Investigation of Efficient Energy Storage System and Optimization with Fibre Optics

Saroj Khanal

A thesis report submitted in partial fulfilment of the

requirements for the award of the degree of

MASTER OF ENGINEERING

(ELECTRICAL AND ELECTRONICS ENGINEERING)

CHARLES DARWIN UNIVERSITY

FACULTY OF SCIENCE AND TECHNOLOGY

October 2025

DECLARATION

I hereby declare that the work herein, now submitted as a thesis report for the degree of Master of Engineering (Electrical and Electronics Engineering) at Charles Darwin University, is the result of my own investigations, and all references to ideas and work of other researchers have been specifically acknowledged. I hereby certify that the work embodied in this thesis report has not already been accepted in substance for any degree and is not being currently submitted in candidature for any other degree.

Signature:

Date: 19 October 2025

DEDICATION

I wholeheartedly thank and dedicate to my parents for helping me in this academic journey to elevate my academic wisdom and push further in the understanding of purpose to pursue forward. This thesis has been one of my contemplated research projects and I have fully delved into it to properly find out the depth knowledge and idea about the interest of my topic that I was always keen to analyse about.

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my supervisor A/Prof Erwin Chan for his continuous support and valuable feedback throughout the thesis research and deliberation. I am also thankful to my unit coordinator of the Master thesis and teams of language and learning advisor as well as academic and research librarian for the valuable insights of thesis report expertise.

TABLE OF CONTENTS

DECLARATION I

DEDICATION II

ACKNOWLEDGEMENTS III

TABLE OF CONTENTS 1

LIST OF FIGURES 2

LIST OF TABLES 3

LIST OF ABBREVIATIONS 4

LIST OF SYMBOLS 5

INVESTIGATION OF EFFICIENT ENERGY STORAGE SYSTEM AND OPTIMIZATION WITH FIBRE OPTICS 6

I. INTRODUCTION 6

- Background 6
- Aim of Research 6
- Structure of Paper 6

II. APPROACH 7

III. EXPERIMENTS / TESTING / MEASUREMENTS / DATA 9

IV. ANALYSIS AND DISCUSSION OF RESULTS 11

V. CONCLUSIONS 15

VI. FUTURE WORK 15

APPENDIX A: LITERATURE REVIEW 16

- Introduction of Literature Review 16
- Body of Literature Review 17
- Conclusions from the Literature Review 27
- References of the Literature Review 28

APPENDIX B: FIGURES 32

APPENDIX C: TABLES 39

REFERENCES 41

LIST OF FIGURES

Figure 1, Range of features intensity composed by each ESS as compared to other 7
Figure 2, Charging mechanism of VRFB [65] 8
Figure 3, Dis- charging mechanism of VRFB [65] 8
Figure 4, Range of features compared among different sensing technique 9
Figure 5, FBG working mechanism in optical fibre 15
Figure 6, MATLAB FMU block of VRFB system 10
Figure 7, Elaborated system architecture of VRFB [66] 11
Figure 8, MATLAB graphical user interface result 1 12
Figure 9, MATLAB graphical user interface result 2. 12
Figure 10, Homer Pro electrical grid system component 12
Figure 11, Homer Pro result 1 13
Figure 12, Homer Pro result 2 13
Figure 13, Output from python pipeline. 13
Figure 14, Typical operation of storage system connected to PV system to resolve intermittency [14] 18
Figure 15, System architecture of vanadium redox flow battery [13] 22
Figure 16,Charging process of redox flow battery [59] 24
Figure 17, Discharging process of redox flow battery [59] 24

LIST OF TABLES

Table 1. Identification of VRFB features analysed from fig1. 10

Table 2. SWOT analysis of VRFB 10

Table 3. SWOT analysis of FBG 14

Table 4. wavelength change in FBG 12

Table 5. Features comparisons of all the ESS 21

Table.6: SWOT analysis of VRFB and FBG in same table 27

LIST OF ABBREVIATIONS

BESS - Battery Energy Storage System

BPM – Bipolar Membrane

CAES – Compressed Air Energy System

CE – Circular Economy

CF – Carbon Felt

ESS - Energy Storing System

EV – Electric Vehicle

FBG – Fibre Bragg Grating

FMU – Functional Mock Up

FO – Fibre Optics

GWh – Giga Watt hour

HESS – Hybrid Energy Storage System

IEEE – Institute of Electrical and Electronics Engineers

Li-ion – Lithium ion

MOF – Metal Organic Framework

MWCNT – Multi Walled Carbon Nano Tubes

Na-S – Sodium Sulphide

OCV – Open Circuit Voltage

PFIS - Probabilistic Fuzzy Inference System

PTFE – Polytetrafluorethylene

PV – Photo Voltaic

QAPSF – Quaternized Polysulfone

R&D – Research and Development

RFB – Redox Flow Battery

SOC- State of Charge

SPEEK – Sulfonated Poly Ether Ether Ketone

TW - Tera Watt

UC – Ultra Capacitor

V2G – Vehicle to Grid

VRFB – Vanadium Redox Flow Battery

List of Symbols

λ_B - FBG resonant wavelength
n_{eff} - effective refractive index
Λ - grating period
α – Thermal expansion coefficient of fibre
ξ – Thermo- optic coefficient
T – Temperature
I – Current
R – Resistance
Q – charge
M– electrolyte concentration
V_{tank} – Volume of electrolyte
F – Faraday constant
N_s – Number of cells
V_o – Voltage of cell
C_{Th} = thermal capacitance of stack
h= heat transfer coefficient
A= surface area of stack
$T_{amb} = 25^oC$
V – Vanadium Ion
O_2 – Oxygen Ion
H^+ – Hydrogen Ion
E^o – Electromotive force

q_{max} – Charge
V_{tank} – Volume of tank
n= moles of vanadium ions reacted

Investigation of Efficient Energy Storage System and Optimization with Fibre Optics

***Abstract*— The global sustainable electric energy solution requires utilization of energy storage system (ESS) with minimum loss, maximum retention and scalable capacity ensuring the grid reliability. This paper investigates the vanadium redox flow battery (VRFB) energy storing system after the detailed techno-chemical and economic feasibility analysis and compared with the pre-existing battery storage systems. Further, the ambience like temperature of energy storage system is assessed by optical sensor like Fiber Bragg Grating (FBG) to provide feedback and maintain the healthy functional state. This thesis assesses the efficiency, power and energy capacity, charge and thermal response in the power system. The output of VRFB from Homer Pro was analysed in python pipeline by passing through the Functional Mock-up Unit (FMU) developed in MATLAB simulation. FMU of VRFB was a physics-based ESS comprising electrochemical and thermal factors along with FBG connection. Additionally, the MATLAB GUI was used to investigate the VRFB operation in different stack size, flow quantity, current and operation time. The results exhibited the optimum retention of SOC and potential scalable viability. The techno-economic standards presented the VRFB's capability for prolonged and reliable storage system comparatively with lower lifetime cost. The MATLAB simulation and GUI along with fused FBG in the system, implies the thermal factor affecting the real scenario of battery operation. This framework for the grid scale implication deems VRFB as a pre-eminent storage system with a wider scope for future research and technological proliferation. For the real-time non-intrusive supervision of ESS, FBG proves to be finest.**

***Keywords*— Energy Storage System, VRFB, FBG**

I. INTRODUCTION

The energy storage systems play the prominent role in success of sustainable and green energy solutions and their effective operations and transmission to main grid. This thesis focuses on efficient electric energy storage system (ESS) and use the technique of Fiber Optics (FO) to monitor and optimize the energy storage system. Energy storage system aids to resolve the issue of intermittency of renewable energy. Additionally, ESS further can be used to improvise system for efficient integration and compatibility [1]. This system will also be useful for other technology of energy storage application being on the verge of application. The research briefly delves the types of energy storage systems and evaluates the feasibility of battery energy storage system analysing its efficiency, cost-effectiveness and other standards

Background

The energy storage system plays the crucial role in the context of present power system. Not only the role of energy efficiency but implementation of energy storage system has several economic benefits like cost increased profitability, enhanced operational flexibility too [2], [4]-[6]. Investments and research have been done extensively to find the best method of energy storing system, but it has varied depending on the feature of use, area of use and energy sources being generated from [16]. In recent years there have been developing stages of energy storing systems based on solid-state battery energy system, flow/liquid state battery system, green hydrogen, hydrogen fuel cells and thermal energy storage systems [3], [8], [10]. Drawing the concept of mass scale of electric energy storage vision, many companies all around the world are enthusiast to develop the innovative way of storing the energy generated from renewable (mostly) and even from non-renewable sources for long-term purpose. Many global companies are extensively focused on R&D of unique means of energy storing methods like converting to surplus energy to compressed air, storing to elements with higher energy holding capacity, thermal energy storage, huge bulks of iron salt water too.

The notion of this kind of research is the best scalable and durable energy storage system that can have prolonged use capacity[40], [49]. Though the one hundred percent feasible system might not be found today but this research and development will eventually lead to the most feasible energy storage system for grid scale capacity [8], [27], [40].

On addition, not only finding the best energy storing system but the best optimization system is necessary in parallel so that the system can be analysed and its healthy operation can lead to prolonged use reducing the cost and hazard factors. The optimization can be done by sensing the various physical and chemical ambience of ESS like temperature, strain, charge flow states etc.

Aim of Research

- Investigate various electric energy storage systems based on criteria like technical, geographical, environmental, economic features.
- Analyse the VRFB system suitability for grid scale energy storage capacity
- Analyse the performance effectiveness between the ESS and fibre optics optimization technique in the grid system.
- Analyse the temperature sensing technique by FBG to monitor the proposed energy storage system.

Structure of Paper

This report has been prepared in the thematic order starting with foundational concept of the electric energy, global scenario of sources of energy systems and energy storing systems. The brief study of various energy storage systems and need for the grid scale is understood.

Further, the exploration among the various currently available and developing energy sources is analysed. On adding, the comparison of this energy storing system is based on their technical capability, environmental toxicity, geographical, economic feasibility, formation of these storage systems etc. After that, the practicable energy storage system is selected based on the preliminary analysis and then the further investigation of the proposed energy storage system is evaluated.

The further analysis delves deeper into technical overview of the proposed system and how to improve it further for best utilization practically.

The next part of the report continues with the analysis of temperature sensing technique of proposed ESS to optimize for safe and durable usage. Among the various available sensing technique, FBG based fibre optics sensing technique is analysed in the paper with the detail focus on its wide scenario of application.

II. APPROACH

Research type

The investigation and analysis of the case for the report have been done by opting the various methods. In the preliminary the previous research on the various energy storage system has been studied. The previous articles have been critically analysed based on the constraints developed for our proposed system. For this part the theoretical analysis has been taken as the primary reason to select the most feasible ESS and optimization system.

Resources used

For the research, IEEE journal papers, various library books and article related to energy storing system, vanadium redox flow battery, thermal sensing techniques and Fibre Bragg grating has been used.

Software used

MATLAB, Homer Pro and Python.

Method

The boundary constraints have been fixed to analyse all the data and to identify our solution which is the preferred storage system for grid scale and temperature sensing technique. The vanadium redox flow battery is investigated to be the best suitable ESS and FBG as the most feasible temperature sensing technique to analyse the system.

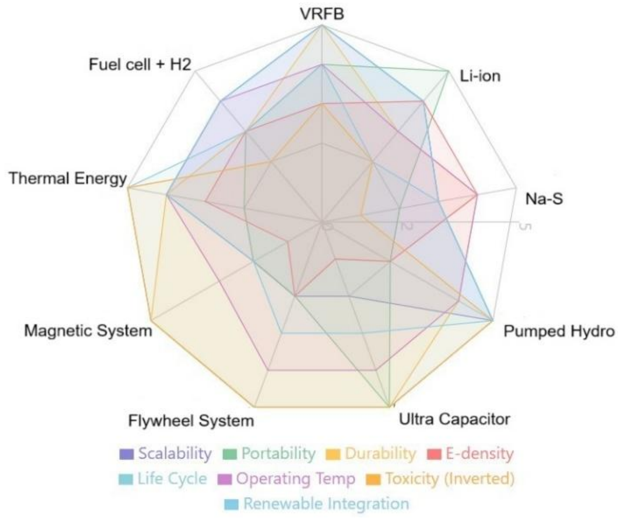

Fig.1: Range of features intensity composed by each ESS as compared to other [figure from features comparison in Python]

The investigation and analysis of vanadium redox flow battery and fibre Bragg grating was based on the theoretical analysis and generating the simulating their operational function based on their mathematical relations as described below.

The literature study and research point out following features of Vanadium Redox Flow Battery (VRFB) [19], [21], [27].

1. Dissociated power and energy capacity:
   The physics behind storing the electrical energy in VRFB battery is storing in the form of liquid electrolyte of vanadium ion states. Then the electrolyte chemical reaction occurs at cell or stack level. So,
   Scaled electrolyte tank capacity = Energy capacity scaled

   Power is generated at cell or stack. It is the rate at which energy can be distributed per mass or volume. It signifies the rate of response in delivering the energy. In VRFB it depends on size and design of stack which accumulated cells, electrodes and flow of electrolyte. So,
   Increasing the stack size = increasing the power capacity

2. Four active ions of same element (vanadium) are used in two different electrolytes to lose and gain electrons for reactions and store or release charge. This helps to avoid cross contamination and capacity loss. More-over a separator membrane is also used in between them to avoid cross contamination of electrolyte allowing ions to exchange.

3. The tendency of electrolyte degrading is significantly low which improves the durable capacity of battery storage system.

4. The aqueous solution of electrolyte is based with water with proves to be non-flammable and safe storage in stationery level. The system can be even kept at 0% SOC without affecting the battery health.

A. Vanadium Redox Flow Battery (VRFB)

VRFB stores electrical energy in the electrolytic tanks in the form of dissolved vanadium ions formed after oxidation and reduction states. During discharging process when current is supplied from storage systems to grid system, vanadium ions oxidize or reduce at electrodes to release electrons and electrical current is generated [13], [44], [46], [51], [54], [57], [58].

Working mechanism: The VRFB energy storage system constitutes of following mechanism. The charge is mainly stored in the form of dissolved vanadium ion oxidation states. Unlike the lithium ion (Li-ion) battery the energy is not stored in the electrode but rather in chemically in electrolytes. Flow of current to negative electrode as electrochemical reaction occurs and charge is stored in higher ionization state. Again, during discharging, electron is released and supplied to grid or load. In both conditions, one tank acts as anolyte and other catholyte performing reduction or oxidation process. The pump forces the flow of electrolytes electrodes. The separator or ion-exchange membrane consists of carbon felt and avoids the dissolution of electrolytes and passes the H^+ ions only to balance the charge. A cell constitutes of cell membrane and electrode. Number of cells forms a stack. The working mechanism is studied as described below in detail.

Faraday's law of electrolysis: The entire process of electrical energy storage in vanadium redox flow battery works on the Faraday's law of electrolysis. According to it, the amount of charge passed (q) is directly proportional to the moles of ions transferred.

Q = n.F [n= moles of vanadium ions reacted, F = Faraday constant]

In the process, SOC (state of charge) traces down the amount of electrolyte's chemical energy converted to electricity and the integral of the system counts the number of electrons that left. When the ions change their oxidation states then their respective colour is changed in respective electrolytic tanks. The difference of energy between oxidized and reduced species in the electrodes is expressed by open circuit voltage (O.C.V) which helps to evaluate the state of charge. When more ions are available for reaction at electrodes, it denotes the higher potential and hence the unbalanced SOC from stable state. Like, the system has maximum chemical driving force at one half of the maximum percentage of SOC, which means, the system can readily react to lose or gain electrons by vanadium ions.

Concentration of products or reactants shifts in electrode potential is described by ln (SOC/(1-SOC)).

In the electrodes, the loss of electron by vanadium ions is oxidation and gain of electrons by vanadium ions is called reduction. Interestingly, we have V^{2+} and V^{3+} in the anolyte and V^{4+} and V^{5+} in catholyte and depending upon the charging or discharging condition the oxidation or reduction occurs in the either side I,e anode or cathode.

$$VO_2^+ + 2H^+ + V^{2+} \rightarrow VO^{2+} + H_2O + V^{3+} \quad (1)$$

$$E^o_{cell} = E^o_{cathode} - E^o_{anode} \approx 1.00-(-0.26) = 1.26V \quad (2)$$

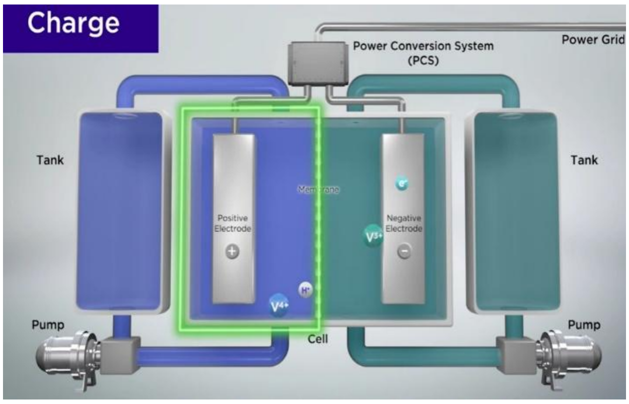

Fig.2: Charging mechanism in VRFB [65]

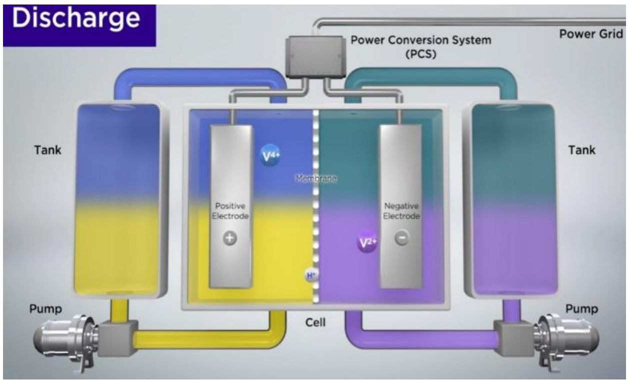

Fig.3: Dis-charging mechanism in VRFB [65]

Now, understanding the release of thermal energy release and effect in the entire system.

The ohmic drop (IR) represented because of the effect of: -

a. Resistance of electrodes (the carbon felt used in the system architecture)
b. Conductivity actions of electrolytes
c. Resistance of the membrane.

Due to these scenarios, the real terminal voltage in the system is always higher during charging process and lower while discharging process than the calculated ideal open circuit voltage. When the current flows during the resistance scenario, heat is dissipated and ohmic heating is observed.

Ohmic heating = I^2R.

When the terminal voltage is not equal to open circuit voltage, energy is absorbed or lost during the side reactions leading to release of heat. To compensate the generated heat the rising temperature is naturally released in the external environment by the medium of natural convection and coolant flow mechanism.

B. Fibre Bragg Grating

There are various methods, the rising temperature in the energy storage system can be measured. From various sensing a literature review and study have been done to identify the suitable sensing technique for energy storing system. Among them fibre Bragg grating, which uses the mechanism of fibre optics is the notable technology and it has been further used for investigation to be used in vanadium redox flow battery storage system [7], [9], [17], [18], [33], [37], [50], [17].

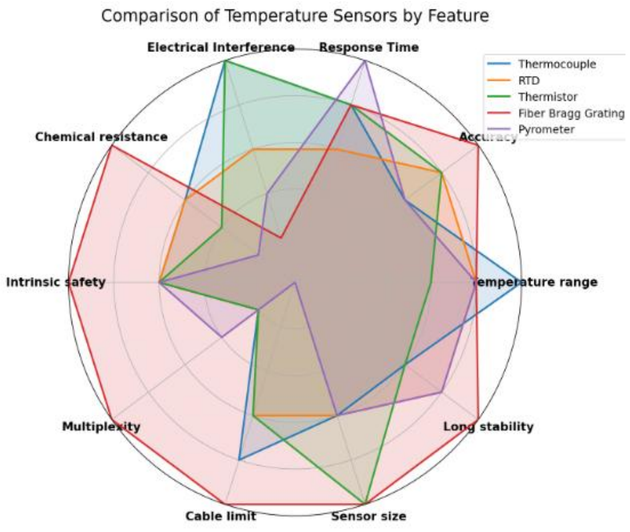

Fig.4: Range of features compared among different sensing technique [figure from features comparison in Python]

In general terms, the part of fibre optics core tube is grated in periodic manner to make a sensor, and this tends to shift the wavelength of reflect the wavelength due to the heat. It acts as a non-invasive and non-intrusive temperature measuring and sensing component inside the battery or energy storage system.

Here the mathematical relations and operations of fibre Bragg grating is elaborated in the note.

$$\lambda_B = 2\, n_{eff}\, \Lambda \tag{3}$$

where, λ_B = Bragg wavelength

n_{eff} = effective refractive index of fibre core

Λ = Grating period

$$\Delta\, \lambda_B = k \cdot \Delta T \tag{4}$$

$$\text{where } k = \lambda_B\, (\alpha + \xi),\ \Delta T = T - T_0 \tag{5}$$

and α = thermal expansion coefficient of fibre

ξ = thermos optic coefficient.

When temperature or strain changes then n_{eff} and Λ changes due to thermos-optic effect and thermal expansion effect respectively.

Wavelength shift occurs due to rise in the temperature.

$$\Delta\, \lambda_B / \lambda_B = (\alpha + \xi)\, \Delta T \tag{6}$$

$$\text{Or } \Delta\, \lambda_B = 2\, n_{eff}\, \Lambda * (\alpha + \xi)\, \Delta T \tag{7}$$

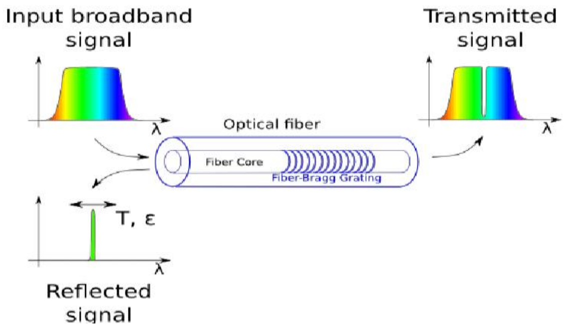

Fig.5: FBG working mechanism in optical fibre [https://www.researchgate.net/figure/Working-principle-of-a-fiber-Bragg-grating-sensor-wavelength-of-the-reflected-signal_fig2_268378207]

In the temperature sensing mechanism of fibre optics, a standard silica FBG core is grated in a single mode by UV laser.

The typical characteristics are mentioned below.

Standard central wavelength of FBG (λ_B) = 1530nm

Temperature sensitivity = 10~15 pm/^{0}C

Measurement range = -20^{0}C to 300^{0}C (when properly coated)

Resolution = ± 0.1^{0}C (with a high-resolution interrogator).

Here, to measure the temperature changes ignoring the strain changes,

$$\Delta\, \lambda_B = k \cdot \Delta T \tag{8}$$

$$\Delta\, \lambda_B = \lambda_B\, (\alpha + \xi)\, \Delta T \tag{9}$$

$$\Delta\, \lambda_B / (\lambda_B\, (\alpha + \xi)) = T - T_o \tag{10}$$

$$T = T_o + \Delta\, \lambda_B / (\lambda_B\, (\alpha + \xi)). \tag{11}$$

The further scrutiny of VRFB was done and analysed in the simulation environment of MATLAB, Homer Pro and python pipeline coherently. The Techno-chemical approach in MATLAB environment and Techno-economic approach in Homer Pro environment were analysed and studied together in Python platform to compare the various characteristics and thermal behaviour affecting the ideal scenario of operation.

III. Experiments / Testing / Measurements / Data

The data has been gathered primarily from various platforms like simulation evaluation and the previous

research articles. The previous research journals have been taken as main source for the preliminary study and source of data in this part of thesis.
In this phase of part A only the theoretical analysis of various systems is done to identify the feasible ESS to investigate further. The further testing and measurement will be done in Part B by simulation and experiments.

Energy Storage	VRFB
Scalability	Very High
Portability	High
Durability	Very High
E-density	Medium
Life cycle	High
Toxicity	Low
Renewable Integration	Very High

Table.1: Identification of VRFB features analysed from fig1.

	VRFB
Strength	Scalable and Prolonged
Weakness	Low Energy Density
Opportunity	Grid Scale Storage
Threats	Portable Device Storage

Table.2: SWOT analysis of VRFB

	FBG
Strength	Multipoint Non-Invasive Sensing
Weakness	Low Commercial Awareness
Opportunity	Massive Scale Sensing
Threats	High Upfront Cost

Table.3: SWOT analysis of FBG

Moreover, the VRFB FMU was created in simulation environment which comprised the core physics of VRFB operation relating to technical and chemical energy flow operations. The data of techno-economic evaluation for the time period of 25 years from Homer Pro simulation environment was passed into the VRFB FMU in the python pipeline to further evaluate the effect of thermal behaviour in battery energy storage system which affects the health and efficiency of battery. The flexible MATLAB graphics user interface was developed to analyse and compare the different scenario of suppled current, flow capacity, number of stacks and operating time to study effect on the stack current and voltage, SOC of battery, temperature and wavelength changes of Fiber sensor to understand the most eminent feature like charge retention, tank size scaling and stack size scaling, efficiency and thermal behaviour.

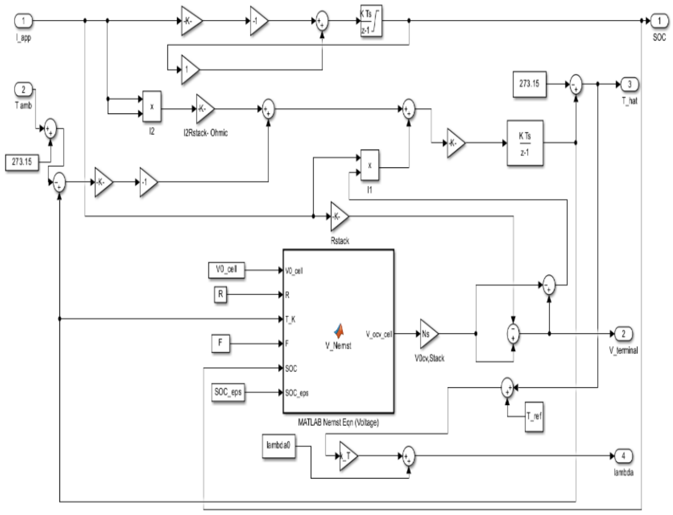

Fig.6: MATLAB FMU block of VRFB system [figure from MATLAB Simulation]

In the MATLAB for the working mechanism and characteristics evaluation of VRFB a techno-chemical model is developed in MATLAB Simulink. It resembles the practical operational characteristics of VRFB energy storage system and temperature sensor mechanism by FBG. The developed model is converted to Functional Mock-up Unit (FMU) block. The output like current and voltages are received from Homer Pro and then fed to the FMU block of VRFB system which then evaluates the practical performance of VRFB in practical condition rather than ideal condition.

The relation developed for FMU block architecture is illustrated below. Here the evaluation is done taking the terms for one individual stack of battery storage system which is the then later evaluated multiple number of cells and stacks.

1. The storing or charging current to the storage system is passed to the block in the form of ‘I_app’. This current could be current generated from any sources like wind power, solar PV, hydro power generation or any other sources.

2. The value of surrounding ambient temperature at the energy storage plant is passed by ‘T amb’.

3. The ‘SOC’ is the output of the energy storage system which evaluates the state of charge while charging, discharging or during any stable condition.

$$SOC_{(t)} = SOC_{(to)} - 1 / q_{max} (\int_o^t I_{app}(\tau)\, d\tau \qquad (12)$$

$$q_{max} = M * V_{tank} * F \qquad (13)$$

SOC not only helps to convey the charge of battery system but also helps to stop the side reactions by providing the feedback The feedback of fully charged, depleted or any percentage stage information helps to operate the system accordingly.

4. The 'T_hat' gives the feedback about the temperature of the system at any period of time. It helps to examine the thermal health of plant.

$$Cth.\ dT/dt = I^2_{app} * R_{stack} + I_{app} (V_{terminal} - V_{ocv,stack}) - hA.(T - T_{amb}) \quad (14)$$

from the equation, Ohmic heating = I^2R (15)

So, for temperature,

$$T_{hat}(t) = T(0) + 1/(Cth) * \int_o^t (I^2_{app}(\tau) * R + I (V-V_0) - hA (T- T_{amb})) d\tau \quad (16)$$

5. The 'V_terminal' is the voltage of the stack as per the current supplied, temperature evaluated, SOC and temperature affecting the entire performance of the system.

$$V_{terminal} = N_s * V_{ocv} - I\_app * R_{stack} \quad (17)$$

And,

$$V_{ocv} = V_o + RT/F * \ln ((SOC - \xi) / (1- SOC + \xi)) \quad (18)$$

Here, in the simulation block the Nernst block has the operation for Nernst equation which tells how the temperature and vanadium ion concentration impacts the voltage of and electrochemical cell.

Given by:

$$E = E^o + RT/F * \ln \text{(oxidized concentration / reduced concentration)}; \quad (19)$$

which in our block is described by;

$$V_{ocv} = V_o + RT/F * \ln ((SOC - \xi) / (1- SOC + \xi)) \quad (20)$$

6. The 'lambda' provides the final values of wavelength from FBG after it is affected by the change in temperature of the system at individual point of time.

$$Lambda\ (\lambda) = lambda_o (\lambda o) + K_T * T_{hat} \quad (21)$$

From above entire relations the standard values used for vanadium redox flow battery storage system simulation in overall investigation is;

M= electrolyte concentration [mol/m^3] = 1600
V_{tank} = Volume of electrolyte [m^3] = 0.083
F = Faraday constant (C/mol) = 96485

N_s = Number of cells = 200
R_o (ohm)= 0.0003 (per cell)
V_o (v)= 1.40 (per cell)
C_{Th} = thermal capacitance of stack (J/k) = 1250
h= heat transfer coefficient (W/k) = 2
A= surface area of stack = 200
T_{amb} = 25°C

$lambda_o$ of FBG= (λo) (nm)= 1530
K_T = thermal sensitivity of FBG (nm/°C) = 0.010

T_{hat} = stack temperature generated
R_{stack} = Ns * R_o
Voc = open circuit voltage

IV. Analysis and Discussion of Results

The results obtained for this part is purely based on evaluation from simulation environment and theoretical analysis from the previous research journals and articles. The detailed assessment for the ESS and sensing technique has been evaluated in literature review section of this report.

The features analysis of VRFB from multiple analysis shows the dynamic features of VRFB as compared to other existing ESS like Li-ion, Na-S, Pumped Hydro, Ultra Capacitor, Flywheel System, Magnetic System, Thermal Energy, Fuel cell + H_2. Though the Li-ion ESS seems to be competing, in the analysis it lacks in the most prominent feature for grid scale use [15], [23], [25], [32], [35], [42], [45]. Li-ion lacks the scalable and pro-longed use capacity due to requirement of multiple thousands of cycle life. Na-S has medium scalability but highest toxicity for usage. Pumped hydro on the other hand is restricted by geographical constraints and has huge investment condition. Ultra capacitors are faster, but they have least scalability, low energy density. Flywheels systems too have least scalability and low energy density. Magnetic system also has least scalability and low energy density. Thermal energy while similar to pumped hydro, is constrained by geographical restriction and lacks portability too. Fuel cell + H_2 are comparatively less durable and more prone to toxicity in comparison to VRFB systems.

The operating mechanism in VRFB is illustrated in the figure attached below.

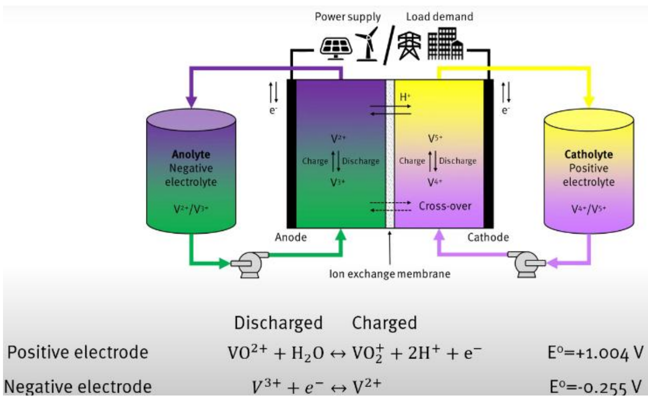

Fig.7: Elaborated system architecture of VRFB [66]

FBGs are gaining popularity due to flexibility in inscribing FBGS and grating periods in same optical fibre to manufacture broad sensors. FBGs are mostly used in multiple fields due to their expandable multiple features of efficiency in response, multiplexing, lower invasiveness, smaller size and immune to electromagnetic interference.

The calculation for Bragg wavelength in FBG is denoted by :

$$\lambda_B = 2\, n_{eff}\, \Lambda \qquad (22)$$

where,

λ_B = FBG resonant wavelength

n_{eff} = effective refractive index

Λ = grating period

The change in temperature of the battery expands/shrinks the fibre and hence its refractive index, which ultimately changes the wavelength of bragg. The wavelength change is detected by interrogator to measure the equivalent temperature.

The interpretation formula is given by;

$$\Delta \lambda_B = k \cdot \Delta T \qquad (23)$$

Where, $k = \lambda B(\alpha+\xi)$ (24)

From the simulation environment, the results is obtained and the performance of VRFB as a energy storage system is investigated.

A. Results from MATLAB graphical user interface analysis:

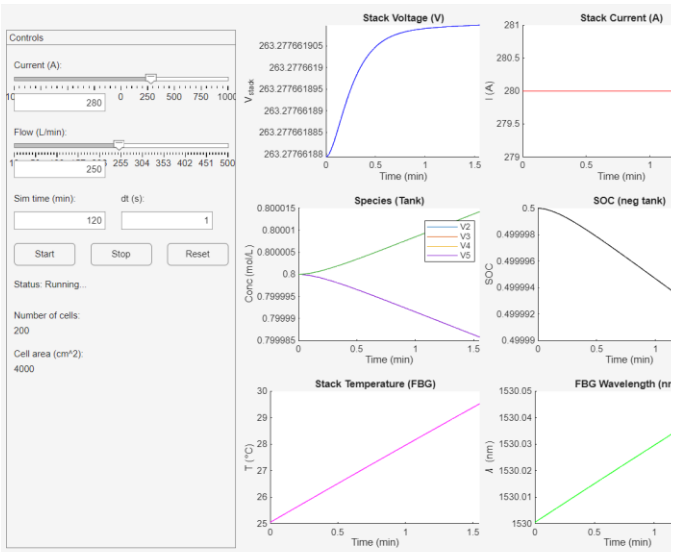

Fig.8: MATLAB graphical user interface result 1.

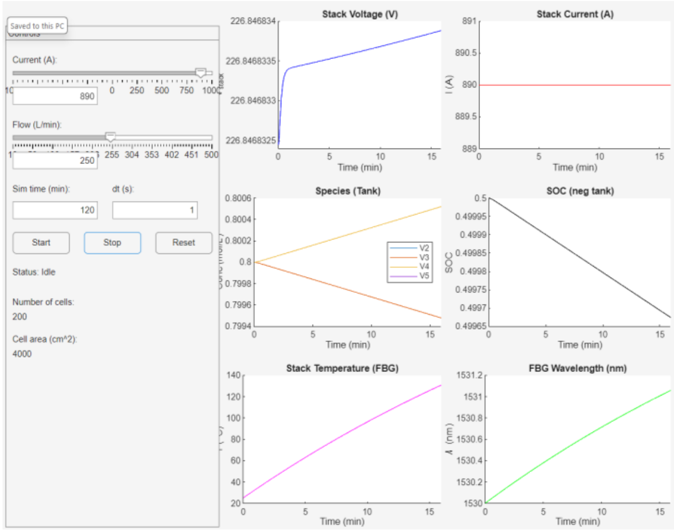

Fig.9: MATLAB graphical user interface result 2.

In the MATLAB graphical user interface, the option for supplied current, flow rate, and simulation time can be varied. In the background, other constant parameters of VRFB and FBG as mentioned above in the experiment section are kept constant and the results are observed. At fixed current supplied:

- Changes in voltage ∝ current supplied
- Change in temperature ∝ voltage
- Change in wavelength ∝ temperature

At the charging and discharging time the species of electrolyte relatively change their colors signifying their changes in oxidation states.

The current of 250A and 890 A is taken at two different cases, flow rate of 250 and simulation of 120 minutes is taken for both cases. Once the charge is fully charged and discharged it remains in the same stage showing no leakage of current or any side reactions. With specific rise in temperature the wavelength changes precisely even for very small changes in wavelength in which K_T shows the changes by 0.01nm changes. The table below shows the change in wavelength per change in temperature from the above results.

T(C)	ΔT	$\Delta\lambda_B$ (nm)	λ_B (nm)
25	0	0	1530
26	1	0.01	1530.01
27	2	0.02	1530.02
28	3	0.03	1530.03
29	4	0.04	1530.04
30	5	0.05	1530.05

Table.4: wavelength change in FBG.

B. Homer Pro simulation

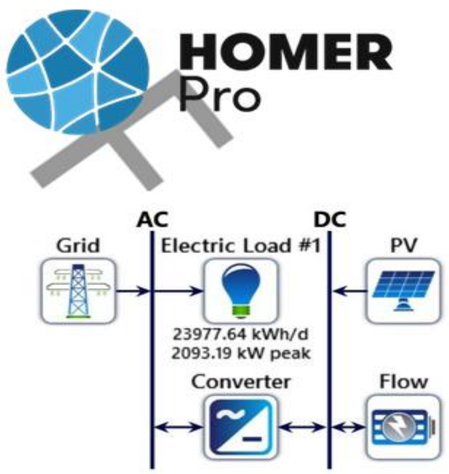

Fig.10: Homer Pro electrical grid system components.

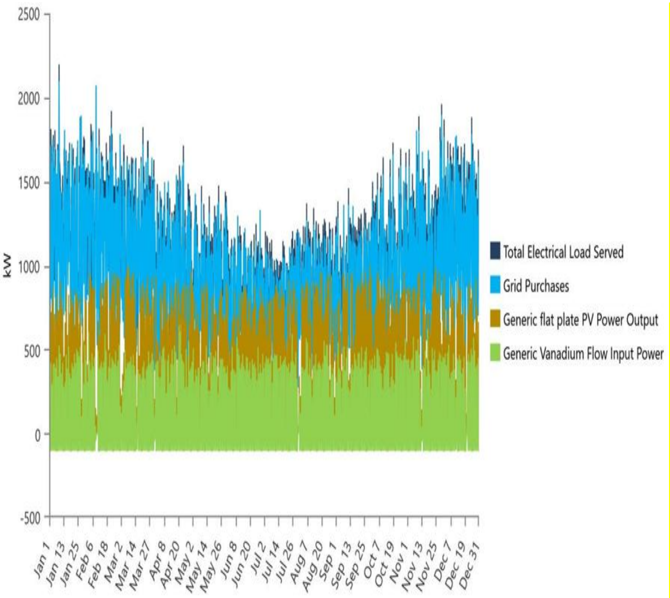

Fig.11: Homer Pro result 1.

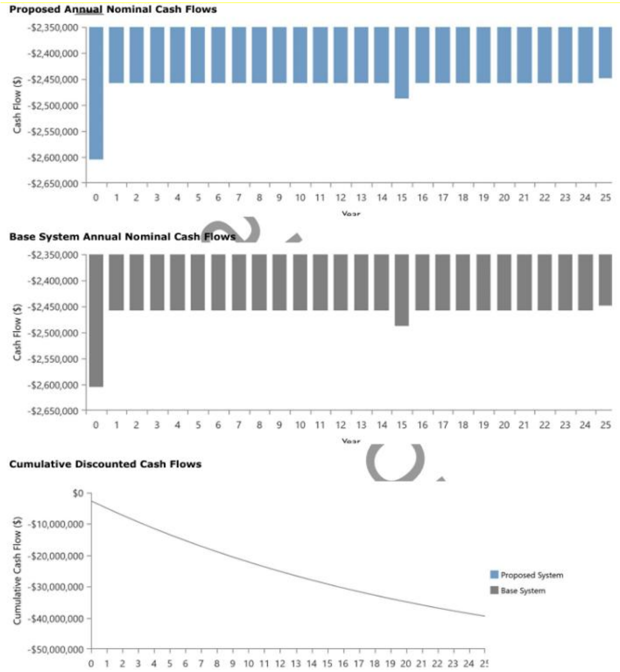

Fig.12: Homer Pro result 2

Homer Pro was used to simulate the entire electricity transmission system in ideal scenario to evaluate the generation of current and techno-economic analysis.

The system included the generic flat plate PV of 1000kW size, system converter of 100 kW, Grid transmission for the load of 999,999kW and VRFB flow battery of size 1Mwh.

The output of the Homer Pro has been taken for Fig.11 related to electrical load, grid purchase compared with flat plate PV output and vanadium flow inputs, and Fig.12 related to cash flows for the system. The result represented 100% renewable energy penetration. The system was evaluated for 25 years of evaluation as the VRFB batteries have a durable life expectancy of tentatively 25 years. The report generated the flow of current for the system. Evaluated the proposed annual nominal cash flows, base system annual nominal cash flows and cumulative discounted cash flows which were negative entire period of time due to initial high cost of the system. But the slower degradation of VRFB and lower operating cost due to lower maintenance resulted in higher cycle of operation and lower levelized cost of energy. From the excel sheet the values of generated current were taken to further analyze in non-ideal condition.

C. Python Pipeline evaluation.

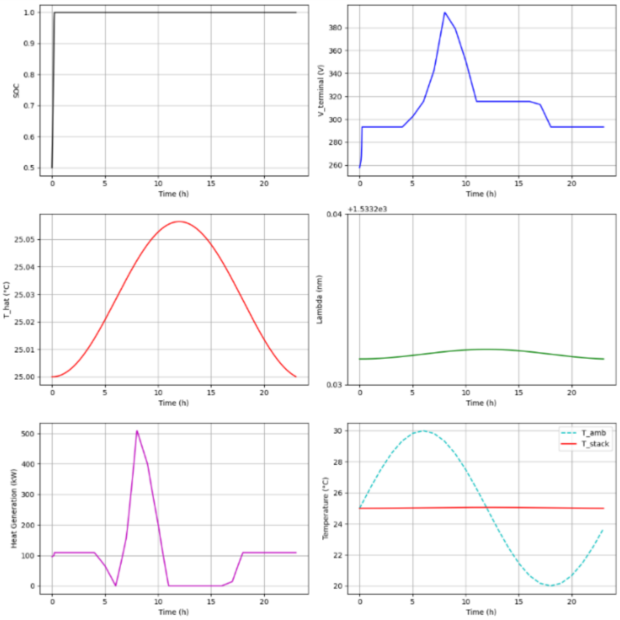

Fig.13: Output from python pipeline.

The simulation of FMU was used to supply the evaluated current from Homer pro to further analyze in

Pipeline integrating both the systems.

1. It was absorbed that SOC remains steady until drawn by the system which shows the retentivity property existence.
2. Voltage ∝ current shows to increase voltage of the system the supplied current can be increased.
3. Stack temperature ∝ current, whenever the current flow amount or speed is increased the stack temperature increases

Here from the overall investigation the system has wide scalability and retention capacity in terms of energy storage ability. The variation in charging time, capacity has effect on temperature, energy storage due to different electro-chemical reactions. The realistic scenario of thermal effects in the storage system was also analysed. FBG integration aided to improve the predictive observation of the system.

Besides the above-mentioned investigations and characteristics [11], [12], [20], [23], [28]-[31], [47], [52], the factors that affect the performance of VRFB storage system are: -

1. Flow rate of the electrolyte and pumping capacity
   The flow rate and pumping capacity affects the overall efficiency of the system

2. Membrane role and resistance
   The material used as a membrane affects the speed and power density of the system ultimately.

3. Self-discharge rate
   The self-discharging rate is the loss of stored energy over a certain period when the system is kept in a stable position without charging or dis-charging.

4. The response time of system while charging or discharging.

5. Safety margin illustrates the choice of technology for critical place use and long-term viability too.

As per the study following are the major current obstructions for the effective use of the VRFB in the energy storage system:

1. Low energy density
   Currently the energy density of VRFB stands around ~25-40Wh/L which is low as compared to Li-ion battery which has 200-300Wh/L. To increase the energy density, it requires massive tanks and large liquid volume handling capacity.

2. Low round trip efficiency
   Due to various factors like loss in the membrane, pumping effects and side reactions, the efficiency drops to between 65-80%. The makeup for low efficiency tends to increase the cost of overall battery storage system.

3. High initial cost in the market
   The low market availability and fewer R& D has resulted in lower usability and extraction of vanadium elements. This has resulted in initial higher cost for setting up the Vanadium Redox Flow Battery system.

Factors that affect the sensitivity of the FBG as analysed from literature review of journals [14], [34], [36], [39], [43], [55], [56] are: -

1. Bragg wavelength (λ_B): - Bragg wavelength has direct impact on performance of FBG because longer wavelength of FBG grated will have higher absolute wavelength shift than the shorter wavelength.

2. Thermo-optic coefficient: - The thermo-optic coefficient has direct influence on n_{eff} which is effective refractive index of fibre core with the rise in temperature

3. Coefficient of thermal expansion: - The coefficient of thermal expansion also has direct impact on the 'Λ' which is grating period. As compared to other factors it has relatively smaller impact due to lower thermal expansion of glass for materials like silica.

4. Coating or packaging the materials: - As studied from literature review, it can be clearly understood the coating of FBG, packaging and grating plays a significant role in the performance of FBG.

Influential role of FBG in the electrical energy storage system: -

1. Real time data transfer and conversion: Due to the flow of data nearly in speed of light, user can get feedback in real time scenario.

$$\Delta T = \Delta \lambda_B / K_T \quad (25)$$

The above equation shows the slightest changes in temperatures with the slightest changes in wavelength.

2. Thermal management and control mechanism: Since the thermal environment management is crucial for energy storage systems due to the eminent changes in temperature, the FBG plays the significant role. The high-speed performance reads the temperature changed in the small fraction of time and are fetched to the control system. With it, the trigger of cooling and heating mechanism can be activated as per the feedback from the system.

3. Diagnostic and safety system: Due to the small size, non-invasive, inertness and non-toxic nature of FBG, it can be placed directly near to the critical components like electrode, separators, electrolytes without any effect of electro-magnetic interference. This nature can aid to diagnose the system from the depth enabling the alarms and data logging functions for individual components to ensure safety of the system.

4. Visualisation and examination feedback: The output from FBG can be easily converted to other systems to examine and visualize the result in different systems like numerical values, graphical representations, triggering set-points, evaluation models etc.

The following unique characteristics have kept the FBG secure for future expectation in the energy storage system.

1. Non-invasive and non-intrusive use
2. Chemical inertness and immune to electrochemical reaction
3. Smaller in size and ability for multiplexing.
4. Quick response and higher accuracy.
5. Long duration stability and safety.

V. CONCLUSIONS

The vanadium redox flow battery is investigated to be the best suitable ESS and FBG as the most reliable temperature sensing technique to analyse the system. The vanadium redox flow battery is one of the popular type of ESS in present context and gaining popularity for further research and development as prominent alternative system to store electric energy.

As analysed various changes in components play vital role in upgrading operational performance of VRFB storage tank as suggested below.

1. The modification and quality of material used as separator.
2. Flow rate and current density changes.
3. Electrode thickness and layer ratio.
4. Ability to decrease the polarisation.
5. Use of impurity or solid electro active materials instead of aqueous vanadium ions electrolytic solution to increase energy density.

Likewise, the performance of FBG can be improved by:

1. Testing ranges of pre-stressing and packaging techniques to improve stability.
2. Choosing different thermal expansion-oriented materials to enhance performance in extensive temperature ranges.
3. Validating the calibration and demodulation technique to improve the precision and spectrum distortion issue.
4. To improve the linearity and sensitivity of FBG, selective coating materials have to be taken into account.

The VRFB has a potential for large scale electric energy storage system due to feasibility for pro-long duration and scalable nature for integration in grids. Likewise, FBG has a potential as a sensing technique in storage systems due to abundance of features like flexible, efficient and effective diagnostic feedback of thermal health [48, 22, 26, 38, 53].

VI. FUTURE WORK

The investigation and analysis done is completely based on the theoretical aspects analysing the research articles, mathematical calculation and evaluation from different simulation platforms. The further analysis to suggests the further changes in the material properties like solubility of electrolyte, alternative electrolytics states like polymer of electrolytes. The technology holds the prospect for depth analysis and research and development in the use of corresponding components. Upon enhancing their capacity and reliability, this proposed system promises for future in grid reliability and sustainable energy performance.

APPENDIX A: LITERATURE REVIEW

Introduction of Literature Review

The foundation of the today's world is entirely dependent on the electricity. Electricity has been a shadow twin in every field and every aspect of humans to live. If the electricity seizes from the source or grid, the whole world blacks out. The depth understanding of the importance of electricity has raised the concerns about the sources of electricity generation, technology for storing the electricity and optimization method to operate the entire electric grid components and storage system in a safe manner. Since the 1970's onwards the push has been further escalated to strength the solutions for renewable energy (RE) and backup storage system. Energy storage system (ESS) functions as buffers between consumer and supplier or generation unit by storing the excess energy [6].

Moreover, the general weaknesses of renewable energy sources are intermittency, time of day generation dependence, seasonal variations, precise placement of generating station, aesthetic considerations, geographical limitations and end of life management. While they rule with the strengths of being renewable source, predictable daily pattern, scalability, low operating costs, decentralized generations, environmental benefits, low maintenance, technological advancements, grid support etc[16].

By 2024, 32% of global energy constitutes of renewable energy and the global energy storage capacity has grown to around 8500GWh which accounts for 2% capacity considering all the energy storage system. With the concern for importance of renewable energy sources and the backup for the grid energy, there has been rise in the research for best energy storage system. The escalating demand for suitable energy storage systems has attracted the vanadium redox flow batteries among the researcher due to its special feature of grid scale capacity usage. The rising analysis on energy storage system has led the concern for safety part to optimize and sense the grid system and specially energy storage systems.

Among the various sensing technique to optimize the energy storage system, fibre optics holds the special attention due to special feature of flexibility, secured and quick features in the grid system usage. Currently, 40% of temperature sensing market is held by fibre optics. Considering the immature stage of market technology for durable energy storage system and optimizing the system, a detailed investigation has been analysed in the paper.

Aim of Literature review

The aim of this literature review is to exhibit the various energy storage system present. Depict the most feasible energy storage system suitable for grid scale use. Additionally, demonstrate the optimization technique of fibre optics as well to measure the temperature of energy storage system.

The organization of the literature review has been organized in the thematic order as per the topic of the thesis developed from the foundation of the electric energy systems, electric energy

sources in the present context and the necessity of electric energy storing system. Then proceeding to comparative study of various existing energy storage system after that selecting the most feasible ESS from the constraint guideline. The constraint for our system is grid scale, durable and scalable energy storage system. After that further technical and architecture investigation is done to study the probable improvements to be done for the practical industry scale use.
Moving forward, the prominent optimizing technique is analysed from fibre optics to operate the proposed ESS for safe and prolonged capacity. Here, FBG temperature sensing technique is investigated for the use in monitoring and measuring the ambience of ESS.

Body of Literature Review

Background on energy storage based electric network systems

There has been depth investigation on best possible way to utilize the energy sources in the power system utility by the use of most feasible energy source, energy storing system and the optimizing system. [1] tries to lay out the advancing concept of hybrid energy storage system (HESS) used for flawless intergation of renewable energy systems in grid. The study shows the generalized idea of HESS being used in power line and energy with the exiting non renewable energy source as optional source. And for the sustainability and long term use, the priority has been give to renewable energy source. It has been described, since the renewable energy are also not relaible due to intermittency a hybrid structure with ESS has been put forward as a solution. The paper has been able to illustrate that no single energy storing system (ESS) can address all grid stability and reliability requirements.

Similarly, [2] also has shown the design and simulation for power management and control by hybrid structure system integrated with diesel generators too at the remote based location. Though the modelling is adequate but still the use of non-renewable sources as primary or backup instead of renewable sources and lacking the priority focus on storage system to full strength does not seems to be a promising future. On the other hand, [22] have put forward the Probabilistic Fuzzy Inference System (PFIS) strategy to manage the energy and forecast the power generation from the renewable sources. Here loads balancing demand is managed using hybrid structured energy storing system to mitigate the issue. Likewise, [42] have opted out the framework of operation for Battery Energy Storage System (BESS) which is aligned to hybrid AC grid. Photovoltaic solar energy which has increased its capacity roughly by nine times from 381.6 GW in 2010 to 3,4 TW in 2019 is showing the intense increase around the globe. Still PV and wind turbines are flawed by issue of fluctuation in energy. Unreliable weather conditions have resulted the challenges of power quality, protection, dispatch control and reliability. Energy storage system plays the vital role to rectify the existing issue and increase the possibility of massive insertion of renewable energy by stabilizing the variation to the acceptable range and recapture the excess energy. This framework has been able to act on reserve capacity, critical analysis of storage system.

[3] have presented the light on the performance analysis of hybrid system composed of VFRB, lithium-ion battery pack in the electric buses propulsion which adds the possibility of advantages for increasing battery life and operating hours due to VRFBs.

Furthermore, While the reality of ever-increasing power demand and supply, regulations and resiliency of system lies in one aspect, there is the consideration of rise of renewable energy on other aspect at the same time. The reliability and resilience of the system is focused on the how often and how long the electricity cut-off could happen and the extent of system to bear load and supply efficiently [40]. Without the ESS the system can have low cost and simple structured but it cannot avoid the underlying predicaments of renewable energy which are intermittency, grid dependence and wastage [16].

All these analyses have proved that till now the energy storing system in the grid are mainly used for backup system than the primary source to store and depend fully on the ESS. The main reason is due to the quantity of energy and duration of time; the energy storing system can withhold with the grid system architecture effectively.

Comparative study of various energy storage systems

The existing common ESS technology includes batteries, supercapacitors, pumped hydro storage, compressed air energy storage, flywheels, thermal energy storage, hydrogen and fuel cell and gravitricity energy storage system [16]. Solar energy generation is contingent upon daylight. Likewise, every renewable energy has setbacks of continuous smooth generation of electricity for supply due to various geographical, technical and environmental conditions. By the advancement and alignment with best ESS helps to mitigate these challenges and secure sustainable energy for future.

The various energy storing systems are analysed distinguishing the various aspects of energy storing system depending on different point of use[1]. Battery incorporated, mainly lithium ion (Li-ion) batteries have the holding capacity for short duration of time. Flow batteries or liquid batteries are flexible to increase capacity, and the main function unit electrolytes are stored externally, so they are generally used for spacious environment. Thermal energy storing system has the system of storing excess electricity in the form of heats in chip-carbon blocks. Pumped hydro storage and compressed air energy storage has high capacity to store energy in the form of potential energy and compressed air energy form respectively but need proper geographical setup. Flywheels, supercapacitors and superconducting magnetic ESS are fast, but they sustain limited energy density and expandability. Hydrogen fuel cells have the energy storage system in electrochemical form, and they pose constraints of safe storage and toxicity in production. Other energy storing systems also basically do in the form of elemental storage which has higher capacity to hold the energy.

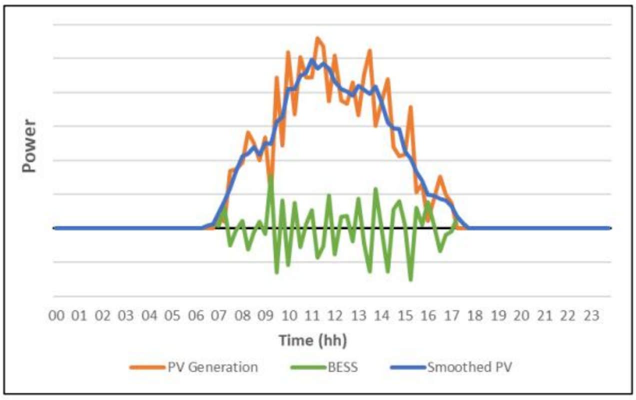

Fig.14: Typical operation of storage system connected to PV system to resolve intermittency [14].

Further drawing the attention of most influential ESS in the present scenario, [6] have analysed the research paper on techno economic analysis, operation control, system sizing, demand response and geographical demand of battery energy storage system (BESS). The study of research paper by author, while modelling the lifetime performance and economics of residential PV-BESS in USA, the proper sized and incentivised PV-BESS tend to be more affordable and competing to utility prices than sole PV systems. The author is able to assess that the BESS and pumped Hydro energy storage as common system to handle intermittency of RE and improve grids capability. The recent trend shows the expected growth to 400GWh per year for the BESS deployments between the year 2022 and 2030. Batteries are the functional unit of electrochemical cells that are able to convert the electrical energy to chemical energy or vice versa

[15] addresses that the best idea of converting other forms of energy to stable chemical form of energy due to its portable and convenient nature. It has led to growth of various types of battery energy storing system and especially Li ion batteries due to portability, low costs, safe and rechargeable nature. The Li batteries which are now being extensively used among the electric vehicle has the safety issue on inflammation. To deal with the issue the author has suggested on having large window gap between highest occupied and lowest unoccupied molecular orbital or to develop solid electrolyte interface which ultimately prevents Li ion plating on carbon anode during fast charging. The existing quantifiable use of Li-ion battery still has the hinderance to be used in grid scale due to the factors of life of battery, inflammation issue, toxicity too.

Here , the author [24] elaborate the lignin nano crystal as a capacitive material to rectify the solution of low energy density for ESS. Super capacitors poise quick charging and discharging rate, extreme power, durable life cycle and operational safety features. While the article by [45] have displayed the various alternatives of hybrid energy storage systems (ESS) to enable their features in electric vehicles (EV) pouring the concept of battery and ultracapacitor (UC). Fusion of battery system with capacitors, magnetic storages and flywheels can decrease the existing problems. The battery technology in EV now is not only sought for longer mileages but also for durable life, excellent retentivity, least time for charging too. Though these features can be enabled by UC, the additional cost and complexity have resulted reluctance of UC in EVs.

[35] analysed the role of compressed air energy system (CAES) to improvise cost effectiveness and reduce the uncertain events in the grid system due to sudden changes in load demands and supply and intermittency of renewable sources. The popular ESS system used in the grid are pumped hydro energy, BESS (Battery energy storage system) and CAES (compressed air energy storage). As CAES has been seen as reliable in large energy storing capacity, charge cycling life and lower geographic constraints.

Author [32] have investigated the past present and future aspects of lead acid battery and have laid out functional characteristics for being used in the industry since a century. Despite its issue of low energy density and health related impacts, about 30%-40% as contrary of Li-B of 90%, still lead acid battery has majority share due to its non-flammable electrolyte component, low cost and high recycling rate. The continuous dissolution and redeposition over each cycle create change in morphology and microstructure of electrode leading to corrosion. The nature of lead sulphate dissolution and lead acid concentration gradient in electrode makes challenge for improving recharging rates. Effective engineering can aid to penetrate the market while addressing issue of health, battery weight and energy density.

While, as stated by [4] to utilize the sub surface energy storage capacity from geological aspects the proper structural information about occurrence, prevailing nature, induced effects, storage dimension and properties of using those sites is necessary.

[48] have assessed the energy storage to be fit for the home electric energy generated from renewable source. Lead acid batteries have the cons of low energy density and longer recharging time. They may have life cycle of 500 to 2000. Nickel Cadmium have negative side of losing capacity with repeated shallow discharges, higher cost and maintenance and environmental hazard. Nickel Metal Hydride capacity drops largely after small number of cycles and high cost too. Li-ion battery on the other hand has long life cycle, no maintenance required, greater power and energy density but still they have high initial cost, needs protective circuitry to limit charges and discharges of power and energy. Super capacitors have high power density but poor energy density and higher cost. Fuel cells are still on the verge of R&D with upfront higher cost. Pumped hydro storage system is not flexible and largely elevated topography based. Redox flow battery has commonly Zinc/Bromide and Vanadium Redox types. They have good specific energy and efficiency, lower cost, environmentally positive, faster chargeable, higher power density but have lower energy density and additional costs for overhead pumps and control system.

Similarly, [21] assessed redox flow batteries RFB) seems favourable for the lasting and massive scale electric energy storage system which is safe and economical too and technology of vanadium which is VRFB is the matured one till date. [26] tries to analyse the best use of solar and wind energy fitting into the battery storage system (BESS) and utilize the advantage of vehicle to grid (V2G), but author lacks the effectiveness on laying out successful V2G integration.

[38] tries to elaborate the possible extensive use of VRFB to multi-storied building integrating with solar PV rather than being confined to grid capability only.
Moreover, the limited availability of Lithium and Cobalt and their environmental cycle have led to the thought of potential alternative inside the family of battery technology due to the rise in global demand [49]. The redox flow battery operates in the principle that energy storing components, electrolytes, are kept out of the main block of the system which gives the perks of scalability and seamless operation and efficient recyclability. The charge transfer mechanism, engineering the reservoir, chemistries of electrolytes and solid electroactive materials play vital role for changing energy density of the system. On addition, [13] have illustrated the modelling and simulation of Flow batteries that have been gaining the limelight with the increase in the demand for the renewable energy sources due to their simple constitution, large scale grid capacity, durable life span, quick response, comparatively safer.
The important factor is, [5] have critically analysed the impacts of industrial products and process to the environment and mitigating plans. The focus has been especially drawn to the EVs and the battery used after entirely analysing the product life cycle and assessments. Further a framework has been proposed on the industrial scale to increase the sustainable lifespan. The methodologies shown was able to illustrate the CE (Circular Economy) progress after pointing the notable issues related to material outflow, insufficient outflow and poor end of life management.

Besides, [16] have listed out various technical, economic, environmental and regulatory challenges to integrate the various ESS to different energy sources and grid systems. One of the challenges for battery preferred storage technology is the decline of operational efficiency with time, disposal and recyclability rate, limited existence of crucial battery elements like Lithium and dilemma of environmental and human resource questionnaire for the extraction of intricate element. This technology still is in the infant stage so shows the hurdle in market maturity competing with other storage technologies.

Energy Storage	Scalability	Portability	Durability	E-density	Life cycle	Operating Temp	Toxicity	Renewable Integration
VRFB	Very High	High	Very High	Medium	High	High	Low	Very High
Li-ion	High	Very High	Medium	High	Low	Medium	Medium	High
Na-S	Medium	Low	High	High	Medium	High	High	Medium
Pumped Hydro	Very High	Low	High	Low	Very High	High	None	Very High
Ultra cacpcitor	Low	Very High	Very High	Very low	Very High	High	None	Medium
Flywheel System	Low	Low	Very High	Low	Very High	High	None	Medium
Magnetic System	Low	Low	Very High	Very low	Very High	Medium	None	Low
Thermal Energy	High	Low	High	Medium	Very High	High	None	High
Fuel cell + H2	High	Medium	Medium	Medium	Medium	High	Medium	High

Table.5 : Features comparisons of all the ESS

The overall comparative study suggests the vanadium redox flow battery as the most prevailing and suitable for grid scale storage system as it has the capacity to scale up and prolonged use with limited drawbacks as compared to similar other ESS.

Structure and working mechanism of the proposed energy storage system

Here the general energy conversion and storage process is done by VO^{2+} / VO^{3+} (negative side) and VO^{2+} / VO_2^+ (positive side) redox pairs of the electrode reactions in which electrolytes of Vanadium ions plays the main role.

The different system architecture of redox flow battery inclusion of tanks, pumps, soluble electrolytes, electrodes, membranes, central reactor proves to be analogous to industrial chemical process and higher advantages in life cycle [44]. The structure of Vanadium Redox Flow Battery (VRFB) has been explained by [52]. The graphite or carbon felts based on carbon electrodes have the ability to provide abundant sites for redox reactions.

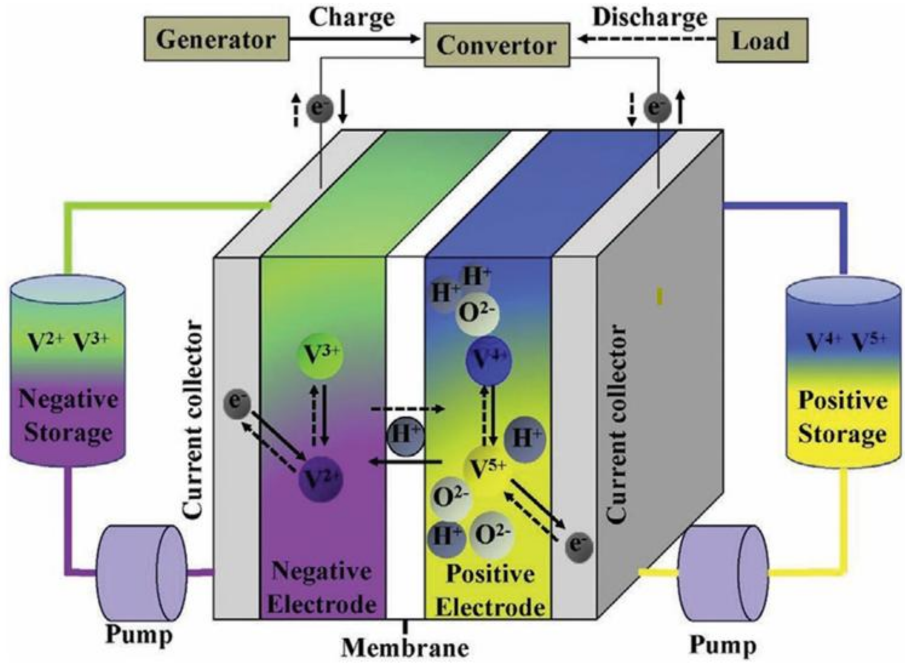

Fig.15: System architecture of vanadium redox flow battery [13]

Here the system architecture of VRFB consists of two electrolyte tanks for the storage of negative and positive electrolytes, the pump to pump the electrolytes in the chamber consisting of electrodes where the ions formation, charge release and charge absorption takes places. The membrane is situated in the middle between the electrodes which separates and avoids the random flow of charges allowing only the specific charges to flow. In this way by the electrochemical reaction, the charging and discharging system operates in VRFB allowing to store the charge from source and discharge to grid in a time of need. And the main advantage is the charge storing (electrolyte) tank is outside so it can be scaled and safely handled.

Investigation of the proposed energy storage system

Though VRFB appears to be the promising ESS, it also has the set of drawbacks that has led to doubts in the market growth. As listed below, critical research has been done looking into the different aspects of VRFB to improve its effectiveness and efficiency in overall feature.

The author [52] draws the modality attraction of researchers to customize and improve the efficiency of VRFB by altering the key components in the system architecture. Rather than conventional carbon and graphite felt as an electrode the prospects of using Prussian blue and carbon felt has shown to be the best for enhancing the efficiency of cell and voltage. Existing carbon felts lack better electrochemical activities and involvement of oxygen in ions makes it more complicated. It conducts substantial energy consumption (overpotential) in activation and transfer of proton and charge. Since the electrodeposition process is in situ, PB catalyst which are uniformly distributed can be anchored onto the substrate of carbon felt (CF) to endure the electrolyte eroding and render to long term stability and high current charging-discharging process. Similarly [28] has also presented the idea of remodification in the use of carbon felt by plasma modification which has the advantages of fast processing, controlled gas conditions and peak energy density. Again in the component modification of membrane, [11] analysed by successfully designing Bipolar Membrane (BPM) of Q/P/S membranes from PTFE (polytetrafluoroethylene) sandwiched between QAPSF (quaternized polysulfone) and SPEEK (sulfonated poly ether ether ketone) which proved to be best. On addition, [31] modified with metal organics frameworks (MOFs) of zeolitic imidazolate framework (ZIF) type containing metals like Fe, Co, Ni, Cu, and Zn onto commercial carbon felts using hydrothermal and layer-by-layer synthesis techniques. which enhanced electrochemical activity, decreased polarization, and greater energy efficiency. Likewise, [41] reconfigures the architecture that graphite felt electrodes for VRFBs are successfully improved by hydrothermal treatment with glucose and urea, which increases surface area, adds nitrogen functionalities, and improves wettability and conductivity.

While [20] draws attention on creation of modified ion exchange membranes for use in VRFBs, with a focus on Nafion 117 and its variants which shows that the modified element presents superior electrochemical stability and selectivity, which makes them an attractive option for energy storage applications.

On other hand, [49] rearranges the configuration to enhance the high energy density and scalable dependence by solid electroactive materials. To compensate the low energy density of redox flow battery which occurred due to fewer concentration of redox-active centres, a conceptual idea of using high energy solid electroactive particles have been raised. The slurry of ionically conducting material is prepared by mixing solid electroactive particles with conductive additive which enables the higher energy density and use of low-cost microporous separators. But the common issue of low energy efficiency due to continuous pumping of slurry had to be improved by strategies. [44] proposed the modification by using the electrolytes of sulfuric acid and hydrochloric acid to increase the efficiency and energy of the system which has the bae concept of Thermally Regenerative Electrochemical Cycle. Similar to this notion, [58] addressed to resolve the issue of capacity fading and decline of performance after prolong operation of VRFB by the solution of asymmetric auto-rebalancing technique. To achieve the high capacity retention and high efficiency which involves SOC monitoring, flow rate control, electrolyte rebalancing, current operation and electrochemical regeneration techniques. [23] experiments show that the addition of multi-walled carbon nanotubes (MWCNTs) improves electrochemical activity, stability, and reversibility.

[18] used simulation method for the approached method of variable flow rate mechanism and current density charge/discharge viewed the improvement in the energy and system efficiency by 9.07% and 8.34% respectively. On the contrary [46] developed the fluid dynamics model as well as include electrolyte transfer of species by the convective, diffusive way and interactions of ions in electrochemical reaction. The theoretical simulation was efficient in predicting performance. [12] investigates improving the performance, stability, and impurity effects of electrolyte modification in VRFBs demonstrating how impurity ions like Na^{+}, Mg^{2+}, Fe^{3+}, and K^{+} affect electrode performance, conductivity, electrolyte stability, and viscosity, and setting impurity thresholds to guarantee effective operation over a broad temperature range. Additionally [18] also show that overall system performance and capacity can be greatly

improved by dynamically adjusting flow rates and current densities at various operational stages. [54] presented the algorithms like particle swarm optimization (PSO), which modifies the model parameters to reflect observed behaviours and guarantees precise prediction and control of the system's electro-thermal performance, and experimental identification can be used to optimize the parameters.

[47] illustrates that the addition of nitrogen functional groups improves the material's wettability, electrical conductivity, and catalytic activity. [27] examines the creation of VRFBs mixed sulphate-chloride electrolytes, showing notable enhancements in energy capacity, stability, and electrochemical performance. [29] highlighted how crucial it is to regulate crossover and water transfer in order to preserve performance. The study talks about how efficiency and capacity retention are greatly impacted by internal resistance.
[57] focused on choosing the right flow rate is essential for optimizing system performance and reducing energy expenses because, although higher flow rates enhance electrochemical reactions and increase the state of charge, they also result in higher pump power consumption and pipeline losses. [10] investigates by increasing electrolyte utilization, decreasing polarization, and preserving ideal flow conditions, a well calibrated combination of electrode thickness and layer ratio improves capacity and efficiency

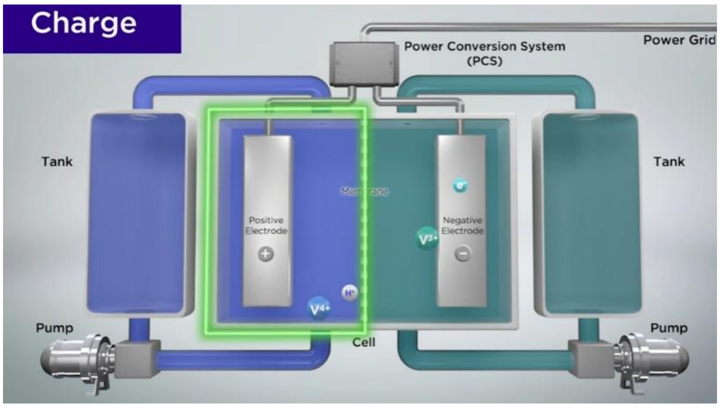

Fig.16: Charging process of redox flow battery [59]

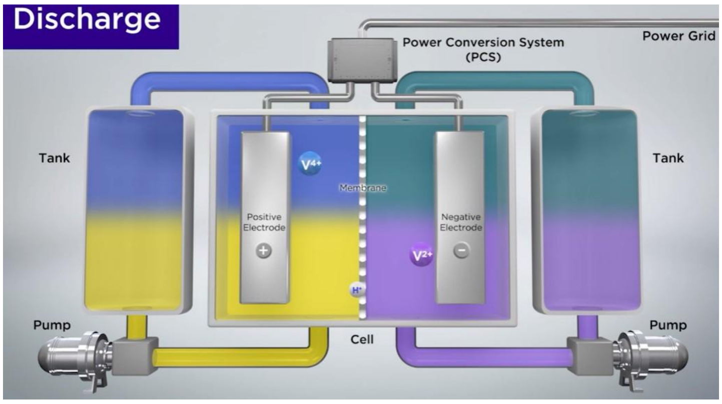

Fig.17: Discharging process of redox flow battery [59]

Still due to its emerging stage there has been many investigations in electrode material like metal oxide/nitride/carbide, graphene oxide, nanofibers, nanowires, NiO nanoparticles etc. More cost effective and efficient method is preferred to develop highly performing VRBs electrodes in industry scale [52].

Critical Analysis:

Foremost challenges are in the existing system are seen as below [16].
Technical challenges:

a. Integration complexity – Integration with different energy sources and grid system requires specific control and management systems.
b. Infrastructure and development – Retrofitting and building new infrastructure for the system can be sophisticated
c. Energy storage – Ensuring the reliable energy storage system is intricate and delicate for the entire system

Economic challenges related to cost, investment and finances:

a. High upfront cost – The initial investment for the system is typically high as the technology is just increasing
b. Uncertainty of ROI – Variability of renewable energy source may lead to uncertainty to predict the accurate ROI
c. Market Maturity – Since the technology is still in the verge of R&D progression and market penetration is in the trailblazing phase, so lack of market maturity leads to disparity in economic factors

Finally on the different perspective too, [25] highlight how important lifecycle management, technology advancements, and ethical sourcing are to reducing social hazards and advancing sustainable energy storage options bad working conditions, human trafficking, and infractions of employment laws, particularly when raw materials are being extracted. Similarly [19] have analysed the progress and leverage of abundance of vanadium resources to scale technology around the globe especially in China which has shown incredible speed in VRFB too.

The analysis shows the various exploration on the components of the VRFB architecture to enhance its properties.

The present context of fibre optics being used in energy storage systems

Various batteries are used in the different industry sectors currently. Grid system, data centres, electric vehicles or portable components etc. Industry is focused on the safety and reliability component with the rise in use of batteries. All the batteries have constraints of working temperature [21]. The durability, life span and thermal runaway safety of all the batteries is linked with its thermal behaviours. In some cases, thermal runaway due to extreme temperatures may lead to fire and explosion. There are many ways to monitor battery thermal behaviour like PTC thermistor (works on the principle of resistance), infrared sensor and FBG system. Depending on the characteristics and area of use the popular used temperature sensing techniques are FBG, thermistor, thermocouple, resistance temperature detector, infrared sensor, semiconductor sensor, bimetallic sensor, pyrometer liquid in glass thermometer etc. Fiber Bragg Grating (FBG) is one of the sensing techniques of fibre optics that is popularly being used today in the field of smart grids or advanced monitoring systems. Due to majority of perks to be able to be used in large quantity at a time, non-conductivity, resistance to electromagnetic interference, small size, multipoint measurement, FBGSs are used in large number of fields.

FBGs are efficient in response, multiplexing, lower invasiveness, smaller size and immune to electromagnetic interference. On the experiment to analyse the type of battery it was found, FBG is feasible and reproductible to embed and measure to any number of side of the battery [33]. It also avoids intrusive and complex analysis process. The testing and calibration of FBG system deems to be crucial for monitoring the thermal component and electronics power modules of wind turbines as well [37]. [50] and [39] have laid the increasing importance and popularity of FBGs due to flexibility in inscribing FBGS and grating periods in same optical fibre to manufacture broad sensors.

Study of optimization system used for sensing technique

Fibre Bragg Gratings are made in the allocated part of fibre optics by grating with the special packaging mechanism to a required wavelength capacity to measure the ambience of another object. Working mechanism of the FBG sensing technique in the battery system employs by change in the wavelength of the specific FBG attached to a battery when the temperature of the battery is changed.

[21] proposed the 32 FBG sensor for real time monitoring of the surface temperature of the lithium battery and evaluated based on thermal behaviour of battery during standard charging and discharging shows with the rise in charging and discharging rates there is the rise in variability of battery surface temperature. Also, for the temperature field distribution, it was analysed that when the positions increased from positive and negative electrode to farther away from tabs the temperatures tend to decrease. [39] when simulated for thermal mapping analysis found that that thermal gradient is recognized from top to bottom but less in the end of charge steps and prominent hot spots between two or multiple batteries lies near positive tab collector.

Further battery monitoring can be advanced by harnessing FBG and combining FBG with an FP interferometer, to clarify the mechanisms of thermal runaway at various SOC levels [56]. Use of FBG sensor has been progressed extensively recently for monitoring battery for precise data and early warnings. Further to enhance the efficiency protective coatings to avoid deterioration and calibration issue over time [8].

Investigation for the proposed sensing technique in the battery system

While the FBG sensing is one of the best, yet it has the space to improve for best utilization in energy storage system for best accuracy and efficiency. [14] demonstrates the pre-stressed packaging technique to improv ethe stability and precision. As the pre-stress maintains the FBG's linearity and guarantees uniform stress distribution, hence minimizing spectrum chirping and widening resulting from unequal stress or shrinkage effects.

Likewise, FBGs can be made into extremely sensitive temperature sensors appropriate for use in space and industry by adding materials with high thermal expansion coefficients [36]. Also, [8] highlighted, inscription using point-by-point femtosecond laser technology can alter spectral breadth, sidelobe suppression ratio, and reflection peak separation are all greatly impacted by important variables such pulse energy, grating length, fibre type, and apodization. Additionally, [17] describes the creation and use of a deep learning-based method for precise Bragg wavelength detection in Fiber Bragg Grating too.

Moreover, [30] and [55] emphasised the research on Fabry- Perot etalons for better calibration and demodulation led to rectify the spectrum distortions and precision in measurement. [9] analysed the combined residual back propagation neural network with convolutional neural network to improve accuracy in signal demodulation. Similarly, by separating the intrinsic mode functions associated with various effects, including aging and the SOC, from measurement noise, the nonlinear empirical mode decomposition improves the accuracy of FBG sensor calibration which raises accuracy of battery temperature monitoring.

Here, [43] illustrated for accurate cryogenic temperature monitoring, FBGs sensors coated with polymer layers, mainly epoxy resin demonstrated the notable change in linearity, response time and sensitivity. [33] have illustrated the theory to optimizing system to make smarter and secure by linking temperature profiles with electrochemical behaviour of battery using the fibre sensors. Further to enhance its working ability and analysing the SOC of the battery [53] and [51] have proposed the different techniques of deep neural networks and multi-phase evolutionary respectively, using the FBG sensing technique.

SWOT analysis of the entire system analysing together for battery storage system technology of VRFB and sensing system technology of FBG:

	VRFB	FBG
Strength	Scalable and Prolonged	Multipoint Non-Invasive Sensing
Weakness	Low Energy Density	Low Commercial Awareness
Opportunity	Grid Scale Storage	Massive Scale Sensing
Threats	Portable Device Storage	High Upfront Cost

Table.6: SWOT analysis of VRFB and FBG

Conclusions from the Literature Review

The overall investigation is done in the literature review section analysing the research papers. It concludes that VRFB is the most promising ESS in the present context but has various changes to be in the system architecture for advanced and promising usage in the power system grid scale. Likewise, FBG enabled temperature sensing is suggested to be the best in optimizing the ESS to operate safe and with flexibility. Furthermore, FBG can be utilized in advanced after few of the component’s remodification so, that the system might setbacks.

The critical challenges in huge scale electric batteries are energy density, rate of charging and discharging, cost of manufacture and prolonged operation, thermal factors and safety, life span of battery and operating lifecycle. All these elements play vital role in selection of specific battery technology and configurations too. Moreover, depending on the technical configurations and system architecture of the batteries most of these element qualities can be improvised while on the other side rectifying the unnecessary side reactions between various reaction poised components like electrodes and electrolytes while reserving the proper proximity between the components and proper engineering of the entire system too.

The energy storage system is poised for the growth and innovation resulting in scalability, increase demand of use, technological advancement and reduction in the cost of further research, storage and transmission, reduction in required elements and resources and, operational cost. The entire system holds for the abundance in growth, sustainable and inclusive green energy future too.

References of the Literature Review

[1] Adeyinka, A. M., Esan, O. C., Ijaola, A. O., & Farayibi, P. K. (2024). Advancements in hybrid energy storage systems for enhancing renewable energy-to-grid integration. *Sustainable Energy Research*, *11*(1). https://doi.org/10.1186/s40807-024-00120-4

[2] Ahmed Adam, A. H., Chen, J., Kamel, S., Safaraliev, M., & Matrenin, P. (2024). Power management and control of hybrid renewable energy systems with integrated diesel generators for remote areas. *International Journal of Hydrogen Energy*, *89*, 320-341. https://doi.org/10.1016/j.ijhydene.2024.09.247

[3] Barelli, L., Bidini, G., Ottaviano, P. A., & Pelosi, D. (2019). Vanadium redox flow batteries application to electric buses propulsion: Performance analysis of hybrid energy storage system. *Journal of Energy Storage*, *24*. https://doi.org/10.1016/j.est.2019.100770

[4] Bauer, S., Dahmke, A., & Kolditz, O. (2017). Subsurface energy storage: geological storage of renewable energy—capacities, induced effects and implications. *Environmental Earth Sciences*, *76*(20). https://doi.org/10.1007/s12665-017-7007-9

[5] Bin, X., & Thakur, J. (2025). Circular economy metrics for batteries: Enhancing sustainability in energy storage systems. *Sustainable production and consumption*, *55*, 470-485. https://doi.org/10.1016/j.spc.2025.02.014

[6] Chatzigeorgiou, N. G., Theocharides, S., Makrides, G., & Georghiou, G. E. (2024). A review on battery energy storage systems: Applications, developments, and research trends of hybrid installations in the end-user sector. *Journal of Energy Storage*, *86*. https://doi.org/10.1016/j.est.2024.111192

[7] Chen, D., Zhao, Q., Li, Y., Liu, S., & Wang, J. (2024). Main Factors for Optimization of PM-FBG Inscribed by Femtosecond Laser Point-by-Point Technology. *Journal of Lightwave Technology*, *42*(9), 3128-3133. https://doi.org/10.1109/jlt.2024.3351195

[8] Chen, D., Zhao, Q., Zheng, Y., Xu, Y., Chen, Y., Ni, J., & Zhao, Y. (2023). Recent Progress in Lithium-Ion Battery Safety Monitoring Based on Fiber Bragg Grating Sensors. *Sensors (Basel)*, *23*(12). https://doi.org/10.3390/s23125609

[9] Chen, S., Yao, F., Ren, S., Wang, G., & Huang, M. (2022). Cost-effective improvement of the performance of AWG-based FBG wavelength interrogation via a cascaded neural network. *Opt Express*, *30*(5), 7647-7663. https://doi.org/10.1364/OE.449004

[10] Chen, W., Kang, J., Shu, Q., & Zhang, Y. (2019). Analysis of storage capacity and energy conversion on the performance of gradient and double-layered porous electrode in all-vanadium redox flow batteries. *Energy*, *180*, 341-355. https://doi.org/10.1016/j.energy.2019.05.037

[11] Dai, J., Dong, Y., Gao, P., Ren, J., Yu, C., Hu, H., Zhu, Y., & Teng, X. (2018). A sandwiched bipolar membrane for all vanadium redox flow battery with high coulombic efficiency. *Polymer*, *140*, 233-239. https://doi.org/10.1016/j.polymer.2018.02.051

[12] Ding, M., Liu, T., & Zhang, Y. (2020). Stability and Electrochemical Performance Analysis of an Electrolyte with Na+ Impurity for a Vanadium Redox Flow Battery in Energy Storage Applications. *Energy & Fuels*, *34*(5), 6430-6438. https://doi.org/10.1021/acs.energyfuels.0c00063

[13] Esan, O. C., Shi, X., Pan, Z., Huo, X., An, L., & Zhao, T. S. (2020). Modeling and Simulation of Flow Batteries. *Advanced Energy Materials*, *10*(31). https://doi.org/10.1002/aenm.202000758

[14] Feng, D., Luo, X., Liu, Y., Ma, C., & Qiao, X. (2021). Performance improvement of FBG sensors based on the pre-stressed package technique. *Optical Fiber Technology*, *65*. https://doi.org/10.1016/j.yofte.2021.102623

[15] Goodenough, J. B., & Kim, Y. (2009). Challenges for Rechargeable Li Batteries. *Chemistry of Materials*, *22*(3), 587-603. https://doi.org/10.1021/cm901452z

[16] Hassan, Q., Algburi, S., Sameen, A. Z., Salman, H. M., & Jaszczur, M. (2023). A review of hybrid renewable energy systems: Solar and wind-powered solutions: Challenges, opportunities, and policy implications. *Results in Engineering*, *20*. https://doi.org/10.1016/j.rineng.2023.101621

[17] Hayle, S. T., Manie, Y. C., Dehnaw, A. M., Hsu, Y.-T., Li, J.-W., Liang, H.-C., & Peng, P.-C. (2021). Reliable self-healing FBG sensor network for improvement of multipoint strain sensing. *Optics Communications*, *499*. https://doi.org/10.1016/j.optcom.2021.127286

[18] Huang, F., Yang, H., Liu, B., Liu, J., Hu, Y., Fu, Y., Xiao, W., He, X.-D., & Wu, Q. (2023). Real-Time Monitoring of Temperature Field Distribution of Three-Element LiB Lithium Battery Using FBG Arrays. *IEEE Sensors Journal*, *23*(24), 30473-30480. https://doi.org/10.1109/jsen.2023.3330860

[19] Huang, K.-L., Li, X.-g., Liu, S.-q., Tan, N., & Chen, L.-q. (2008). Research progress of vanadium redox flow battery for energy storage in China. *Renewable Energy*, *33*(2), 186-192. https://doi.org/10.1016/j.renene.2007.05.025

[20] Huang, S.-L., Yu, H.-F., & Lin, Y.-S. (2017). Modification of Nafion® Membrane via a Sol-Gel Route for Vanadium Redox Flow Energy Storage Battery Applications. *Journal of Chemistry*, *2017*, 1-10. https://doi.org/10.1155/2017/4590952

[21] Huang, Z., Liu, Y., Xie, X., Huang, Q., & Huang, C. (2023). Experimental study on efficiency improvement methods of vanadium redox flow battery for large-scale energy storage. *Electrochimica Acta*, *466*. https://doi.org/10.1016/j.electacta.2023.143025

[22] Kaluthanthrige, R., & Rajapakse, A. D. (2021). Demand response integrated day-ahead energy management strategy for remote off-grid hybrid renewable energy systems. *International Journal of Electrical Power & Energy Systems*, *129*. https://doi.org/10.1016/j.ijepes.2020.106731

[23] Kim, J., & Park, H. (2018). Impact of nanofluidic electrolyte on the energy storage capacity in vanadium redox flow battery. *Energy*, *160*, 192-199. https://doi.org/10.1016/j.energy.2018.06.221

[24] Kim, S. K., Kim, Y. K., Lee, H., Lee, S. B., & Park, H. S. (2014). Superior pseudocapacitive behavior of confined lignin nanocrystals for renewable energy-storage materials. *ChemSusChem*, *7*(4), 1094-1101. https://doi.org/10.1002/cssc.201301061

[25] Koese, M., Blanco, C. F., Vert, V. B., & Vijver, M. G. (2022). A social life cycle assessment of vanadium redox flow and lithium-ion batteries for energy storage. *Journal of Industrial Ecology*, *27*(1), 223-237. https://doi.org/10.1111/jiec.13347

[26] Lehtola, T. (2024). Solar energy and wind power supply supported by battery storage and Vehicle to Grid operations. *Electric Power Systems Research*, *228*. https://doi.org/10.1016/j.epsr.2023.110035

[27] Li, L., Kim, S., Wang, W., Vijayakumar, M., Nie, Z., Chen, B., Zhang, J., Xia, G., Hu, J., Graff, G., Liu, J., & Yang, Z. (2011). A Stable Vanadium Redox-Flow Battery with High Energy Density for Large-Scale Energy Storage. *Advanced Energy Materials*, *1*(3), 394-400. https://doi.org/10.1002/aenm.201100008

[28] Li, Y., Lu, J., Gao, M., Wang, K., Xiong, Z., & Jiang, K. (2023). Improvement of Vanadium Redox Flow Battery Efficiency Through Carbon Felt Electrodes Modification by Atmospheric Dielectric Barrier Discharge. *Plasma Chemistry and Plasma Processing*, *43*(6), 1673-1684. https://doi.org/10.1007/s11090-023-10365-4

[29] Lim, H., Yi, J. S., & Lee, D. (2019). Correlations of Through-Plane Cell Voltage Losses, Imbalance of Electrolytes, and Energy Storage Efficiency of a Vanadium Redox Flow Battery. *ChemSusChem*, *12*(7), 1459-1468. https://doi.org/10.1002/cssc.201802633

[30] Liu, Q., Yang, D., Xing, M., Yan, C., & Liu, B. (2025). Research on operating mechanism and state of battery based on fiber Fabry-Pérot cavity. *Sensors and Actuators A: Physical*, *382*. https://doi.org/10.1016/j.sna.2024.116175

[31] Lobato-Peralta, D. R., Molina-Serrano, A. J., Luque-Centeno, J. M., Sánchez-Laganga, B., Sebastián, D., Carrasco-Marín, F., Lázaro, M. J., & Alegre, C. (2025). Improving energy storage

properties of carbon felt electrodes for vanadium redox flow batteries via ZIF modifications. *Chemical Engineering Journal*, *515*. https://doi.org/10.1016/j.cej.2025.163534
[32] Lopes, P. P., & Stamenkovic, V. R. (2020). Past, present, and future of lead–acid batteries. *Science*, *369*(6506), 923-924. https://doi.org/10.1126/science.abd3352
[33] Matuck, L., Santos, J. P., Freitas, F., Fontes, L. B., Bierlich, J., Geniès, S., Pinto, J. L., Ferreira, M. S., Raccurt, O., & Nascimento, M. (2024). Towards smart and secure batteries: Linking pressure and temperature profiles with electrochemical behavior through hybrid optical fiber sensors. *Chemical Engineering Journal*, *500*. https://doi.org/10.1016/j.cej.2024.156806
[34] Matuck, L. C., Cabrita, P. D., Pinto, J. L., Marques, C. A., & Nascimento, M. S. (2023). Customized Optical Fiber Birefringent Sensors to Multipoint and Simultaneous Temperature and Radial Strain Tracking of Lithium-Ion Batteries. *Advanced Sensor Research*, *2*(7), n/a. https://doi.org/10.1002/adsr.202200046
[35] Mazaheri, H., Moeini-Aghtaie, M., Fotuhi-Firuzabad, M., Dehghanian, P., & Khoshjahan, M. (2021). A linearized transmission expansion planning model under N − 1 criterion for enhancing grid-scale system flexibility via compressed air energy storage integration. *IET Generation, Transmission & Distribution*, *16*(2), 208-218. https://doi.org/10.1049/gtd2.12226
[36] Mishra, V., Lohar, M., & Amphawan, A. (2016). Improvement in temperature sensitivity of FBG by coating of different materials. *Optik*, *127*(2), 825-828. https://doi.org/10.1016/j.ijleo.2015.10.014
[37] Mohammed, A., Hu, B., Hu, Z., Djurovic, S., Ran, L., Barnes, M., & Mawby, P. A. (2020). Distributed Thermal Monitoring of Wind Turbine Power Electronic Modules Using FBG Sensing Technology. *IEEE Sensors Journal*, *20*(17), 9886-9894. https://doi.org/10.1109/jsen.2020.2992668
[38] Mondal, M., Mandal, K. K., & Datta, A. (2022). Solar PV driven hybrid gravity power module—Vanadium redox flow battery energy storage for an energy efficient multi-storied building. *International Journal of Energy Research*, *46*(13), 18477-18494. https://doi.org/10.1002/er.8460
[39] Nascimento, M., Paixão, T., Ferreira, M. S., & Pinto, J. L. (2018). Thermal Mapping of a Lithium Polymer Batteries Pack with FBGs Network. *Batteries*, *4*(4). https://doi.org/10.3390/batteries4040067
[40] Peng, F. Z., Liu, C.-C., Li, Y., Jain, A. K., & Vinnikov, D. (2024). Envisioning the Future Renewable and Resilient Energy Grids—A Power Grid Revolution Enabled by Renewables, Energy Storage, and Energy Electronics. *IEEE Journal of Emerging and Selected Topics in Industrial Electronics*, *5*(1), 8-26. https://doi.org/10.1109/jestie.2023.3343291
[41] Qiu, J., Huang, B., Liu, Y., Chen, D., & Xie, Z. (2020). Glucose-derived hydrothermal carbons as energy storage booster for vanadium redox flow batteries. *Journal of Energy Chemistry*, *45*, 31-39. https://doi.org/10.1016/j.jechem.2019.09.030
[42] Ramos, F., Pinheiro, A., Nascimento, R., de Araujo Silva Junior, W., Mohamed, M. A., Annuk, A., & Marinho, M. H. N. (2022). Development of Operation Strategy for Battery Energy Storage System into Hybrid AC Microgrids. *Sustainability*, *14*(21), 13765. https://doi.org/10.3390/su142113765
[43] Ren, Y., Song, H., Cai, Q., Cai, Z., Liu, Y., & Wang, B. (2024). Modeling analysis and experimental study on epoxy packaged FBG sensor for cryogenic temperature measurement. *Optical Fiber Technology*, *84*. https://doi.org/10.1016/j.yofte.2024.103710
[44] Reynard, D., Dennison, C. R., Battistel, A., & Girault, H. H. (2018). Efficiency improvement of an all-vanadium redox flow battery by harvesting low-grade heat. *Journal of Power Sources*, *390*, 30-37. https://doi.org/10.1016/j.jpowsour.2018.03.074
[45] Rezaei, H., Abdollahi, S. E., Abdollahi, S., & Filizadeh, S. (2022). Energy management strategies of battery-ultracapacitor hybrid storage systems for electric vehicles: Review, challenges, and future trends. *Journal of Energy Storage*, *53*. https://doi.org/10.1016/j.est.2022.105045
[46] Rudolph, S., Schröder, U., Bayanov, I. M., & Hage, D. (2014). Measurement, simulation and in situ regeneration of energy efficiency in vanadium redox flow battery. *Journal of Electroanalytical Chemistry*, *728*, 72-80. https://doi.org/10.1016/j.jelechem.2014.05.033

[47] Shao, Y., Wang, X., Engelhard, M., Wang, C., Dai, S., Liu, J., Yang, Z., & Lin, Y. (2010). Nitrogen-doped mesoporous carbon for energy storage in vanadium redox flow batteries. *Journal of Power Sources*, *195*(13), 4375-4379. https://doi.org/10.1016/j.jpowsour.2010.01.015

[48] Speidel, S., & Bräunl, T. (2016). Leaving the grid—The effect of combining home energy storage with renewable energy generation. *Renewable and Sustainable Energy Reviews*, *60*, 1213-1224. https://doi.org/10.1016/j.rser.2015.12.325

[49] Ventosa, E. (2022). Semi-solid flow battery and redox-mediated flow battery: two strategies to implement the use of solid electroactive materials in high-energy redox-flow batteries. *Current Opinion in Chemical Engineering*, *37*. https://doi.org/10.1016/j.coche.2022.100834

[50] Wahl, M. S., Spitthoff, L., Muri, H. I., Jinasena, A., Burheim, O. S., & Lamb, J. J. (2021). The Importance of Optical Fibres for Internal Temperature Sensing in Lithium-ion Batteries during Operation. *Energies*, *14*(12). https://doi.org/10.3390/en14123617

[51] Wang, C., Wang, Y., Dong, L., & Yao, F. (2023). SOC estimation of lithium battery based on the combination of electrical parameters and FBG non-electrical parameters and using NGO-BP model. *Optical Fiber Technology*, *81*. https://doi.org/10.1016/j.yofte.2023.103581

[52] Xia, L., Long, T., Li, W., Zhong, F., Ding, M., Long, Y., Xu, Z., Lei, Y., Guan, Y., Yuan, D., Zhang, Y., Jia, C., Sun, L., & Sun, Q. (2020). Highly Stable Vanadium Redox-Flow Battery Assisted by Redox-Mediated Catalysis. *Small*, *16*(38), e2003321. https://doi.org/10.1002/smll.202003321

[53] Xia, X., Wu, W., Li, Z., Han, X., Xue, X., Xiao, G., & Guo, T. (2024). State of Charge Estimation for Commercial Li-Ion Battery Based on Simultaneously Strain and Temperature Monitoring Over Optical Fiber Sensors. *IEEE Transactions on Instrumentation and Measurement*, *73*, 1-11. https://doi.org/10.1109/tim.2024.3390696

[54] Xiong, B., Yang, Y., Tang, J., Li, Y., Wei, Z., Su, Y., & Zhang, Q. (2019). An Enhanced Equivalent Circuit Model of Vanadium Redox Flow Battery Energy Storage Systems Considering Thermal Effects. *IEEE Access*, *7*, 162297-162308. https://doi.org/10.1109/access.2019.2952212

[55] Yao, G., Yin, Y., Li, Y., & Yi, H. (2021). High-precision and wide-wavelength range FBG demodulation method based on spectrum correction and data fusion. *Opt Express*, *29*(16), 24846-24860. https://doi.org/10.1364/OE.433914

[56] Yu, K., Chen, W., Deng, D., Wu, Q., & Hao, J. (2024). Advancements in Battery Monitoring: Harnessing Fiber Grating Sensors for Enhanced Performance and Reliability. *Sensors (Basel)*, *24*(7). https://doi.org/10.3390/s24072057

[57] Zou, T., Shi, X., & Yu, L. (2021). Study on energy loss of 35 kW all vanadium redox flow battery energy storage system under closed-loop flow strategy. *Journal of Power Sources*, *490*. https://doi.org/10.1016/j.jpowsour.2021.229514

[58] Zou, W.-J., & Jung, S. (2025). Asymmetric auto-rebalancing of electrolyte for high capacity retention and high energy efficiency of vanadium redox flow batteries. *Applied Energy*, *388*. https://doi.org/10.1016/j.apenergy.2025.125663

[59] Sumitomo Electric Group. (2023, Febrary 13). *How Vanadium Redox Flow Battery works – VRFB explained* [Video]. YouTube. https://youtu.be/TSsqCazP1V0

[60] Billy Wu. (2021, November 14). *Vanadium redox flow battery working principle explained with animation* [Video]. YouTube. https://youtu.be/t9zwgL7UpDA

APPENDIX B: FIGURES

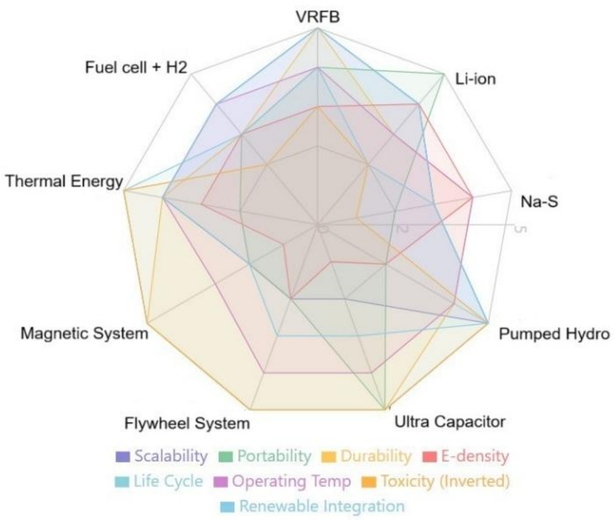

Fig.1: Range of features intensity composed by each ESS as compared to other [figure from features comparison in Python]

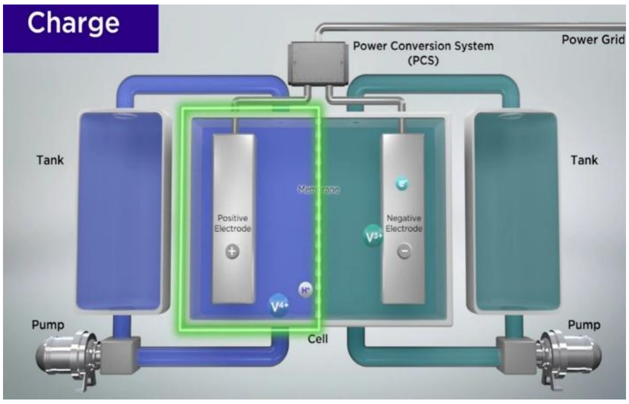

Fig.2: Charging mechanism in VRFB [65]

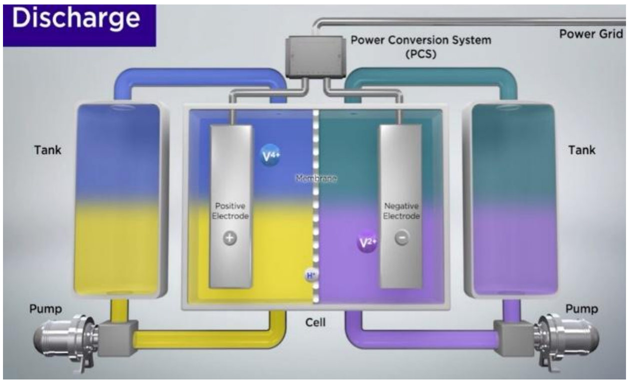

Fig.3: Dis-charging mechanism in VRFB [65]

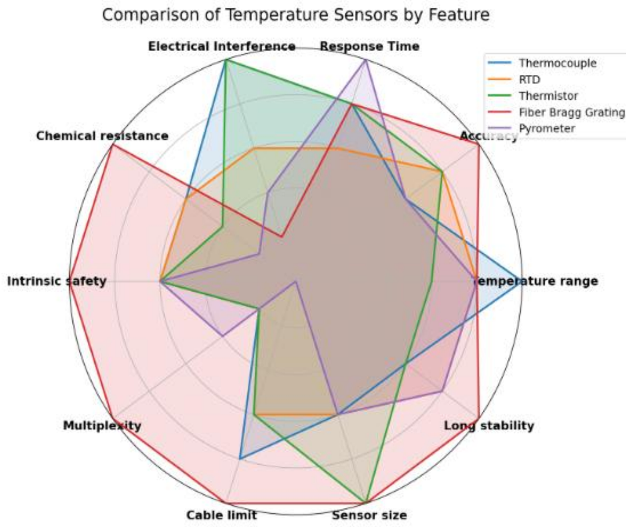

Fig.4: Range of features compared among different sensing technique [figure from features comparison in Python]

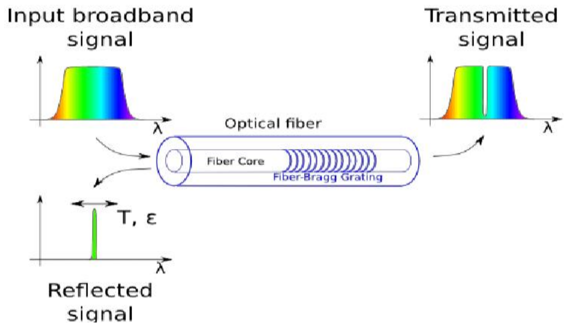

Fig.5: FBG working mechanism in optical fibre

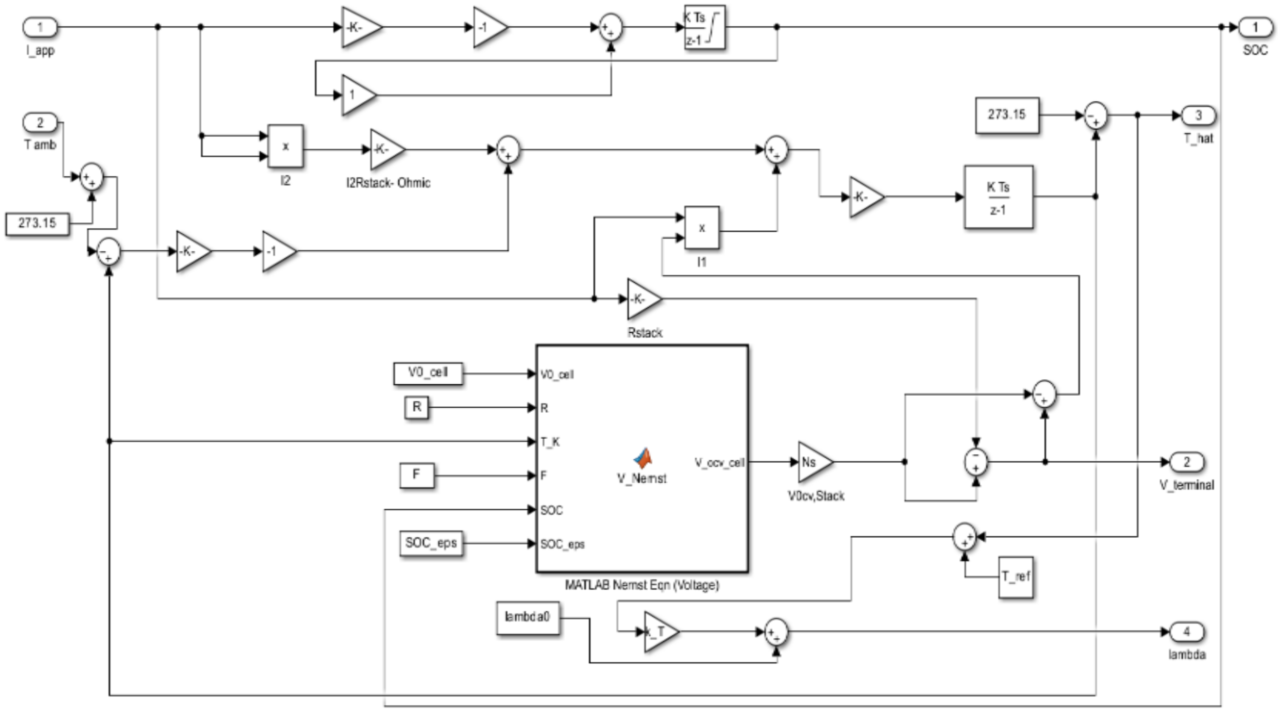

Fig.6: MATLAB FMU block of VRFB system

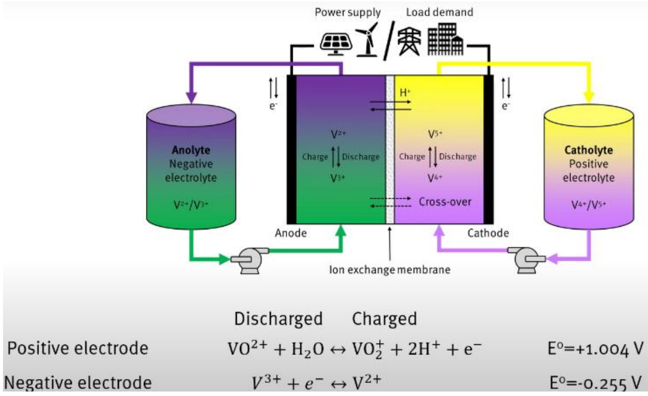

Fig.7: Elaborated system architecture of VRFB [66]

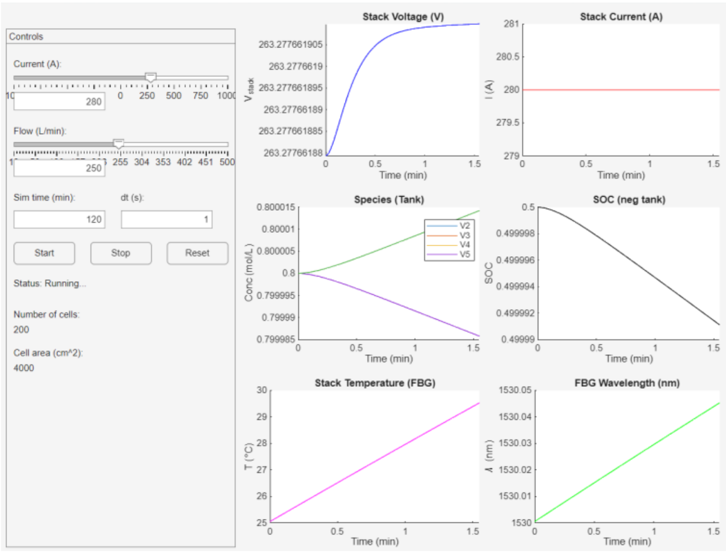

Fig.8: MATLAB graphical user interface result 1.

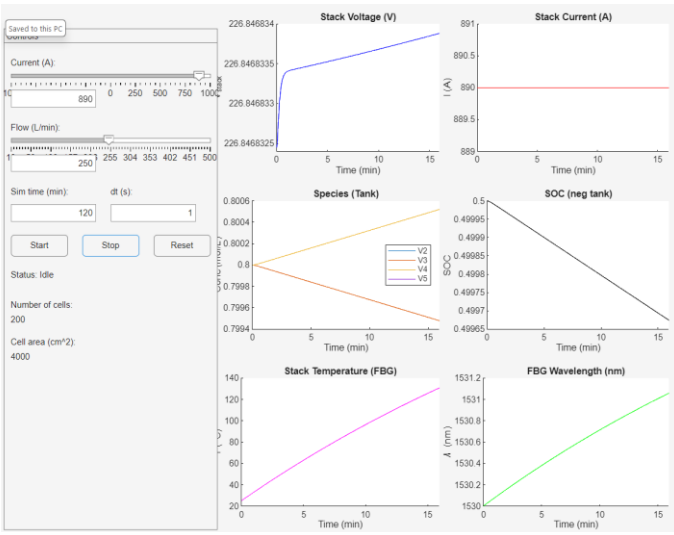

Fig.9: MATLAB graphical user interface result 2.

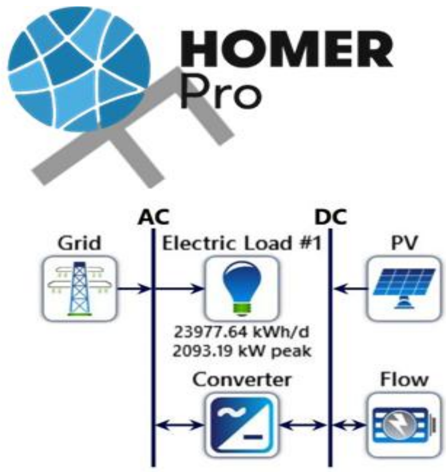

Fig.10: Homer Pro electrical grid system components.

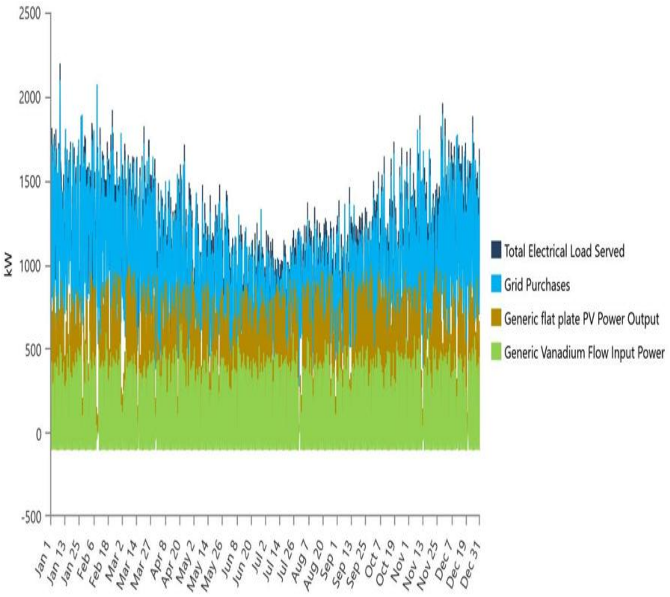

Fig.11: Homer Pro result 1.

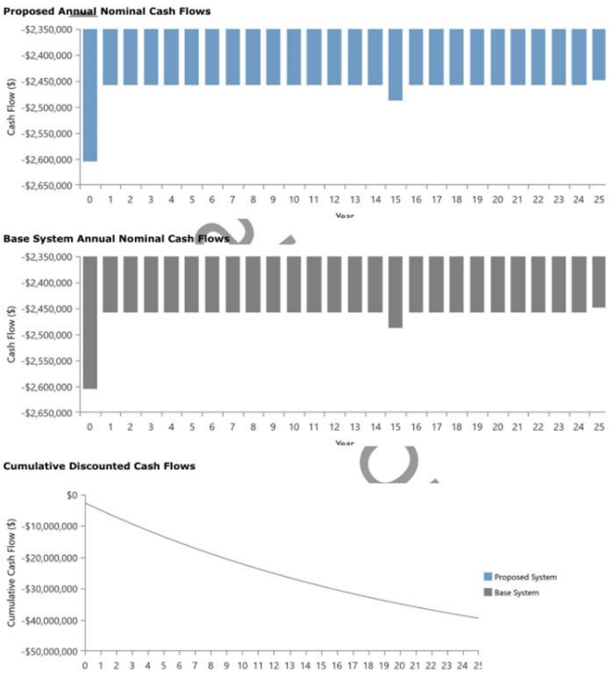

Fig.12: Homer Pro result 2

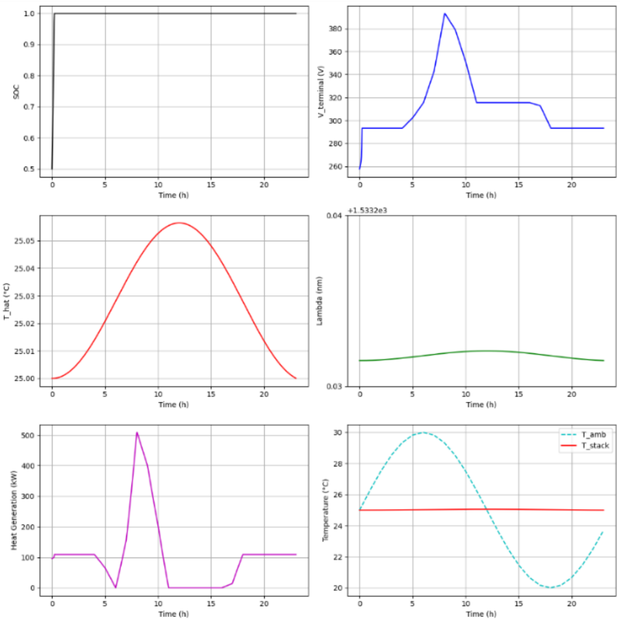

Fig.13: Output from python pipeline.

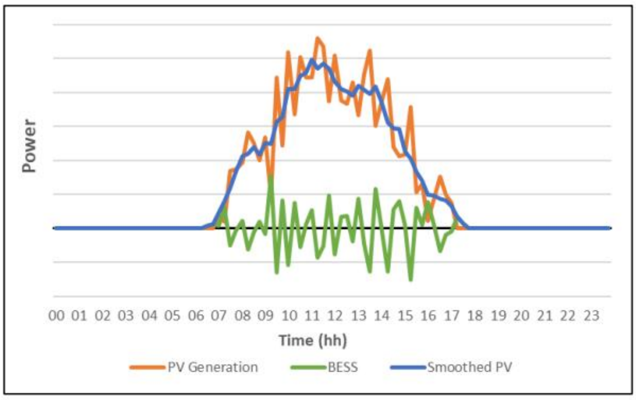

Fig.14: Typical operation of storage system connected to PV system to resolve intermittency [14].

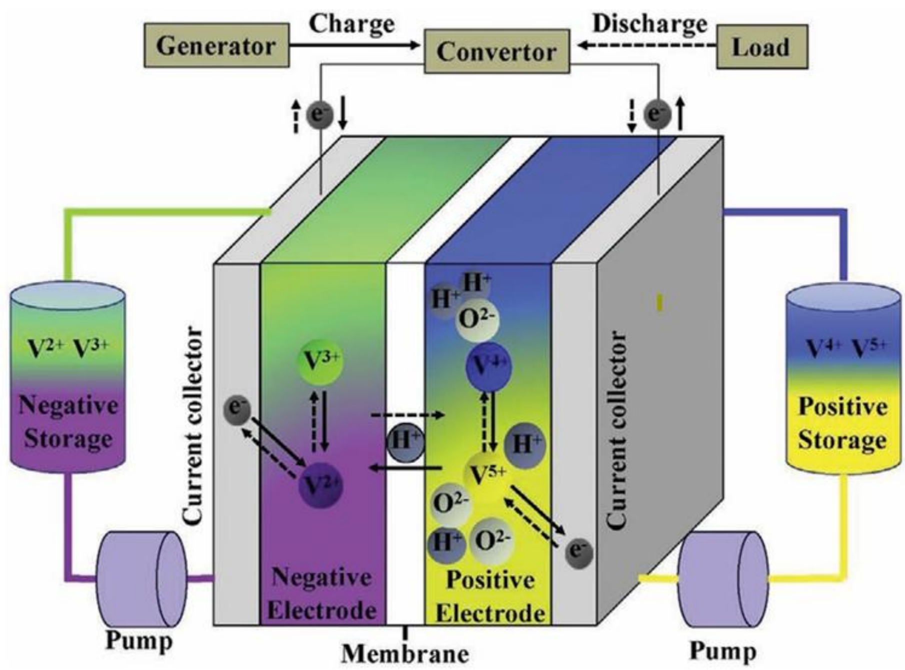

Fig.15: System architecture of vanadium redox flow battery [13].

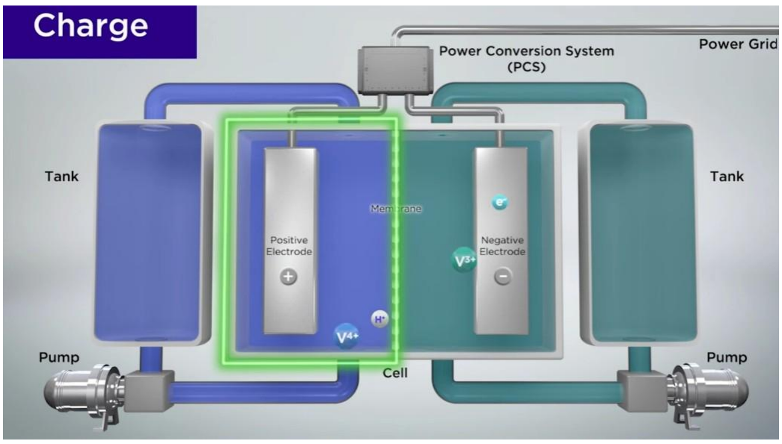

Fig.16: Charging process of redox flow battery [59]

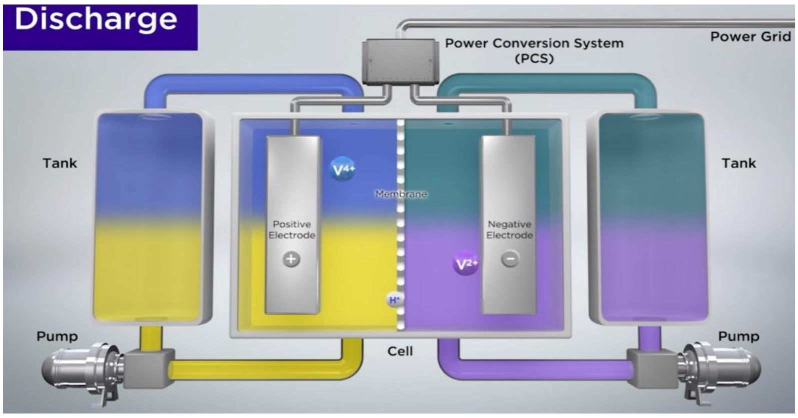

Fig.17: Discharging process of redox flow battery [59]

APPENDIX C: TABLES

Energy Storage	VRFB
Scalability	Very High
Portability	High
Durability	Very High
E-density	Medium
Life cycle	High
Toxicity	Low
Renewable Integration	Very High

Table.1: Identification of VRFB features analysed from fig1.

	VRFB
Strength	Scalable and Prolonged
Weakness	Low Energy Density
Opportunity	Grid Scale Storage
Threats	Portable Device Storage

Table.2: SWOT analysis of VRFB

	FBG
Strength	Multipoint Non-Invasive Sensing
Weakness	Low Commercial Awareness
Opportunity	Massive Scale Sensing
Threats	High Upfront Cost

Table.3: SWOT analysis of FBG

T(C)	ΔT	$\Delta\lambda_B$ (nm)	λ_B (nm)
25	0	0	1530
26	1	0.01	1530.01
27	2	0.02	1530.02
28	3	0.03	1530.03
29	4	0.04	1530.04
30	5	0.05	1530.05

Table.4: wavelength change in FBG.

Energy Storage	Scalability	Portability	Durability	E-density	Life cycle	Operating Temp	Toxicity	Renewable Integration
VRFB	Very High	High	Very High	Medium	High	High	Low	Very High
Li-ion	High	Very High	Medium	High	Low	Medium	Medium	High
Na-S	Medium	Low	High	High	Medium	High	High	Medium
Pumped Hydro	Very High	Low	High	Low	Very High	High	None	Very High
Ultra cacpcitor	Low	Very High	Very High	Very low	Very High	High	None	Medium
Flywheel System	Low	Low	Very High	Low	Very High	High	None	Medium
Magnetic System	Low	Low	Very High	Very low	Very High	Medium	None	Low
Thermal Energy	High	Low	High	Medium	Very High	High	None	High
Fuel cell + H2	High	Medium	Medium	Medium	Medium	High	Medium	High

Table.5 : Features comparisons of all the ESS

	VRFB	FBG
Strength	Scalable and Prolonged	Multipoint Non-Invasive Sensing
Weakness	Low Energy Density	Low Commercial Awareness
Opportunity	Grid Scale Storage	Massive Scale Sensing
Threats	Portable Device Storage	High Upfront Cost

Table.6: SWOT analysis of VRFB and FBG in same table

REFERENCES

[1] Adeyinka, A. M., Esan, O. C., Ijaola, A. O., & Farayibi, P. K. (2024). Advancements in hybrid energy storage systems for enhancing renewable energy-to-grid integration. *Sustainable Energy Research*, *11*(1). https://doi.org/10.1186/s40807-024-00120-4

[2] Ahmed Adam, A. H., Chen, J., Kamel, S., Safaraliev, M., & Matrenin, P. (2024). Power management and control of hybrid renewable energy systems with integrated diesel generators for remote areas. *International Journal of Hydrogen Energy*, *89*, 320-341. https://doi.org/10.1016/j.ijhydene.2024.09.247

[3] Barelli, L., Bidini, G., Ottaviano, P. A., & Pelosi, D. (2019). Vanadium redox flow batteries application to electric buses propulsion: Performance analysis of hybrid energy storage system. *Journal of Energy Storage*, *24*. https://doi.org/10.1016/j.est.2019.100770

[4] Bauer, S., Dahmke, A., & Kolditz, O. (2017). Subsurface energy storage: geological storage of renewable energy—capacities, induced effects and implications. *Environmental Earth Sciences*, *76*(20). https://doi.org/10.1007/s12665-017-7007-9

[5] Bin, X., & Thakur, J. (2025). Circular economy metrics for batteries: Enhancing sustainability in energy storage systems. *Sustainable production and consumption*, *55*, 470-485. https://doi.org/10.1016/j.spc.2025.02.014

[6] Chatzigeorgiou, N. G., Theocharides, S., Makrides, G., & Georghiou, G. E. (2024). A review on battery energy storage systems: Applications, developments, and research trends of hybrid installations in the end-user sector. *Journal of Energy Storage*, *86*. https://doi.org/10.1016/j.est.2024.111192

[7] Chen, D., Zhao, Q., Li, Y., Liu, S., & Wang, J. (2024). Main Factors for Optimization of PM-FBG Inscribed by Femtosecond Laser Point-by-Point Technology. *Journal of Lightwave Technology*, *42*(9), 3128-3133. https://doi.org/10.1109/jlt.2024.3351195

[8] Chen, D., Zhao, Q., Zheng, Y., Xu, Y., Chen, Y., Ni, J., & Zhao, Y. (2023). Recent Progress in Lithium-Ion Battery Safety Monitoring Based on Fiber Bragg Grating Sensors. *Sensors (Basel)*, *23*(12). https://doi.org/10.3390/s23125609

[9] Chen, S., Yao, F., Ren, S., Wang, G., & Huang, M. (2022). Cost-effective improvement of the performance of AWG-based FBG wavelength interrogation via a cascaded neural network. *Opt Express*, *30*(5), 7647-7663. https://doi.org/10.1364/OE.449004

[10] Chen, W., Kang, J., Shu, Q., & Zhang, Y. (2019). Analysis of storage capacity and energy conversion on the performance of gradient and double-layered porous electrode in all-vanadium redox flow batteries. *Energy*, *180*, 341-355. https://doi.org/10.1016/j.energy.2019.05.037

[11] Dai, J., Dong, Y., Gao, P., Ren, J., Yu, C., Hu, H., Zhu, Y., & Teng, X. (2018). A sandwiched bipolar membrane for all vanadium redox flow battery with high coulombic efficiency. *Polymer*, *140*, 233-239. https://doi.org/10.1016/j.polymer.2018.02.051

[12] Ding, M., Liu, T., & Zhang, Y. (2020). Stability and Electrochemical Performance Analysis of an Electrolyte with Na+ Impurity for a Vanadium Redox Flow Battery in Energy Storage Applications. *Energy & Fuels*, *34*(5), 6430-6438. https://doi.org/10.1021/acs.energyfuels.0c00063

[13] Esan, O. C., Shi, X., Pan, Z., Huo, X., An, L., & Zhao, T. S. (2020). Modeling and Simulation of Flow Batteries. *Advanced Energy Materials*, *10*(31). https://doi.org/10.1002/aenm.202000758

[14] Feng, D., Luo, X., Liu, Y., Ma, C., & Qiao, X. (2021). Performance improvement of FBG sensors based on the pre-stressed package technique. *Optical Fiber Technology*, *65*. https://doi.org/10.1016/j.yofte.2021.102623

[15] Goodenough, J. B., & Kim, Y. (2009). Challenges for Rechargeable Li Batteries. *Chemistry of Materials*, *22*(3), 587-603. https://doi.org/10.1021/cm901452z

[16] Hassan, Q., Algburi, S., Sameen, A. Z., Salman, H. M., & Jaszczur, M. (2023). A review of hybrid renewable energy systems: Solar and wind-powered solutions: Challenges, opportunities,

and policy implications. *Results in Engineering*, *20*. https://doi.org/10.1016/j.rineng.2023.101621

[17] Hayle, S. T., Manie, Y. C., Dehnaw, A. M., Hsu, Y.-T., Li, J.-W., Liang, H.-C., & Peng, P.-C. (2021). Reliable self-healing FBG sensor network for improvement of multipoint strain sensing. *Optics Communications*, *499*. https://doi.org/10.1016/j.optcom.2021.127286

[18] Huang, F., Yang, H., Liu, B., Liu, J., Hu, Y., Fu, Y., Xiao, W., He, X.-D., & Wu, Q. (2023). Real-Time Monitoring of Temperature Field Distribution of Three-Element LiB Lithium Battery Using FBG Arrays. *IEEE Sensors Journal*, *23*(24), 30473-30480. https://doi.org/10.1109/jsen.2023.3330860

[19] Huang, K.-L., Li, X.-g., Liu, S.-q., Tan, N., & Chen, L.-q. (2008). Research progress of vanadium redox flow battery for energy storage in China. *Renewable Energy*, *33*(2), 186-192. https://doi.org/10.1016/j.renene.2007.05.025

[20] Huang, S.-L., Yu, H.-F., & Lin, Y.-S. (2017). Modification of Nafion® Membrane via a Sol-Gel Route for Vanadium Redox Flow Energy Storage Battery Applications. *Journal of Chemistry*, *2017*, 1-10. https://doi.org/10.1155/2017/4590952

[21] Huang, Z., Liu, Y., Xie, X., Huang, Q., & Huang, C. (2023). Experimental study on efficiency improvement methods of vanadium redox flow battery for large-scale energy storage. *Electrochimica Acta*, *466*. https://doi.org/10.1016/j.electacta.2023.143025

[22] Kaluthanthrige, R., & Rajapakse, A. D. (2021). Demand response integrated day-ahead energy management strategy for remote off-grid hybrid renewable energy systems. *International Journal of Electrical Power & Energy Systems*, *129*. https://doi.org/10.1016/j.ijepes.2020.106731

[23] Kim, J., & Park, H. (2018). Impact of nanofluidic electrolyte on the energy storage capacity in vanadium redox flow battery. *Energy*, *160*, 192-199. https://doi.org/10.1016/j.energy.2018.06.221

[24] Kim, S. K., Kim, Y. K., Lee, H., Lee, S. B., & Park, H. S. (2014). Superior pseudocapacitive behavior of confined lignin nanocrystals for renewable energy-storage materials. *ChemSusChem*, *7*(4), 1094-1101. https://doi.org/10.1002/cssc.201301061

[25] Koese, M., Blanco, C. F., Vert, V. B., & Vijver, M. G. (2022). A social life cycle assessment of vanadium redox flow and lithium-ion batteries for energy storage. *Journal of Industrial Ecology*, *27*(1), 223-237. https://doi.org/10.1111/jiec.13347

[26] Lehtola, T. (2024). Solar energy and wind power supply supported by battery storage and Vehicle to Grid operations. *Electric Power Systems Research*, *228*. https://doi.org/10.1016/j.epsr.2023.110035

[27] Li, L., Kim, S., Wang, W., Vijayakumar, M., Nie, Z., Chen, B., Zhang, J., Xia, G., Hu, J., Graff, G., Liu, J., & Yang, Z. (2011). A Stable Vanadium Redox-Flow Battery with High Energy Density for Large-Scale Energy Storage. *Advanced Energy Materials*, *1*(3), 394-400. https://doi.org/10.1002/aenm.201100008

[28] Li, Y., Lu, J., Gao, M., Wang, K., Xiong, Z., & Jiang, K. (2023). Improvement of Vanadium Redox Flow Battery Efficiency Through Carbon Felt Electrodes Modification by Atmospheric Dielectric Barrier Discharge. *Plasma Chemistry and Plasma Processing*, *43*(6), 1673-1684. https://doi.org/10.1007/s11090-023-10365-4

[29] Lim, H., Yi, J. S., & Lee, D. (2019). Correlations of Through-Plane Cell Voltage Losses, Imbalance of Electrolytes, and Energy Storage Efficiency of a Vanadium Redox Flow Battery. *ChemSusChem*, *12*(7), 1459-1468. https://doi.org/10.1002/cssc.201802633

[30] Liu, Q., Yang, D., Xing, M., Yan, C., & Liu, B. (2025). Research on operating mechanism and state of battery based on fiber Fabry-Pérot cavity. *Sensors and Actuators A: Physical*, *382*. https://doi.org/10.1016/j.sna.2024.116175

[31] Lobato-Peralta, D. R., Molina-Serrano, A. J., Luque-Centeno, J. M., Sánchez-Laganga, B., Sebastián, D., Carrasco-Marín, F., Lázaro, M. J., & Alegre, C. (2025). Improving energy storage properties of carbon felt electrodes for vanadium redox flow batteries via ZIF modifications. *Chemical Engineering Journal*, *515*. https://doi.org/10.1016/j.cej.2025.163534

[32] Lopes, P. P., & Stamenkovic, V. R. (2020). Past, present, and future of lead–acid batteries. *Science*, *369*(6506), 923-924. https://doi.org/10.1126/science.abd3352

[33] Matuck, L., Santos, J. P., Freitas, F., Fontes, L. B., Bierlich, J., Geniès, S., Pinto, J. L., Ferreira, M. S., Raccurt, O., & Nascimento, M. (2024). Towards smart and secure batteries: Linking pressure and temperature profiles with electrochemical behavior through hybrid optical fiber sensors. *Chemical Engineering Journal*, *500*. https://doi.org/10.1016/j.cej.2024.156806

[34] Matuck, L. C., Cabrita, P. D., Pinto, J. L., Marques, C. A., & Nascimento, M. S. (2023). Customized Optical Fiber Birefringent Sensors to Multipoint and Simultaneous Temperature and Radial Strain Tracking of Lithium-Ion Batteries. *Advanced Sensor Research*, *2*(7), n/a. https://doi.org/10.1002/adsr.202200046

[35] Mazaheri, H., Moeini-Aghtaie, M., Fotuhi-Firuzabad, M., Dehghanian, P., & Khoshjahan, M. (2021). A linearized transmission expansion planning model under N − 1 criterion for enhancing grid-scale system flexibility via compressed air energy storage integration. *IET Generation, Transmission & Distribution*, *16*(2), 208-218. https://doi.org/10.1049/gtd2.12226

[36] Mishra, V., Lohar, M., & Amphawan, A. (2016). Improvement in temperature sensitivity of FBG by coating of different materials. *Optik*, *127*(2), 825-828. https://doi.org/10.1016/j.ijleo.2015.10.014

[37] Mohammed, A., Hu, B., Hu, Z., Djurovic, S., Ran, L., Barnes, M., & Mawby, P. A. (2020). Distributed Thermal Monitoring of Wind Turbine Power Electronic Modules Using FBG Sensing Technology. *IEEE Sensors Journal*, *20*(17), 9886-9894. https://doi.org/10.1109/jsen.2020.2992668

[38] Mondal, M., Mandal, K. K., & Datta, A. (2022). Solar PV driven hybrid gravity power module—Vanadium redox flow battery energy storage for an energy efficient multi-storied building. *International Journal of Energy Research*, *46*(13), 18477-18494. https://doi.org/10.1002/er.8460

[39] Nascimento, M., Paixão, T., Ferreira, M. S., & Pinto, J. L. (2018). Thermal Mapping of a Lithium Polymer Batteries Pack with FBGs Network. *Batteries*, *4*(4). https://doi.org/10.3390/batteries4040067

[40] Peng, F. Z., Liu, C.-C., Li, Y., Jain, A. K., & Vinnikov, D. (2024). Envisioning the Future Renewable and Resilient Energy Grids—A Power Grid Revolution Enabled by Renewables, Energy Storage, and Energy Electronics. *IEEE Journal of Emerging and Selected Topics in Industrial Electronics*, *5*(1), 8-26. https://doi.org/10.1109/jestie.2023.3343291

[41] Qiu, J., Huang, B., Liu, Y., Chen, D., & Xie, Z. (2020). Glucose-derived hydrothermal carbons as energy storage booster for vanadium redox flow batteries. *Journal of Energy Chemistry*, *45*, 31-39. https://doi.org/10.1016/j.jechem.2019.09.030

[42] Ramos, F., Pinheiro, A., Nascimento, R., de Araujo Silva Junior, W., Mohamed, M. A., Annuk, A., & Marinho, M. H. N. (2022). Development of Operation Strategy for Battery Energy Storage System into Hybrid AC Microgrids. *Sustainability*, *14*(21), 13765. https://doi.org/10.3390/su142113765

[43] Ren, Y., Song, H., Cai, Q., Cai, Z., Liu, Y., & Wang, B. (2024). Modeling analysis and experimental study on epoxy packaged FBG sensor for cryogenic temperature measurement. *Optical Fiber Technology*, *84*. https://doi.org/10.1016/j.yofte.2024.103710

[44] Reynard, D., Dennison, C. R., Battistel, A., & Girault, H. H. (2018). Efficiency improvement of an all-vanadium redox flow battery by harvesting low-grade heat. *Journal of Power Sources*, *390*, 30-37. https://doi.org/10.1016/j.jpowsour.2018.03.074

[45] Rezaei, H., Abdollahi, S. E., Abdollahi, S., & Filizadeh, S. (2022). Energy management strategies of battery-ultracapacitor hybrid storage systems for electric vehicles: Review, challenges, and future trends. *Journal of Energy Storage*, *53*. https://doi.org/10.1016/j.est.2022.105045

[46] Rudolph, S., Schröder, U., Bayanov, I. M., & Hage, D. (2014). Measurement, simulation and in situ regeneration of energy efficiency in vanadium redox flow battery. *Journal of Electroanalytical Chemistry*, *728*, 72-80. https://doi.org/10.1016/j.jelechem.2014.05.033

[47] Shao, Y., Wang, X., Engelhard, M., Wang, C., Dai, S., Liu, J., Yang, Z., & Lin, Y. (2010). Nitrogen-doped mesoporous carbon for energy storage in vanadium redox flow batteries. *Journal of Power Sources*, *195*(13), 4375-4379. https://doi.org/10.1016/j.jpowsour.2010.01.015

[48] Speidel, S., & Bräunl, T. (2016). Leaving the grid—The effect of combining home energy storage with renewable energy generation. *Renewable and Sustainable Energy Reviews*, *60*, 1213-1224. https://doi.org/10.1016/j.rser.2015.12.325
[49] Ventosa, E. (2022). Semi-solid flow battery and redox-mediated flow battery: two strategies to implement the use of solid electroactive materials in high-energy redox-flow batteries. *Current Opinion in Chemical Engineering*, *37*. https://doi.org/10.1016/j.coche.2022.100834
[50] Wahl, M. S., Spitthoff, L., Muri, H. I., Jinasena, A., Burheim, O. S., & Lamb, J. J. (2021). The Importance of Optical Fibres for Internal Temperature Sensing in Lithium-ion Batteries during Operation. *Energies*, *14*(12). https://doi.org/10.3390/en14123617
[51] Wang, C., Wang, Y., Dong, L., & Yao, F. (2023). SOC estimation of lithium battery based on the combination of electrical parameters and FBG non-electrical parameters and using NGO-BP model. *Optical Fiber Technology*, *81*. https://doi.org/10.1016/j.yofte.2023.103581
[52] Xia, L., Long, T., Li, W., Zhong, F., Ding, M., Long, Y., Xu, Z., Lei, Y., Guan, Y., Yuan, D., Zhang, Y., Jia, C., Sun, L., & Sun, Q. (2020). Highly Stable Vanadium Redox-Flow Battery Assisted by Redox-Mediated Catalysis. *Small*, *16*(38), e2003321. https://doi.org/10.1002/smll.202003321
[53] Xia, X., Wu, W., Li, Z., Han, X., Xue, X., Xiao, G., & Guo, T. (2024). State of Charge Estimation for Commercial Li-Ion Battery Based on Simultaneously Strain and Temperature Monitoring Over Optical Fiber Sensors. *IEEE Transactions on Instrumentation and Measurement*, *73*, 1-11. https://doi.org/10.1109/tim.2024.3390696
[54] Xiong, B., Yang, Y., Tang, J., Li, Y., Wei, Z., Su, Y., & Zhang, Q. (2019). An Enhanced Equivalent Circuit Model of Vanadium Redox Flow Battery Energy Storage Systems Considering Thermal Effects. *IEEE Access*, *7*, 162297-162308. https://doi.org/10.1109/access.2019.2952212
[55] Yao, G., Yin, Y., Li, Y., & Yi, H. (2021). High-precision and wide-wavelength range FBG demodulation method based on spectrum correction and data fusion. *Opt Express*, *29*(16), 24846-24860. https://doi.org/10.1364/OE.433914
[56] Yu, K., Chen, W., Deng, D., Wu, Q., & Hao, J. (2024). Advancements in Battery Monitoring: Harnessing Fiber Grating Sensors for Enhanced Performance and Reliability. *Sensors (Basel)*, *24*(7). https://doi.org/10.3390/s24072057
[57] Zou, T., Shi, X., & Yu, L. (2021). Study on energy loss of 35 kW all vanadium redox flow battery energy storage system under closed-loop flow strategy. *Journal of Power Sources*, *490*. https://doi.org/10.1016/j.jpowsour.2021.229514
[58] Zou, W.-J., & Jung, S. (2025). Asymmetric auto-rebalancing of electrolyte for high capacity retention and high energy efficiency of vanadium redox flow batteries. *Applied Energy*, *388*. https://doi.org/10.1016/j.apenergy.2025.125663

[59] Derrien, N., Lehujeur, M., Chapeleau, X., Durand, O., Gallet, A., Roussel, N., Yven, B., & Abraham, O. (2025). Challenges of Embedding Fiber Bragg Grating Sensors in Castable Material: Influence of Material Shrinkage and Fiber Coatings on Ultrasonic Measurements. *Sensors (Basel, Switzerland)*, *25*(9), Article 2657. https://doi.org/10.3390/s25092657

[60] Ying, Y., Yi, Q., & Gao, Z. (2025). Temperature and refractive index sensing using a chirped tilted fiber Bragg grating (CTFBG) cascaded with a fiber Bragg grating (FBG). *Instrumentation Science & Technology*, 1–15. https://doi.org/10.1080/10739149.2025.2453944

[61] Zaynetdinov, M., See, E. M., Geist, B., Ciovati, G., Robinson, H. D., & Kochergin, V. (2015). A Fiber Bragg Grating Temperature Sensor for 2-400 K. *IEEE Sensors Journal*, *15*(3), Article 6949060. https://doi.org/10.1109/JSEN.2014.2368457

[62] Monteiro, C. S., Rodrigues, A. V., Viveiros, D., Linhares, C., Mendes, H., Silva, S. O., Marques, P. V. S., Tavares, S. M. O., & Frazão, O. (2021). Optical Fiber Sensors for Structural Monitoring in Power Transformers. Sensors (Basel, Switzerland), 21(18), Article 6127. https://doi.org/10.3390/s21186127

[63] Kuroda, K. (2025). Multichannel Temperature Sensor Based on Fiber Bragg Grating Combined With Fiber-Cavity Ring-Down Technique. *Microwave and Optical Technology Letters*, *67*(7), Article e70297. https://doi.org/10.1002/mop.70297

[64] Markos, C., Stefani, A., Nielsen, K., Rasmussen, H. K., Yuan, W., & Bang, O. (2013). High-Tg TOPAS microstructured polymer optical fiber for fiber Bragg grating strain sensing at 110 degrees. *Optics Express*, *21*(4), 4758–4765. https://doi.org/10.1364/OE.21.004758

[65] Sumitomo Electric Group. (2023, Febrary 13). *How Vanadium Redox Flow Battery works – VRFB explained* [Video]. YouTube. https://youtu.be/TSsqCazP1V0

[66] Billy Wu. (2021, November 14). *Vanadium redox flow battery working principle explained with animation* [Video]. YouTube. https://youtu.be/t9zwgL7UpDA