughly 2.5 V on charging, but it drops underneath 2 V amid release with a vitality thickness of 37.5 to 120 Wh/L. The high working potential window is accomplished by utilizing methane sulfonic corrosive instead of unadulterated water as the dissolvable, hence minimizing the decay of water into hydrogen and oxygen, as well as supporting in zinc plating. The redox response of Ce (III)/Ce (IV) is kinetically slow and Ce (III) contains a to some degree low diffusivity. High corrosive quality encourages the dissolvability of Ce (IV); be that as it may, the dissolvability of Ce (III) diminishes at higher corrosive concentrations. Other electrochemical couples counting zinc/chlorine, zinc/ ferricyanide, and vanadium/cerium have been considered. Whereas non-aqueous electrolytes by and large infer higher costs than watery electrolytes and must be confirmed for natural and chemical compatibility, the development of the working potential window is alluring, as the cell potential distinction encompasses a coordinate effect on the sum of control that can be conveyed for a specified current density [14].

2.6 Advantages and Disadvantages of Various Batteries

Lead Acid Battery

Advantages

1. It is accessible in all shapes and sizes.
2. It requires low maintenance.
3. Its reliability and working capabilities are good.
4. It offers the most excellent power for control and energy per KWH.
5. It has the longest life cycle.
6. Almost 97% of lead can be reused and reused in modern batteries.

7. It performs good performance at low and high temperatures.
8. Low-cost and basic fabricate Low cost per watt-hour.
9. It has the longest life cycle and has a large environmental advantage.

Disadvantages

1. Lead is heavier compare to other elements.
2. It is naturally threatening.
3. It can be charged slowly. For a fully saturated charge, it takes 14 to 16 hours.
4. It has low energy density, poor weight to energy ratio.
5. It cannot be stored in discharge conditions.
6. It has limited cycle life and repeated deep cycling reduces battery life.

Lithium Ion Battery

Advantages

1. It has a high energy density.
2. They don't require and support to guarantee their performance.
3. Its rate of charge loss is less.
4. It has a greater number of charge and discharge cycles.
5. It can operate at a higher voltage than other rechargeable batteries.
6. It incorporates a moo self-discharge rate.
7. Its specific energy and energy density is high.
8. They Have high coulombic and vitality effectiveness.
9. They are less weight.

Disadvantages

1. It needs a high cost compared to other batteries.
2. Its complete discharge can damage the battery.
3. Amazingly delicate to high temperature.
4. It has a very short lifespan.
5. Need a protective circuit to maintain voltage and current within safe limits.
6. They are not available in all standard cell types.

Sodium Sulfur Battery

Advantages

1. It has a high energy and power density.
2. It has high efficiency of charge and discharge.
3. It has a long cycle of life.
4. It is created from reasonable materials.
5. They have a high cycle efficiency typically in the range of 75-90%.
6. These batteries have good cycling flexibility.
7. It has low support requirements.
8. These batteries are suitable for large-scale non-mobile applications such as grid energy storage.
9. The battery has no self-discharge.

Disadvantages

1. It has a high operational temperature with lower efficiency.
2. It shows some danger of explosion upon degradation.
3. It shows difficulties in making megawatt-scale batteries include thermal management and safety.
4. It requires a warm source for operational conditions.
5. It drains part of the battery’s efficiency since the heat source needed.

Nickel Metal Hydride Battery

Advantages

1. It is ecologically friendly.
2. It has a high energy density.
3. It has a lower cost than a lithium-ion battery.
4. It has a 30% higher capacity than a standard Nickel-cadmium battery.
5. It contains no toxic metals.
6. They contain only mild toxins, so it is profitable for recycling.
7. It is simple in storage and transportation.

8. They are less prone to memory than the Nickel-cadmium battery. Intermittent exercise cycles are required less frequently.

Disadvantages

1. It has a limited service life.
2. It has a limited discharge current.
3. Its high load currents reduce the battery’s cycle life.
4. It requires high support costs.
5. About 20% more expensive than Nickel-cadmium battery.
6. They have some memory effect problems.
7. More complex charge algorithm is needed than a Nickel-cadmium battery.

Redox Flow Battery

Advantages

1. 1. It has an independent system design for power and capacity.
2. 2. High efficiency; above than 75%.
3. 3. It has a long period lifespan.
4. 4. These batteries have low self-discharge ability.
5. 5. It is also ecologically neighborly.
6. 6. Its operation safety is much.
7. 7. They are very suitable for applications in the energy storage sector.

Disadvantages

1. It has poor electrolyte stability.
2. Its solubility capacity also less.
3. Low-rated operation current density responsible for high material cost.
4. It requires a high cost of ion exchange membrane.
5. Have a low selectivity to the vanadium ions.

2.7 History of Development of Redox Flow Batteries

The batteries' full-scale production began in the 1970s. In 1974, L. H. Thaller of the National Aeronautics and Space Administration (NASA) of the United States proposed the concept of the RF battery method [15]. The Fe/Cr system was the focus of NASA's study, which ended in 1984 with the release of the Final Report. In Japan, the Electrotechnical Lab was conducting basic research at the time, and the implementation of the Fe/Cr system as a project of the New Energy and Industrial Technology Development Organization was progressing (NEDO). The V system was developed by the University of New South Wales (UNSW) in Australia around 1985. Electric power companies and manufacturers in Japan collaborated enthusiastically on research into the practical use of RF batteries, and the V system was partially implemented in 2001. The following table 1 is a description of the evolution of the Fe/Cr system and the V system:

Table 1: History of RF Battery Development.

Year	**Developments**
1949	✓ Kangro: Cr/Cr and other systems
1974	✓ Battelle: Cr/Cr, Fe/Cr, V, Mo, Mn and other systems
1974	✓ NASA released the principle of the RF battery—U.S. basic patent. ✓ Fe/Cr system 1 kW, Final Report ETL started the research and development of RF Battery.
1980	✓ NEDO (Moonlight Project) established the project "Advanced Battery Electric Power Storage System." ✓ RF (ETL./Mitsui Engineering and Shipbuilding [MES]), NaS (Yuasa Battery), Zn/Br (Meidensha), and Zn/Cl_2 (Furukawa Electric) ✓ ETL, Fe/Cr system, 1 kW; MES, 60 kW NEDO (Sunshine Project) ✓ RF battery for solar power generation (MES and Ebara
1985	✓ University of New South Wales (UNSW; Australia) released the V system RF battery and applied a basic patent.
1989	✓ ETL. and Kashima Kita Electric Power developed V system RF battery for the use of vanadium from the soot. ✓ V system, 1 kW (Ebara); 10 kW (MES); 200 kW (Kashima Kita) KEPCO and Sumitomo Electric ✓ Fe/Cr system, 60 kW; V system (450 kW)

1998	✓ ETL. and Kashima Kita ✓ 10 kW Redox Super Capacitor on-vehicle test.
2001	✓ Sumitomo Electric put V system RF battery into practical use (for load leveling, instantaneous voltage sag compensation and emergency use). NEDO verified the RF battery for stabilizing the wind power output fluctuation. Sumitomo Electric: 170 kW ('00), 6 MW.
2011	✓ The development of RF batteries is proceeding worldwide, including in the U.S., Europe and China.

2.7.1 Iron–Chromium (Fe/Cr) System

Expectations developed in Japan around 1980 for the construction of large-capacity energy storage batteries that would supplement pumped hydro energy storage to increase the load factor, which was declining at the time due to load leveling. RF, sodium/sulfur, zinc/bromine, and zinc/chlorine batteries are among the four advanced batteries being developed by NEDO's Moonlight Project. The ETL was primarily responsible for RF battery analysis [16]. The laboratory began by conducting fundamental experiments on a variety of redox pairs before moving on to realistic research on the Fe/Cr mechanism with the aid of a hydrochloric acid solution. Mitsui Engineering and Shipbuilding Co., Ltd. (MES) produced and tested 10 kW and 60 kW system designs as part of the NEDO initiative from 1984 to 1987, in addition to these fundamental technological advancements [17]. In 1985, Kansai Electric Power Co., Inc. (KEPCO) and Sumitomo Electric Industries, Ltd. (Sumitomo Electric) began developing RF batteries on their own, and in 1989, they tested a 60-kW class Fe/Cr system RF battery [18].

The Fe/Cr system has the subsequent problems: the metal ions' conductor reaction is slow; as a result of the various metal ions area unit utilized in positive and negative reactions, every particle is mixed through the membrane and therefore step by step decrease the battery capacity; the metal ions' oxidation-reduction potential is about to the H gas generation potential and a little quantity of H gas is generated from the negative conductor close to the tip of the charge, thereby reducing the battery capability owing to variations within the SOC between the positive and negative electrodes. The problem of redox ion mixing between the positive and negative electrodes was technically solved by KEPCO and Sumitomo Electric using a single-fluid Fe/Cr method in which

Fe ions and Cr ions are combined in both the positive and negative electrodes. The electrode properties were improved, and different types of accessories known as rebalancing systems, which change the SOC for both the positive and negative electrodes over time, were proposed to solve the problem of hydrogen gas production. MES substituted Fe ions with Br ions for the positive electrode and studied Cr/Br structures in order to improve the energy density of the Fe/Cr system [19]. Similarly, the ETL and Ebara Corp. collaborated on a feasibility study for the Cr/Cl scheme. The V/O_2 device, which uses air on the positive electrode, was also investigated.

2.7.2 Vanadium System (V/V system)

Prof. Maria Kazacos of the UNSW proposed V device RF batteries, which use V ions at both the positive and negative electrodes, around 1985 and applied for a basic patent in 1986 in Australia, where vanadium supplies are plentiful [20,21]. For economic purposes, V system RF batteries were not pursued with zeal in Japan, which lacks natural vanadium capital. However, Kashima Kita Electric Power Corp. (Kashima Kita) and the ETL developed a technology for recycling vanadium from the soot of thermal power plants' fuels burnt. As a result, the economic importance of V system RF batteries was assessed, and production of these batteries began in the region [22]. The electrical phenomenon of the V system was just about one.4 V, that was 1.4 times as giant as that of the Fe/Cr system, so that, providing the cells and energy potency was an equivalent, the output was double. The performance was observed to be many times as high since the electrode reaction of V ions was comparatively quick in practical application. In comparison to the Fe/Cr system, the system used V ions at both the positive and negative electrodes, but even though ions were mixed between the positive and negative electrodes across the membrane, the battery power did not decrease.

Since the redox potential of V ions at the negative electrode was higher than that of Cr ions, hydrogen gas production was incredibly low, obviating the need for rebalances the device in practical application. Because of these advantages and the applicability of Fe/Cr system battery technology, the invention of V system RF batteries began in earnest in Japan around 1989. Kashima Kita built a 200 kW/800 kWh system for testing in 1997. In 1996, KEPCO and Sumitomo Electric produced a 450 kW/900 kWh system [23]. Following that, work on the small-capacity system for customer application continued, and in 2000, a 100 kW/800 kWh system designed for buildings was constructed in an office building and verification operations were carried out [24].

In 2001, Sumitomo Electric produced practical products for a variety of applications, including load-leveling, instantaneous voltage sag compensation, and emergency power supply [25].

2.8 Summary

We addressed the evaluation of energy systems and batteries, as well as battery concepts and types, in this chapter. Redox flow batteries, their flow mechanism, and applications were thoroughly discussed. In this session, the benefits and drawbacks of different battery systems were also presented.

One of the most pressing problems in the production of redox flow batteries is increasing energy density. Recent RFB Research has suggested a number of approaches to higher energy density, as reviewed. Various redox organisms, in particular, have been investigated to increase concentration and cell voltage in both aqueous and non-aqueous systems. Meanwhile, the Vanadium redox flow method may be a promising way to boost RFB's energy density to new heights.

Chapter 3

Vanadium Redox-Flow Battery Technology

3.1 Introduction

A prototype vanadium redox flow battery was designed by the University of New South Wales in Australia in 1984. This was the first time a flow battery membrane had the same chemical on both sides. Flow batteries, according to scientists, maybe the secret to replacing coal and nuclear power plants with wind and sunlight. The vanadium redox flow battery (VRFB) is a flow-assisted electrochemical device with high energy efficiency, long lifetime, design versatility, and low maintenance that shows great promise for grid-scale energy storage [26]. There are a number of benefits and drawbacks associated with VRFB technology in particular. The following are some of the benefits of VRFB technology:

- There was no solution contamination due to vanadium ion diffusion through the membrane.
- Ion crossover regeneration occurs naturally as a result of normal battery activity.
- Depending on the treatments and conditions exposed to the materials, moderate efficiency (between 70–90 percent for monitored laboratory setups).
- In comparison to other flow batteries, there is less gas evolution during short charge cycles.
- Electrolyte recycling between applications is a possibility. On the other hand, there are several drawbacks to VRFB technology.
- To prevent thermal precipitation of vanadium species, thermal control systems are used to hold the system between 10°C and 40°C.
- Some ion-exchange membranes and the positive electrode terminal deteriorate due to V^{5+}'s high oxidation properties.
- Gases generated at the electrode can harm the cell and reduce its performance.
- Gas evolution drained the battery charge and reduced the electrode surface area.

3.2 Working Principle of Vanadium Redox Flow Battery

The electrochemical redox stream cell comprises two half-cells that are isolated by a separator which can be an anionic trade film, a cationic trade layer, or a permeable layer. The fluid electrolyte stores electrical vitality within the shape of chemical particles which are dissolvable in fluid watery or nonaqueous electrolytes. The electrolytes of the negative half-cell (anolyte) and the positive half-cell (catholyte) are each circulated by a pump in isolated circuits. Both electrolyte distribution circuits are isolated by a separator. The work of the separator is to anticipate electrical brief circuits, avoid cross blending of the electrolyte, and guaranteed the particle trade over the separator equalizes the electrical charge of the anolyte and catholyte (Fig. 10). The particles that are traded depend on the kind of redox stream battery; the foremost common sorts are cationic trade films such as NAFION®. These per fluorinated and sulfonated layers have been utilized for decades and are exceptionally steady against chemical assault and oxidative erosion caused by tall possibilities. These films are generally utilized in corrosive electrolyte frameworks for vanadium redox stream cells or iron-chromium cells. Charge adjusting is effectively done by the transport of hydrated protons (hydronium-ion) through the layer.

These films are accessible around the world through a few commercial providers as a result they are fluorinated layers the cost is very high. The moment sort of layer is the anionic trade layer. In this case, the counter particle of the dynamic species is dependable for the charge adjust. These anionic-type films are in common cheaper, but chemical solidness needs to be carefully checked.

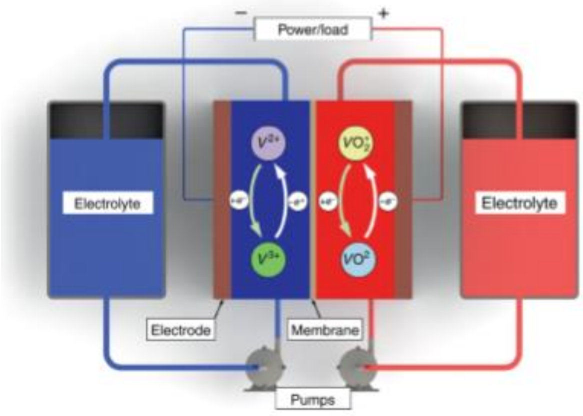


Figure 10: Working principle of vanadium redox flow batteries.

A vanadium-based electrolyte is broadly utilized in-stream batteries. This is often due to the simplicity and soundness of the electrolyte framework within the watery stage. In a fluid arrangement, four distinctive but steady valence states of vanadium exist (V^{2+}, V^{3+}, V^{4+} and V^{5+}). In anolyte vanadium (+2 and +3) particles exist as V^{2+}, V^{3+}, whereas the +4 and +5 valence states of vanadium exist as they were as oxo-complexes (VO^{2+}, VO_2^+). By changing the valence states of vanadium species, vitality might be put away electrochemically. These basic redox reactions are:

$$V^{2+} \rightleftharpoons V^{3+} + e^-, \quad E^{\varnothing} = -0.255\ V \tag{15}$$

$$VO^{2+} + H_2O \rightleftharpoons VO_2^+ + e^- + 2H^+, \quad E^{\varnothing} = +1.004\ V \tag{16}$$

The oxidation of V^{2+} discharges one electron, and V^{3+} is shaped. This makes a standard potential of 0.255 V. The oxidation of V^{4+} to V^{5+} by the synchronous part of a water atom discharge, a proton, and one oxygen molecule which frames the oxo complex. This conveys a standard potential of +1.004 V [27]. The in general standard potential for the response is 1.259 V. In a fluid electrolyte, the vanadium salts in all the four distinctive valence states—V^{+2}, V^{+3}, V^{+4}, and V^{+5}—must be dissolvable in concentrations which ought to be as tall as conceivable. The more vanadium salts held in a steady arrangement without precipitation the higher the volumetric vitality thickness of the electrolyte. The vanadium salt in valence state 5 has the most reduced dissolvability. The taking after condition portrays the response harmony between strong vanadium pentoxide and vanadium +5 in solution [28]:

$$1/2V2O_5(s) + H^+ \rightleftharpoons VO_2^+ + 1/2H_2O \tag{17}$$

The higher the proton concentration (corrosive concentration) the more the balance is moved to the correct side (rule of le Chatellier) and the more the V^{+5} vanadium (within the shape of VO_2^+) can be kept within the arrangement. Besides, the tall proton concentration of the electrolyte comes about in high electrolyte conductivity which in turn leads to great cell execution. The sulfuric corrosive is more often than not at a concentration of between 2 mol L^{-1} and 6 mol L^{-1} [29].

Exceptionally as of late blended electrolytes of sulfuric and hydrochloric acids have been utilized as electrolytes. The expansion of hydrochloric corrosive and so chlorine particles permits very high vanadium concentrations within the arrangement at indeed higher temperatures. The higher solidness of the electrolyte is caused by the arrangement of a chloro–oxo complex, and this steady complex anticipates the condensation response and precipitation of vanadium pentoxide [30]. This blended electrolyte has the advantage of higher vitality thickness and temperature stability but, on the other hand, can result in the conceivable discharge of harmful chlorine gas at the positive cathode during the charging handle. Besides, the nearness of chlorine seems to compromise fabric steadiness within the cell [31].

3.3 Vanadium Redox Flow Batteries Characteristics and Performance

The current state of the G1 and G2 vanadium redox flow batteries in terms of performance, charge and discharge characteristics, and cycle life is summarized in this chapter. First, the system's energy equilibrium must be created. The energy losses due to the cooling system (if necessary), the control system, the circulation system, as well as the coulombic and voltage efficiencies corresponding to both the charging and discharging processes, will all have an impact on the overall efficiency of this system [32].

As shown in Equation 18, the coulombic efficiency (η_C) can be defined as the ratio between the capacity input during charge (Q_{chg}) and the capacity output during discharge (Q_{dis}), where Ichg is the constant current during charging, t_{chg} is the charging time, I_{dis} is the constant current during discharging, and t_{dis} is the discharging time.

$$\eta \mathrm{C} = \frac{\mathrm{Qdis}}{\mathrm{Qchg}} = \frac{\mathrm{Idis} - \mathrm{tdis}}{\mathrm{Ichg} - \mathrm{tchg}} \tag{18}$$

The irreversible reactions, ion diffusion through the membrane, and shunt current losses all contribute to coulombic losses [32].

As shown in Equation 19, the voltage efficiency (η_V) is defined as the ratio of the average voltage during discharging (U_{dis}) to the average voltage during charging (U_{chg}).

$$\eta \mathrm{V} = \frac{\mathrm{ptUchg}}{\mathrm{Udis}} \tag{19}$$

Over-voltages occur during the charging and discharging cycles, resulting in voltage losses [32]. Cell energy efficiency (E) is defined as the product of the voltage efficiency and the coulomb efficiency, as shown in Equation 20 [33].

$$\eta \mathrm{E} = \eta \mathrm{V} \times \eta \mathrm{C} \tag{20}$$

The efficiency of these cells is determined by factors such as cell components, cell design, and cell stack form (e.g. countercurrent versus equicurrent modes). Furthermore, the efficiency of a given cell may vary based on the number of charges/discharge cycles the device has experienced, as well as the actual current density (in mA/cm^2), which is the current intensity per unit area of the membrane.

According to Vetter et al., the coulombic, voltage, and energy efficiencies (respectively) of a vanadium redox G1 technology with 700cm^2 of the active area were calculated with different current densities using a 1kW test device [34]. Figure 11 shows that for very low current densities (10mA/cm^2), the coulombic efficiency is low due to the long charging time, while for higher current densities (80mA/cm^2), the coulombic efficiency is high but the energy efficiency is lower due to over-voltages at the electrodes during the charge and discharge, which lowers the voltage efficiency [34].

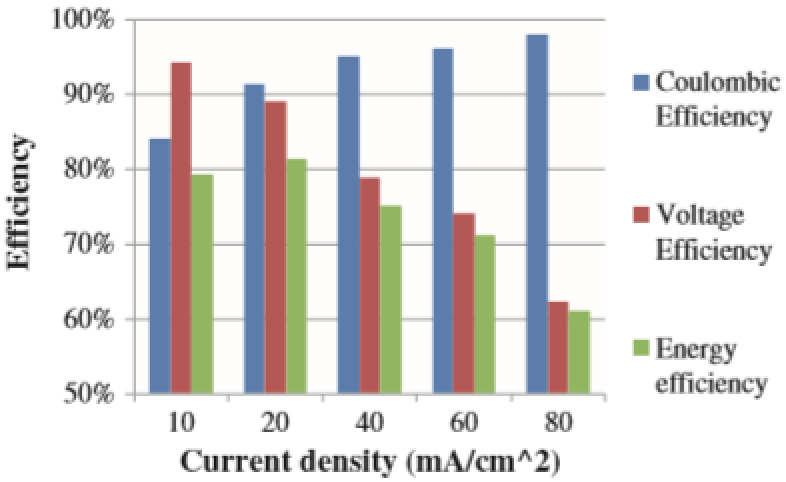


Figure 11: Reported coulombic, voltage and energy efficiencies of a G1.

The redox couples that are used determine the voltage of each cell unit during discharge and charge. However, due to energy losses associated with internal resistance, over-voltage losses due to finite kinetic half-cell reactions (activation overvoltage), and mass transport limitations, the cell's potential during discharge would be lower than it was during charging (concentration overvoltage). Figure 12 (a) depicts a typical disparity between the charge and discharge voltages.

Figure 12 (b) depicts a standard charge/discharge curve for a G2 technology vanadium redox cell with a 20mA/cm2 charge/discharge current density. When Figure 12 (a) shows that these values are lower than those corresponding to the G1 technology.

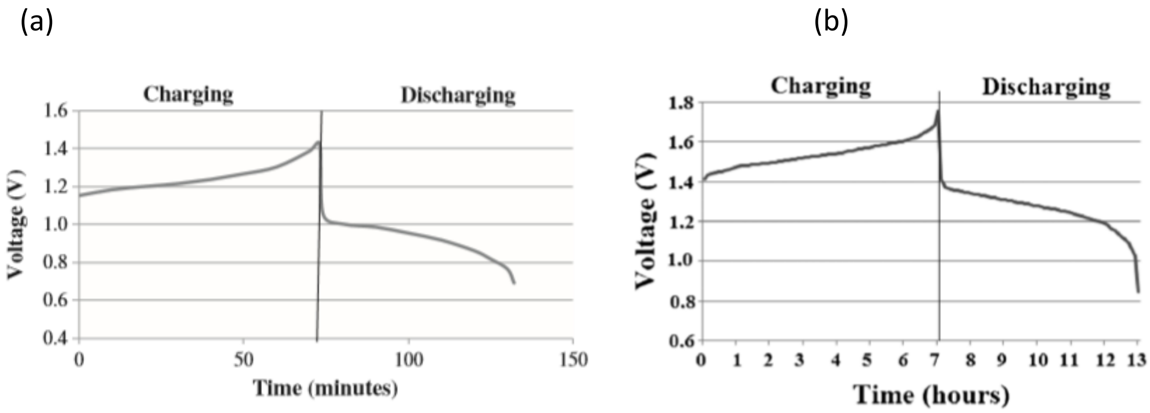


Figure 12: (a) Typical charge/discharge cycle of a single cell (G1 technology) for a current density of 40 mA/cm^2, (b) Typical charge/discharge curve for a vanadium redox G2 cell at current density of 20 mA/cm^2.

The coulombic and voltage efficiencies as a function of temperature and current density are shown in Figures 13 (a) and 13 (b). The trends in coulombic and voltage efficiencies with current density in G2 technology are close to those in G1 technology (Figure 11).

Figure 13 (c) shows the overall energy efficiency, and it can be checked that for $20mA/cm^2$, the overall efficiency of 70% can be achieved.

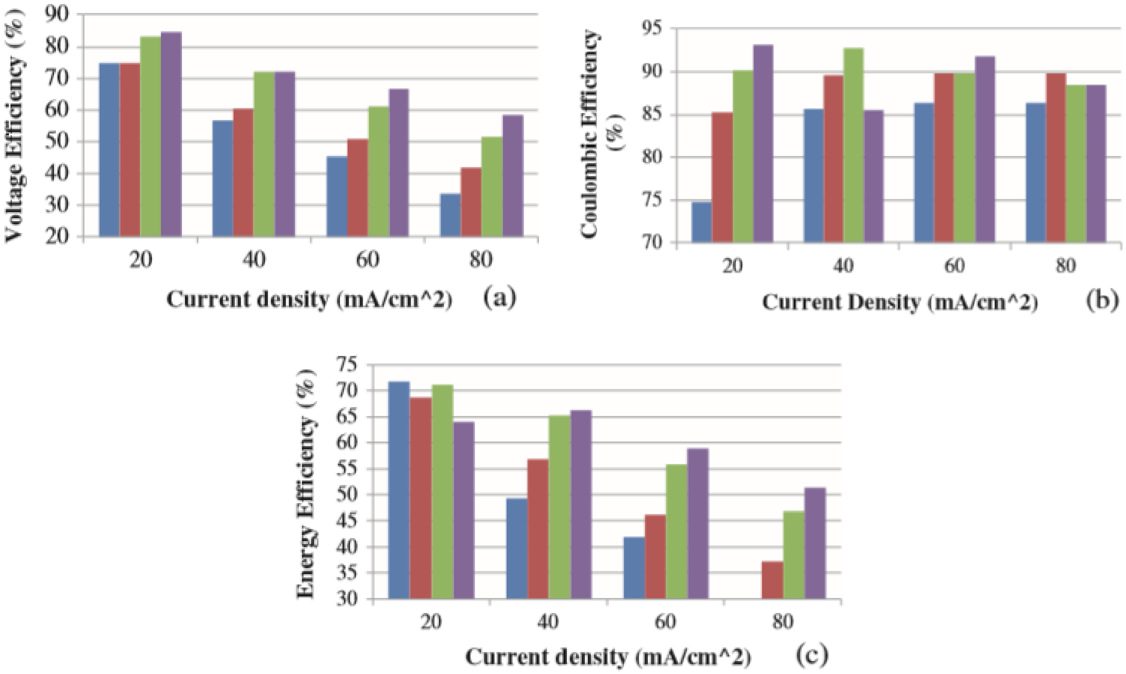


Figure 13: (a) Voltage, (b) Coulombic and (c) Energy efficiency as a function of current density and temperature for a G2 technology vanadium redox cell.

Since the maximum power output is a function of the flow rate, one of the most important characteristics of a VRFB is the flow rate that the corresponding pumping system can provide [35]. The theoretical flow rate of a VRFB system is a function of the current, the direction of the current (charge or discharge), and the SoC (considering a standard four-tank configuration; in batch mode, the flow rate is solely dependent on the current) [35]. When using the method for small values of SoC, this could be impractical. Divide the number of moles of vanadium oxidized per second by the molarity of vanadium ions in solution to get the minimum required flow rate [36].

Equation 21 can be used to measure the Faraday constant (F) and the minimum required flow rate (Q) given the number of cells (N), the current (I), and the concentration of vanadium in the solution (C_V) [36].

$$Q = \frac{I \times N}{F \times Cv} \times \left(\frac{L}{S}\right) \tag{21}$$

Higher voltages are typically induced by higher flow rates because the concentration of reaction products inside the cells at each side of the membranes during the process is lower (on average) [37]. However, because of the additional pumping power needed, there is additional energy consumption. If this is too high, it will reduce overall energy efficiency, so it is important to find the optimum value that will optimize the system's efficiency. For the reasons mentioned above, the availability of a variable pumping strategy is a critical factor in maximizing the system's overall efficiency. As a result, operating with flow rates higher than the theoretical is commonplace. In addition, the liquid electrolytes drain heat from the cell stack in a manner close to that of a specific cooling circuit [38].

3.4 Components of Vanadium Redox Flow Batteries

3.4.1 Membranes

The membrane may be a part that separates the 2 half-cells, preventing the mixture of the 2 electrolytes and also the passage of electrons, whereas permitting the transport of ions to finish the circuit throughout the passage of a current. Typically, the membranes are into ion exchange membranes or ion exchange membranes in line with the kind of ionic teams hooked up to the membrane matrix. So, the ion exchange membranes permit the passage of anions, whereas the ion exchange membranes permit the passage of cations [39].

Membranes can also be classified according to their components, which include perfluorinated ionomers, partially fluorinated polymers, nonfluorinated hydrocarbons, and so forth. Perfluorinated materials (Nafion®, Flemion®, NEOSEPTA-F®, Gore Select®, and others) are the most common due to their chemical stability, high conductivity, and mechanical power [40].

To evaluate and test a membrane for use in a vanadium redox battery, it is common to apply a range of test procedures, which include various types of measurements such as vanadium ion permeability, ion exchange capacity, ionic conductivity, area resistance, chemical stability, thermal stability, water transport, and cell performance [40,41,42]. These test procedures are vital for membrane characterization. For example, the vanadium ion permeability will allow the transport of vanadium ions from one half-cell to the other during operation, which leads to an accumulation of vanadium ions in one half-cell and a dilution in the other. This will reduce the capacity of the battery over time. However, this accumulation can be eliminated by periodically remixing the solutions of the two half cells. The required frequency of this remixing process will depend on the membrane properties and on the system operation.

On the opposite hand, the membranes should conjointly resist the extremely aerobic V^{5+} ions utilized in the G1 technology or to the elements utilized in the G2 technology [43]. Another issue related to the activity membranes is that the water transfer from one half-cell to a different, that causes the precipitation of metal salts in one half-cell and their dilution within the different. It looks that the direction of water transfer relies upon the character of the membrane. For a cell with an associate degree ion exchange membrane, the water transfer is from the positive to the negative half-cell, whereas for a cell with an ion-exchange membrane, the other can happen. Another to partly solve this drawback looks to be the alternating associate degreed consecutive use of an ion followed by an ion-exchange membrane within the same multicell stack [43].

More recent studies on the transfer of water as an operation in the state of charge (SoC) to an ion-exchange membrane are created. They showed that the well-liked direction of water transport depends on the SoC. As an example, for SoC between 500% and 100%, water transfer takes place preferentially from the negative half-cell to the positive, whereas for values of SoC but five-hundredth, the alternative happens [44].

The membrane is a critical component in a vanadium redox flow battery system since it determines the system's efficiency and economic viability, and it can account for up to 20% of the total system cost, making it an impediment to many redox flow batteries' commercialization [40]. As a result, when developing specific redox flow battery cell solutions, special care should be taken to choose the membrane that provides the best cost-performance ratio.

3.4.2 Liquids Electrolytes

An ion-exchange membrane separates two different electrolytes in a redox flow battery. But first, it's important to distinguish between the terms "supporting electrolyte" and "electrolyte."

The electrolyte is a solution that ionizes and conducts current [45]. An electrolyte that supports the reduced and oxidized forms of a redox couple is known as a supporting electrolyte. During the oxidation and reduction of the redox couple, it also assists the corresponding cations and anions in order to balance the charge of the redox ions in the solution. The supporting electrolyte also provides additional ions, which improve solution conductivity and help current flow. In the active materials, the energy is thus contained in two separate electrolytes.

It is beneficial to increase the concentration of active materials, such as vanadium ions in a G1, in order to increase the energy density of the electrolytes, reduce the volume of the tanks necessary for a given amount of energy, and reduce the flow rate required to sustain a given power output.

The energy density of 25Wh/kg (equivalent to 33Wh/L) corresponds to the maximum vanadium ion concentration that can be dissolved in the supporting electrolyte (2M or less) [46]. The stability of V^{5+} ions at temperatures above 40°C and the solubility limit of V^{2+} and V^{3+} ions in supporting electrolytes at temperatures below 5°C limit this concentration [40].

It is preferable to increase the hydrogen ion concentration in the supporting electrolyte in order to lower cell resistivity. This lowers the ionic conduction resistance across the membrane. This is why sulfuric acid is commonly used as a supporting electrolyte. Higher H^+ and sulfate concentrations, on the other hand, are necessary for V^{5+} species stabilization at high temperatures.

To make tetravalent vanadium ions, dissolve 0.1M to 2M $VOSO_4$ (vanadyl sulfate) in 0.1M to 5M H_2SO_4 in an aqueous solution. These tetravalent vanadium ions can be electrochemically oxidized to produce catholyte, a pentavalent vanadium ion solution. Tetravalent vanadium ions, on the other hand, can be electrochemically reduced to form anolyte, a solution of divalent vanadium ions [47]. The following are the reactions that occur during the initial charging [47]:

$$\text{In positive half-cell: } V^{4+} \rightarrow V^{5+} + e^{-} \tag{22}$$

$$\text{In negative half-cell: } V^{4+} + 2e^{-} \rightarrow V^{2+} \tag{23}$$

As can be seen from the above calculations, the positive electrolyte needs twice the number of coulombs to fully charge the negative electrolyte during the initial charge point. As a result, the positive electrolyte should have a higher flow rate.

Mixed electrolytes have been suggested in recent research. For example, Li et al. [48] show that using a mixed H_2SO_4/HCl supporting electrolyte, 2.5M vanadium can be dissolved, raising the energy density to 39.2Wh/L. They also demonstrated that 3M vanadium can be dissolved with a 43.1Wh/L energy density, but with stability issues at temperatures below -5°C. The operating temperature of this mixed electrolyte will range from -5°C to 50°C, and the resulting viscosity will be lower, lowering pumping losses [48].

3.4.3 Electrodes

Carbon-based materials, such as carbon or graphite felts, carbon cloth, carbon black, graphite powder, and so on, are commonly used as positive and negative electrodes in vanadium redox flow batteries [49]. In terms of operating range, stability, and reversibility, these electrodes have shown great promise.

The electrodes are a critical component of the efficiency of vanadium redox flow batteries, just as they are in other battery technologies. The electrode material should have a low bulk resistivity and a large specific area in order to improve the electrodes' electrochemical activity [50]. The energy efficiency of battery systems is expected to improve as the electrode's electrochemical activity improves [49]. Several groups have investigated the surface alteration of the electrodes in order to boost the efficiency of vanadium redox flow batteries [50].

Coating graphite and carbon felt with metal improves the electrode's conductivity while also improvingly the stability of the flowing electrolyte [50]. Wang et al. [51] investigated the use of iridium-coated carbon felt electrodes in a G1 cell and discovered that the cell's resistance decreased by 25% while its energy efficiency improved from 56.8% to 62 percent.

Tsai et al. [52] investigated the use of graphene-modified graphite (GMG) composite electrodes and came to the conclusion that using GMG could increase the reversibility and current density of a G1. As a result, an electrode of this kind has a lot of potential in G1s. Liu et al. investigated the use of carbon paper as electrode material in no-gap vanadium redox flow batteries and found that it outperforms carbon felt.

In a separate study, Li et al. [49] developed a novel graphite/graphite oxide (GO) composite electrode for G1 that can act as both a positive and negative electrode. This composite electrode outperforms single graphite electrodes in terms of efficiency, peak current density, and charge transfer resistance of the electrode reactions. The presence of oxygen functional groups and extra specific surface areas induced by the GO contribute to the electrode's improved electrochemical efficiency.

3.4.4 Bipolar Plates

The number of single cells connected in series and the current flowing through them decides the output power of a redox flow battery. As a result, in order to achieve a device with high power output, multiple single cells must be connected in series to form a cell stack. By enabling the series link of single cells, bipolar plates are an important component in redox flow batteries and fuel cells. These components are expensive, accounting for 30 to 50 percent of a fuel cell stack's total cost [53].

Graphite, carbon, carbon plastic, and other materials are commonly used for bipolar plates. To reduce the internal resistance of the cell stack, these materials must have a high electrical conductivity. They should also be able to withstand the touch pressure that they are exposed to when pressed against the electrodes in order to prevent liquid leakage. To avoid liquid leakage, the contact pressure between the electrodes (made of carbon or graphite felt) and the bipolar plates is critical. However, if the assembly's contact forces are too high, the electrolyte flow resistance would be too high. Conversely, if the contact forces are too low, the electrode and bipolar plate would have a high electric contact resistance. Qian et al. suggested using a novel electrode-bipolar plate assembly consisting of graphite felt and a flexible graphite bipolar plate attached to each other via an adhesive conducting layer to solve this problem. The tests revealed that this novel electrode-bipolar plate assembly reduced resistivity and ensured impermeability while also providing 81-percent energy efficiency for a current density of $40mA/cm^2$ [54].

Because of its high electrical conductivity, low density, and ease of machining, graphite is one of the most commonly used materials for bipolar plates. However, it has a few drawbacks, such as being brittle, which makes stack assembly difficult, raises machining costs, and necessitates the use of thick bipolar plates due to its porous nature. Several groups produced graphite composites by preparing a bulk molding compound material followed by a hot-pressing process to improve the performance of bipolar plates in fuel cells. Unfortunately, since vanadium redox flow batteries operate at higher acidity levels than fuel cells, bipolar plates designed for fuel cells could not be modified for use in VRFB [55].

Lee et al. [56] recently produced a carbon composite bipolar plate for VRFBs using graphite, carbon black, and resin, and concluded that the electrochemical stability was improved, with good electrical conductivity and efficiency, using a compression molding process. Sumitomo Electric Industries, Ltd. recently patented a new kind of bipolar plate for redox flow batteries made of an electrically conductive composite material with liquid sealant properties that have higher conductivity, mechanical strength, and plasticity than standard plates. A thermoplastic resin, a carbonaceous material (graphite or carbon black), and carbon nanotubes were combined to create this composite material.

3.4.5 Gasket

In the VRFB application, gaskets are used to mate coupling components and create a seal between them, preventing electrolytes from leaking out. Gaskets are often used to separate the bipolar plate and the membrane, allowing the electrode to make sufficient contact with both.

PTFE, PVC, and silicone gaskets make up the bulk of the gaskets used in the VRFB program. In order to achieve a satisfactory degree of contact between the membrane and the bipolar plate in a VRFB cell, the electrode will typically need some compression. To achieve this optimum contact/pressure, the gasket configuration and overall gasket thickness can be used. To create the necessary gap between the membrane and bipolar layer, harder materials (such as PTFE) are frequently used. A secondary sealant may be used to ensure that it seals properly inside the stack without requiring undue pressure [57]. Applying sealant by hand (rather than using an automated, more detailed process) can result in PTFE gasket/frame deformation and cell leakage due to uneven application [57]. As silicone-style gaskets are used, this is less of a concern.

3.4.6 Collector Plate

In the literature, the word "current collector" is thrown around haphazardly; some sources refer to copper plates at either end of the stack as current collectors, while others conflate them with bipolar plates [58]. Since the new collectors and bipolar plates can be used interchangeably in a single cell assembly, copper plates are often omitted. If a metallic plate is used as the current collector, the two criteria are high conductivity and low cost; if the metallic plates are not used, the current collector's usual criteria are the same as for the bipolar plate.

Damage to the bipolar plate, particularly if copper is used, may cause electrolytes to seep through to the metal, resulting in copper contamination, hydrogen evolution in the negative half-cell, and battery stack failure. Reynard et al. [58] investigated the problem in a commercial VRFB and devised a method for plating out dissolved copper with an electrode before removing it with an oxidative solution.

3.4.7 Cell Stack Frame and Storage Tanks

Because of the high acidity of vanadium redox flow batteries, acid corrosion-resistant materials are needed. PVC or polyethylene is commonly used for the cell stack frame and storage tanks. To make the cell stack assembly and connect the single cells, stainless steel pins and bolts are usually used, with appropriate sealants (e.g. silicone rubber) laid between joints to prevent liquid electrolyte leakage [59].

Sumitomo Electrical Industries, Ltd. recently according to the employment of a versatile storage rubber tank to require the advantage of the fluid battery characteristics to insert storage tanks in underground areas (e.g. underground deposits) through manholes.

3.5 Typical Applications for Vanadium Redox Flow Batteries

Vanadium redox flow batteries, along with other traditional battery systems, are already in use in a variety of stationary electricity storage applications. However, due to their uniqueness, they are most often used in applications with low power/energy ratios. More than 20 G1 demonstration projects with different implementations have already been completed around the world [46]. VRFBs benefit from their independence between rated power and stored energy in these applications, an advantage that will gradually outweigh their energy density limitations and additional complexity. Load leveling, peak shaving, uninterruptible power supply (UPS), and combining renewable energies (wind/solar power generation) are some of the most popular applications for VRFBs.

A load-leveling battery is used to provide more consistent electric energy consumption over time. It saves money by storing energy during low-cost periods and then supplying it during premium tariff periods. Mitsubishi Chemicals mounted a 200kW/800 kWh G1 system for load leveling at Kashima-Kita Electric Power in Japan in 1996, as an example of this use [60].

Occasionally, in many sectors, there are periods of extremely high-power demand for a limited period of time. This will normally necessitate an increase in the electrical peak power negotiated with the power utility. To avoid this additional expense, high-capacity batteries that operate only briefly during peak power events are often used, minimizing (shaving) the electrical grid's instantaneous power peaks demand and allowing for lower negotiated peak power. Sumitomo Electric Industries Ltd, for example, installed a 1.5MW/1.5 MWh G1 system at Tottori Sanyo Electric in Japan for a peak shaving application [61].

One use for future flow battery peak shaving may be the quick charging of electric vehicles in existing gas stations. Although flow batteries lack the energy density needed for EV installation, they could be used to charge the vehicle during peak electric demand, allowing electric grid usage to transition to off-peak times (when the battery would be charged from the grid with low contracted power). This could be accomplished by storing VRFB Electrolyte in deactivated gas station tanks. Aside from the microgrid benefits of this system (local electricity production incorporation, electricity storage for auto use during short blackouts), this approach also has the benefit of laying the groundwork for the potential supply of vehicles equipped with flow batteries, should they become feasible.

The gradual conversion of deactivated gas tanks to flow battery solution storage will provide a sleek transition of the gasoline station business model from the present fossil-fuel-based economy to the electrical quality paradigm, in line with demand amendment. Although flow batteries fail to attain energy density for mobile applications within the close to future and square measure solely used for the peak shaving in eV fast-charging operations, this philosophy can stay relevant. In separate, ongoing article submissions, the authors evaluate the strategy's technical, energy, and economic viability.

Combining VRFBs with renewable energy sources is another application for them. These are frequently intermittent in nature (for example, wind and solar energy), which is bad for grid stability. Furthermore, their power generation often falls short of demand, necessitating the development of an energy buffer that stores excess energy for later release during periods of higher demand. This is particularly useful in the case of wind turbines, which normally produce at their peak during the night when demand is lowest. While many hydropower plants can reverse and store energy by pumping, wind turbines are mostly located in remote locations and require local storage to maximize production. Energy storage is also essential for buildings that are not connected to the electrical grid and are located outside of populated areas, as they can generate electricity with a photovoltaic, microhydraulic, or wind power system and store it in a battery for later use during the day.

The VRFBs seem to be a viable choice in both of the above scenarios. Several studies have been conducted on the use of VRFBs in photovoltaic and wind generation systems. Vetter et al. [62] contrasted the use of lead-acid batteries and one G1 for a small black forest mountain restaurant with a hybrid photovoltaic device that stores energy in a tank. They concluded that the G1 is the best choice with the lowest annualized life cycle costs for large energy storage with long autonomy times because their specific investment cost (€/kWh) decreases with increasing power, while a lead-acid battery's specific investment cost is constant and independent of capacity.

Vanadium solution has much no degradation in terms of anticipation and maintenance wants, and RFCs are foretold to last over twenty years. It's going to be necessary to repair or freshen up the stack and pump parts on an everyday basis (e.g. pump bearings and seals) [63].

3.6 Summary

In this chapter, we have discussed elaborately the working principles of vanadium redox flow batteries, their various configurations, characteristics, and the phenomenon of VRFB's. At this review, we also discuss all of its components, and typical application. The efficiency of a VRFB is determined by a variety of factors, including the flow cell construction, which has a significant impact on the system's efficiency. The coulombic efficiency was 90%, and the voltage efficiency measured over the state of charge range of 10% to 90% was 81 percent. The vanadium redox cell's overall energy efficiency of 73 percent, combined with the system's simplicity, makes it one of the most promising energy storage systems currently under development.

Chapter 4

Economic Analysis of VRFB

4.1 Introduction

The vanadium redox flow battery is the most promising, widely studied, and pursued RFB technology (VRFB). Unlike traditional batteries, which store chemicals within the battery, the capacity of the vanadium flow battery can be scaled independently of the power by simply making larger tanks for the vanadium where the energy is stored. Vanadium batteries have a low energy capacity, but they have a very long cycle life and are easily recyclable. These features make them ideal for applications that require stationary electricity storage, such as storing solar energy during the day for use at night.

4.2 Comparison with Conventional Batteries

To evaluate the potential of flow batteries, a comparison with traditional battery technologies is needed [64]. Since there are so many different types of batteries, this paper will only compare lead-acid and lithium-ion batteries as framing technologies.

Since conventional batteries are fully sealed and do not require circulation systems, they have a significant advantage over flow batteries. Redox flow batteries, on the other hand, have many separate parts and a pumping mechanism that can be damaged and need to be replaced over the battery's lifetime. Flow batteries, on the other hand, have more design flexibility due to the inherent conformability of liquids, which allows for extreme flexibility in storage tank geometry. Furthermore, the power and energy storage capacities are separate, making it simple to scale up the system's size by simply adding more liquid electrolyte storage. Furthermore, except in the event of electrolyte crossover, these batteries have a long cycle life due to the low oxidation of the liquid electrolytes over time [65]. Furthermore, the fact that the power generation unit is physically isolated from the energy storage unit can be a benefit since the storage tanks can be stored underground or in a building's basement, while the cell stack can be placed anywhere where the heat can be dissipated more easily. As a result, the design and installation of the auxiliary cooling system could be simplified. The fluid circulation also aids in the cooling of the cell stack. As previously mentioned, VRFBs seem to be the most advantageous and widely used of the various existing flow battery technologies, but they have a much lower energy density than traditional battery technologies. Of course, for applications where packaging is critical, such as mobile applications, this would be the most significant constraint.

Lithium batteries are a more advanced technology than other batteries, with a high energy density and low weight, making them ideal for portable electronic and transportation applications [66]. Due to their lower energy capacity, vanadium flow batteries are best suited to stationary applications where the battery does not need to be moved. Lithium batteries store chemical energy inside the battery electrodes, so more batteries are needed to increase battery capacity. Lithium batteries usually discharge to their rated capacity in a few hours or less. By the size of the tanks used to store the vanadium solutions, vanadium flow batteries can easily be built with a higher capacity (>5 hours). Another problem with lithium batteries is their short cycle life: their output degrades over time, particularly if they are discharged at high rates or deeply. Vanadium redox flow batteries, on the other hand, have a much longer cycle life and can be completely discharged without losing capacity. They're much easier to recycle, and vanadium solutions can be reused after the battery's life cycle is over. Flow batteries made of vanadium are currently more costly than lithium batteries. Flow batteries, on the other hand, could be less expensive in the long run. Since lithium batteries are a more mature technology, vanadium batteries will become more competitive for stationary energy storage applications over time.

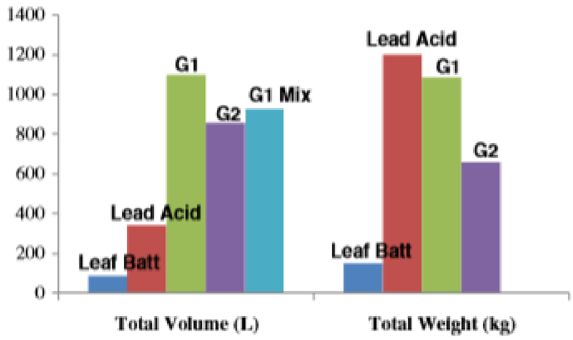


Figure 14: Comparison between the lithium ion battery of the Nissan Leaf EV and their VRFB and lead-acid battery equivalents.

While considering the energy density of different batteries, keep in mind that the values reported for conventional batteries (e.g. lithium-ion and lead-acid) refer to the total volume of the battery, while the energy density of a flow battery is determined solely based on the volume occupied by the liquid electrolyte, excluding the cell stack, pumps, and piping. However, this was done since multiple cell stacks with different amounts of energy stored can be added to a device. Table 2 shows a comparison of VRFB, lead-acid, and lithium-ion batteries.

Table 2: Comparison between VRFBs and conventional batteries.

	VRFB (G1)	VRFB G1 with H_2SO_4/HCL mixed acid	VRFB (G2)	Lead acid (Stationary)	Lithium ion
Open circuit voltage	1.4	1.4	1	2.1	4.1
Energy density (Wh/kg)	25	-	50	20	150
Energy density (Wh/L)	33	43.1	70	70	400

It is possible to assume for a lithium-ion battery based on the findings of Table 2. A lead-acid battery of the same size will be 7.5 times heavier and almost six times larger. A VRFB G1 battery, on the other hand, will be just six times heavier but 12 times larger than a Li-ion battery, whereas a VRFB G2 battery will be just three times heavier but nearly six times larger. At first glance, the VRFB G2 technology appears to be comparable in volume and weight to a stable lead-acid method. However, as previously said, these energy densities only apply to liquid electrolytes in the case of VRFBs. Their volume and weight would be greatly increased if the stack, pumps, and pipes were included. However, caution should be exercised when testing Li-ion battery values for specific applications, such as electric mobility. For example, Ikezoe et al. [67] developed a 90kW and 24 kWh lithium-ion battery pack used in the Nissan Leaf electric vehicle is made up of 48 modules, each with four cells and a power density of 132Wh/kg and 213Wh/L. These energy densities, on the other hand, are calculated using modules of four cells, which includes the support materials for four cells. Each cell has a capacity of 33.1Ah and an average voltage of 3.8V, with dimensions of 2902167.1mm and a mass of 799g. This means that each Leaf battery cell will have a 157Wh/kg or 283Wh/L energy density in fact. Without the structure and control mechanism, the Leaf battery has a total mass of 153kg and a total volume of 85L. The total mass of the battery system in these systems is approximately 300kg.

Table 3 compares the characteristics of the Nissan Leaf's lithium-ion battery to those of lead-acid batteries and VRFBs with equal power/capacity. The weight and volume of the cell stack were measured using Nafion N117 membranes (a DuPont trademark), SIGRACELL GFA3EA electrodes, and SIGRACET TF6 bipolar sheets in the case of VRFBs (trademark by SGL group). With a maximum current density of 100mA/cm2 and a capacity of 90kW and a voltage of 400V, the maximum current of the Nissan Leaf Battery is 225A, implying that the area resistivity of the corresponding VRFB would be about 0.225m^2.

Table 3: Characteristics of lead-acid batteries and VRFBs that are comparable to the Nissan Leaf's lithium-ion battery.

	Leaf battery (Li-ion)	**Lead acid (Stationary)**	**VRFB (G1)**	**VRFB G1 with H_2SO_4/HCL mixed acid**	**VRFB (G2)**
Number of cells (Serial connection)	192	190	286	286	400
Volume of cell stack (L)	-	-	370	370	517
Weight of cell (kg)	-	-	127	127	178
Volume of liquid electrolyte (L)	-	-	727	558	343
Weight of liquid electrolyte (kg)	-	-	960	-	480
Total volume (L)	85	343	1097	928	859
Total weight (kg)	157	1200	1087	-	657

So, knowing that the aforesaid membranes have a thickness of 183µm and a mass of 360g/m^2, the electrodes have a thickness of 3mm (But ought to be compressed two-hundredth right down to the thickness of two.48mm each) and a mass of 300g/m^2, and every cell is going to be five.143mm thick and with a mass of 216g [68]. Between every two cells, a bipolar plate, with a thickness of 0.6mm and a mass of 229.5g (1020g/m2), is going to be set [68]. Table 5's findings are depicted graphically in Figure 14. While VRFBs are lighter than lead-acid batteries for the same performance, they are much bulkier, taking up between 850 and 1100L of space depending on the technology. As a result, this technology is best suited for local storage applications rather than electric vehicle applications. These findings are in line with those of other studies that have been published [69].

4.3 Commercial Applications of The Vanadium Redox Battery Energy Storage System (VRB-ESS) And Economic Analysis

One of the most important goals of this research is to develop economic metrics for assessing the VRB-investment ESS's costs and benefits by using realistic bases and rational assumptions. This section contains a thorough economic study of the VRB-integration ESS into various energy power bases using commercial applications.

For the following two factors, the VRB-ESS equipment may be useful to the power grid. First, the VRB-ESS will meet the power grid's need for diversification [70]. The low efficiency of power grids was the basis for the VRB-ESS technology's economical paper. The electrical grid is now expected to meet peak power demand as well as power savings during off-peak hours. The VRB-ESS can help maintain a consistent electricity rate by storing off-peak energy for peak demand. Second, when developing ESS fitted, the capital investments and operational benefits of VRB-ESS should be taken into account. As a result, the segment includes the economic viability of VRB-ESS by charging them during off-peak hours and discharging them during peak hours.

4.3.1 Single Energy System (At Office Buildings)

VRB storage systems can be used as the uninterrupted power supply (UPS) for office buildings instead of traditional lead-acid batteries. Table 4 summarizes the different types of UPS. The VRB system has the following two key advantages, which enable it to be used in office buildings as a battery-backed UPS with long-term power. For starters, it can answer in under a minute. During standby mode, the charged electrolytes are already deposited in positive and negative tanks, respectively. Second, when the VRB device is used as a long-term backup power source, proper cell stacks and electrolytes can be mounted separately. The benchmarking of various types of batteries is demonstrated in this section.

Table 4: The summery of the UPS system.

	Practical power range (KVA)	Voltage conditioning	Efficiency	Inverter always operating
Standby	0-0.5	Low	Very low	No
Line Interactive	0.5-3	Design dependent	Very low	Design dependent
Standby On-Line Hybrid	0.5-5	High	Low	Partially
Standby Ferro	3-15	High	Low	No
Double Conversion On-Line	5-5000	High	Low	Yes
Delta Conversion On-Line	5-5000	High	High	Yes

Total Investment Cost Analysis

Consider a real-life office building in Beijing. It has a total of 20 floors, each with an 80kVA capacity. Due to the lack of detail, we'll assume the UPS is 3 hours long and 1kVA equals 0.8 kW. As a result, the total power is (80*20) = 1600 kVA, or 1280 kW. The online double-conversion battery is a viable option. The overall costs of the VRB-ESS are determined as follows using Equation 24. The cumulative costs of VRB systems are denoted by TC_{VRB}. The variable costs are referred to as VC, and the fixed costs are referred to as FC. The capacities of the cell stacks and electrolytes are represented by x_1 and y_1, respectively, and the units are kW and kWh. The units are $/kW and $/kWh, respectively, and the scaled power costs are a and b. The VRB-ESS determinants are listed in Table 5.

$$TC_{VRB} = VC+FC = (x_1\times a+y_1\times b) +FC\ (\$) \tag{24}$$

$$TC_{VRB\ (GoodLevel)} = VC+FC \tag{25}$$

$$=3030.3\times1280+227.3\times3840+454.5+151.5+96969.7$$

$$= 4849191 \text{ dollar}$$

$$TC_{VRB\ (AppropriateLevel)} = VC+FC \tag{26}$$

$$=1212.1\times1280+151.5\times3840+454.5+151.5+96969.7 = 2230823.7 \text{ dollar}$$

$$TC_{VRB\ (NormalLevel)} = VC+FC =606.1\times1280+98.5\times3840+454.5+151.5+96969.7 \tag{27}$$

$$= 1251623.7 \text{ dollar}$$

Table 6 also includes a benchmarking analysis of different batteries of the same size. It is estimated to show the VRB battery's precise economic benefit.

Table 5: The total cost of VRB-ESS in office building associated with capacity 1280 kW/3840kWh (3 hours).

Name		Measurement	Unit	Unit Price ($)	Total Price ($)
Cell stacks	Good level	kW	1280	3030.3	3,878,784
	Appropriate level			1212.1	1,551,488
	Normal level			606.1	775,808
Electrolyte	Good level	kWh	3840	227.3	872,832
	Appropriate level			151.5	581,760
	Normal level			98.5	378,240
Electrolyte circulation pump		per	2	454.5	909
Control system		per	1	151.5	151.5
Inverter		Per	Market price is based on the 500kW, costs $37878.8	96,969.7	-
Total cost	Good level	set	1	-	4849646.2
	Appropriate level			-	2231278.2
	Normal level			-	1252078.2

Table 6: The benchmarking comparison of investment cost by equipped with different (Capacity 1280kW / 3840kWh (3 hours)).

	VRFB		Lithium battery	Lead-acid battery
Single investment	Good level	$4,849,545.6	$1,163,636.4	$314,242.4
	Appropriate level	$2,231,363.6		
	Normal level	$1,251,969.7		
Lifespan of battery	10 years		3 years	2.2 years
Investment costs for 10 years	Single investment		$3,878,787.9	$1,428,333.3
Investment costs for 15 years	Good level	$4,849,545,6	$5,818,181.8	$2,142,578.8
	Appropriate level	$2,231,363.6		
	Normal level	$1,630,151.5		

4.3.2 Multiple Energy Systems (At Homeowner Distributed Solar Energy (E.G. Rooftop Photo-Voltaic))

This section is designed to assess the viability of using the VRB-ESS in conjunction with a photovoltaic device in the residential sector with government subsidies.

Solar energy is a clean renewable energy source that can be used to increase power generation while also addressing environmental issues. In recent years, the key research trend has been to concentrate on theoretically optimized receiver methodologies in solar power plants. Another area of research that is currently being pursued is market-based applications, such as the use of distributed photovoltaic power generation.

The future of distributed photovoltaic energy generation is bright. It is a new method of comprehensive energy and power generation use. Its aim is to directly transform solar energy into electrical energy by using photovoltaic modules. The benefits of distributed photovoltaic power generation include not only the ability to increase power production in conjunction with power plants but also the ability to effectively solve the problem of power loss in long-distance transportation.

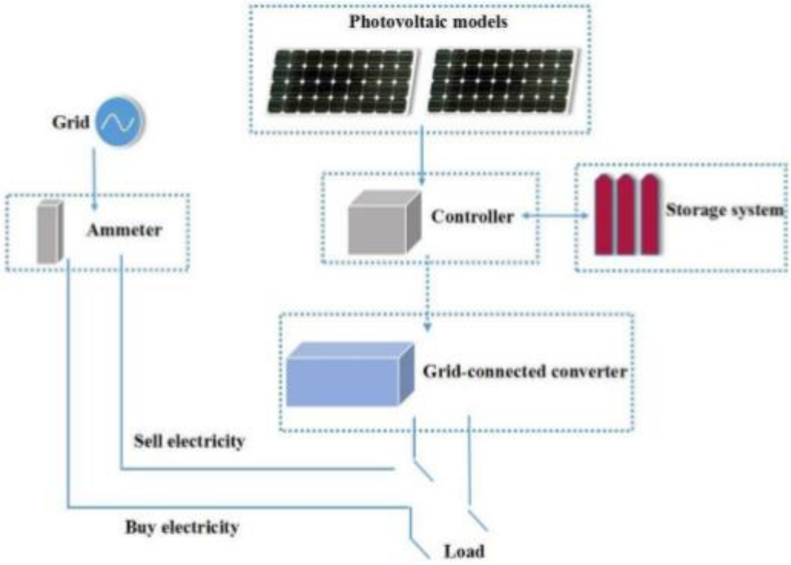


Figure 15: The principle of solar energy grid-connected distributed photo-voltaic power generation system.

Furthermore, it can be built as an addition to a household's power generation system to provide self-supply electricity. For a constant and reliable power supply, distributed photovoltaic power generation should be connected to the public power grid. The roof photovoltaic power generation system is now the most commonly accepted model, with the following options: (1) off-grid photovoltaic power generation system; (2) grid-connected photovoltaic power generation system. The use of a VRB-ESS inside a photovoltaic generation system is appropriate for improving the photovoltaic system's efficiency and reducing the impact of solar power fluctuation. It can be used to stabilize the production of electricity produced by renewable energy sources, reducing CO_2 emissions and thus contributing to environmental protection. Figure 15 depicts the concept of a solar energy grid-connected distributed photovoltaic power generation system.

A household case has been considered with the implementation of a distributed photovoltaic power generation system, according to a recent report. The case will be fitted with VRB-ESS, and economic analysis of this integrated framework will be determined. Furthermore, this research will provide residents and businesses with operational business models. In order to ensure that both of them benefit from the latest application.

Total Investment Cost Analysis

Before beginning the evaluation process, consider the following hypotheses preconditions. All of the hypotheses are based on real-world situations and evidence. Hypotheses have the following preconditions (based on reality): (1) Assuming that the household's operating period is 20 years. The distributed photovoltaic power generation system has a total installed capacity of 19 kW and is made up of 72 blocks of solar panels. It has a 20-year lifespan. (2) It produces 60 kWh per day, but the family only uses 10 kWh per day. According to the scheme, a homeowner would receive a subsidy of $ 0.06/kWh for a period of 20 years. The government would give the company $0.6 per worker. The distributed photovoltaic power generation system's energy can be sold to the grid network. The market price for electricity would be $0.07 per kWh. (3) The VRB-ESS is designed to discharge 5 hours a day.

Table 8 shows the overall investment costs of the VRB-ESS fitted with a distributed photovoltaic power generation system. Eq. (28) to Eq. (30) show the household's cash flow.

$$\mathrm{DCF} = P_{\mathrm{generate}} + P_{\mathrm{sell}} \tag{28}$$
$$= 60\mathrm{kW} \times \$0.06/\mathrm{kWh} + (60\mathrm{kW} - 10\mathrm{kW}) \times \$0.07/\mathrm{kWh} = \$7.2$$

$$\mathrm{ACF} = \mathrm{DCF} \times 365 = \$7.2 \times 365 = \$2628 \tag{29}$$

$$Y_{\mathrm{payback}} = \frac{\mathrm{C}}{\mathrm{ACF}} = \frac{\$26{,}621.2}{\$2628} = 10.1 \text{ years} \tag{30}$$

Solar panels have a 20-year life expectancy under the hypothesis conditions. As a result, Eq. (31) shows the benefit for the remaining years.

$$P_{\mathrm{Remain}} = \mathrm{ACF} \times Y_{\mathrm{remain}} = \$2628 \times (20-10) = \$26{,}280 \tag{31}$$

P_{generate} reflects the value obtained by producing electricity through a distributed photovoltaic power generation system, where DCF represents daily cash flow. The benefit gained by selling the remaining electricity to the grid network is referred to as P_{sell}. P_{remain} refers to the system's average profit for the remaining years. The payback period is Y_{payback}, the gross investment expense is C, and the annual cash flow is ACF.

Table 7: The Total investment cost of VRB-ESS associated with a capacity of 12kW/60kWh (5 hours).

Name	Measurement	Unit	Unit Price ($)	Total Price ($)
Electrolyte of VRFB (Normal level)	kWh	60	98.5	
Cell stack of VRFB (Normal level)	kW	12	606.1	7273.2
Electrolyte circulation pump	set	2	454.5	909
Control system	set	1	151.5	151.5
Inverter	kW	2	454.5	909
Total cost	set	1	-	15,151.5

Table 8: The total investment cost of VRFB-ESS equipped with the distributed photovoltaic power generation system.

Name	Measurement	Unit	Unit price ($)	Total price ($)
P-Si solar cell	per	72	151.5	10,909.1
Photovoltaic power station distribution box	19kW set	1	424.2	424.2
AC grid distribution box	set	1	0	0
Cable	per set	50	1.8	90.9
AC low voltage circuit breaker	per	1	45.5	45.5
Electrical meter	per	1	0	0
Total cost of VRFB (From table 8)	set	1	-	15,151.5
Total cost	set	1	-	26,624.2

4.3.3 Several Hybrid Energy Systems (At Wind Power and Solar Power Station)

The main goal of the wind power and solar power station equipped with the VRFB storage system, as published by the Chinese government, is to increase the efficiency of non-fossil energy and fossil energy at the same time and to significantly boost renewable energy production. Non-fossil energy consumption can account for 15-20% of overall primary energy consumption between 2020 and 2030.

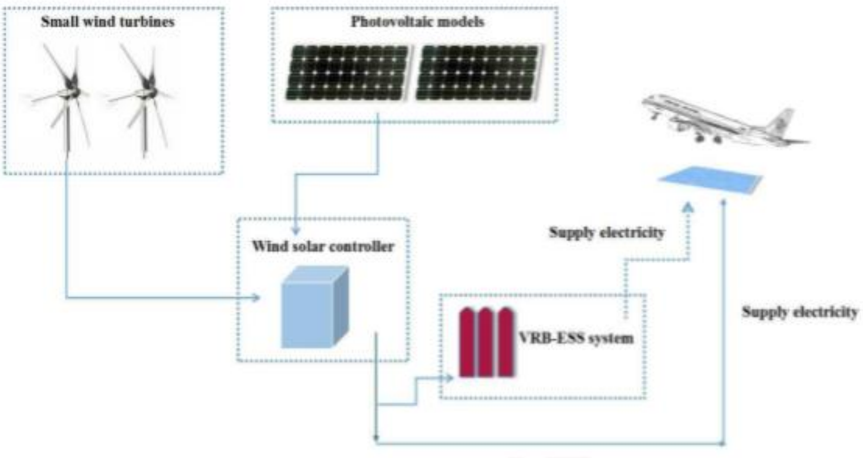


Figure 16: The principle of the wind power and solar power station equipped with the VRB storage system.

This section provides an economic study of hybrid energy systems based on the previous analysis and policy requirements. This study-wide building has a full-scale size with Terminal 3 (hereinafter referred to as T3) of Beijing capital airport for analytical purposes and functional comparison. It's put together with a complete system that includes the wind turbine, photovoltaic generator, and VRB-ESS. Figure 16 depicts the concept of multiple energy-based systems. Aside from renewable-energy-generated electricity, the VRB-ESS will economically supply power by taking advantage of peak-value market prices. As a result, the system's advantage is challenging energy management, which can be used to boost the terminal's electricity production, increase economic benefits, minimize or delay further capital investments, and improve the quality of power services.

Total Investment Costs Analysis

According to the above-mentioned optimized study, a hybrid renewable system's lifetime is estimated to be ten years. It is available from 8:00 a.m. to 16:00 p.m. every day. As a result, the proper power is 94.7 MW, with a capacity of 757.2 MW/h. During the valley time, the VRB-ESS should be completely charged in order to discharge 3 hours during the high peak period and 5 hours during the peak period. As shown in Table 9, this section offers a benchmarking comparison of the use of standard level electrolytes, acceptable level electrolytes, and direct electricity supply.

When the hybrid system is fitted with normal level electrolytes, the total investment cost is 334.2 million, and when it is assembled with acceptable level electrolytes, the total investment cost is 431.7 million. During the high peak time and the peak period in 10 years, if the terminal building directly adopts the energy supply without the VRB-ESS, the purchasing cost is 572.4 million [71,72,73,74].

Table 9: The use of a standard level electrolyte, an acceptable level electrolyte, and direct electricity supply were compared in a benchmarking study (Capacity : 757.2 MWh / 94.7 MW (8 hours)).

Name	Measurement	Unit price ($)		Unit	Total price for the usage of normal level electrolyte ($)	Total price for the usage of appropriate level electrolyte ($	Purchase costs of direct electricity supply ($)
Electrolyte of VRFB	kWh	Normal	98.5	757200	74.6 million	114.7 million	572.4 million
		Appropriate	151.5				
Cell stack of VRFB	kW	Normal	606.1	94656	57.4 million	114.8 million	
		Appropriate	1212.1				
Electrolyte circulation pump	set	454.5		2	909	909	
Control system	set	151.5		1	151.5	151.5	
Inverter	set	Market price is based on the 500kW, costs $37878.8		1	7.2 million	7.2 million	
Wind turbines	kW	545.5		94656	51.6 million	51.6 million	

Photovoltaic generators	kW	1515.2	94656	143.4 million	143.4 million	
Total costs	set	-	1	334.2 million	431.7 million	

Where, The Purchase cost of direct electricity supply,

$DC_{buy} = (\$0.2183\times3\text{hrs}+0.2003\times5\text{hrs})\times94656\text{kW}\times365\text{days}\times10\text{years}$

= \$572,353,351.7 = \$572.4 million.

4.4 Summary

With the increased use of renewable energy, the demand for stationary energy storage is rapidly expanding. Vanadium flow batteries are expected to play a larger role in these applications in the coming decades, owing to the benefits described above. By better balancing supply and demand, vanadium batteries would allow for more efficient use of electricity. This would improve the production and usage of renewable energy sources including solar and wind, as well as traditional fossil fuel and nuclear-powered generation. Vanadium flow batteries are likely to be used in residential, commercial, and industrial structures, as well as built into power grids. The technology is becoming more affordable, which will be critical for the application of vanadium flow batteries. Battery design and material advances can help reduce costs by improving efficiency while also shrinking the size and expense of the battery. A reliable supply chain for low-cost vanadium that can be used in flow batteries is also needed.

Chapter 5

Conclusion

Conclusion

There is growing pressure for a reduction in global fossil fuel usage for economic, domestic political, geopolitical, and environmental reasons. Current energy resources must be used even more effectively as a result of a variety of policies, with energy storage technology playing a key role. Governments must also have greater financial and political support for clean energy projects, as well as other alternatives such as nuclear power.

Low-cost, high-performance redox flow batteries are in high demand for renewable and grid energy storage up to multi-megawatt levels. In the current report, a systematic analysis of VRFBs was conducted. Due to their high cycle life, compact nature, and independence between energy stored and rated electricity, this is a very promising technological solution for large-scale stationary electric energy storage. However, the high cost of their components and the small number of established manufacturers worldwide have limited their use thus far, despite the recent appearance of several promising and fully functional commercial VRFB packages.

The evaluation of the vanadium redox flow energy storage method, as well as its various typical and commercial applications, has been addressed in this review article. We looked at cost analysis for a variety of commercial applications in order to better understand and apply the vanadium battery method for low-cost energy storage.

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