MULTIPLE-CRITERIA DECISION-MAKING BASED ENERGY STORAGE SYSTEM SELECTION FOR MARINE RENEWABLE ENERGY STORAGE SYSTEMS

by

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ABSTRACT

SHRAVANI KONKA. Multiple-criteria decision-making based Energy Storage System Selection for Marine Renewable Energy Storage Systems . (Under the direction of DR. LINQUAN BAI)

An exponential increase in energy demand worldwide induces researchers to opt for alternative energy sources that are cleaner. The most effective solution to the global warming risk is to use sustainable sources. Researchers consider oceans can contribute towards environmentally friendly energy. The energy carried by the ocean through tides and waves creates a vast source of kinetic energy. Tidal, Photovoltaic (PV), Wind Energy, and Wave Energy are essential ocean energy resources identified by the researchers. The energy from these sources is termed as Marine Renewable Energy (MRE). When disconnected from the primary grid, energy sources work in isolation mode. The intermittent nature of MRE reckons using an energy management system in its isolation mode. Energy Storage Systems (ESS) act as the energy buffer considering the erratic nature of MRE. Using excessive power from generators, ESS stores energy and supplies when power from the MRE is scarce. Energy storage consultant considers ESS's robustness and futuristic potential while selecting Energy Storage alternatives. Performance parameters of these alternatives help the consultants choose the appropriate ESS. Performance parameters (qualitative and quantitative) of the ESS alternatives are the criteria for deciding the best ESS alternative. ESS selection is a Multiple Criteria Decision Making (MCDM) problem with multiple criteria and alternatives. MCDM method is the complex decision-making process that can solve the selection of alternatives in this multicriteria /multi- alternative situation.

This research attempts to select the best ESS among alternatives using MCDM methods. MCDM method develops a multi-objective formulation in which the performance parameters of each alternative are compared to other alternatives. Energy density, power rating, discharge time, cycle efficiency, lifetime, and specific cost are the criteria

to choose the best ESS. The alternatives chosen are Pumped Hydro Storage, Flywheel battery, Lithium Battery, Sodium Sulphur Battery, Lead Acid Battery, Compressed Air Energy Storage, Redox Flow Battery, and Nickel Cadmium Battery. MCDM problem is solved using the Vlse Kriterijumska Optimizacija Kompromisno Resenje (VIKOR) method, Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), and Preference ranking organization method for enrichment evaluation(PROMETHEE) methods. Results obtained from these MCDM methods are investigated. The VIKOR method is found to be most promising in the overall performance. MATLAB-based models are developed for all the three methods, and the suitable method for accurate decision-making for selecting the most appropriate ESS is determined.

The chapters of the thesis are organized as follows. Chapter 1 discusses working with different MRE systems and ESS alternatives that can be used for MRE. The motivation for the research is also discussed. Chapter 2 reviews the existing literature, highlighting different MCDM applications and the gaps in the previous implementations. Chapter 3 defines the problem statement of the research. Chapter 4 states the objectives of this research. Chapter 5 introduces the importance of MCDM systems and discusses the methodology involved in all three MCDM methods. Chapter 6 details the MCDM formulation used for the rest of the thesis. Chapter 7 discusses the results obtained by the TOPSIS and PROMETHEE methods. The results obtained by the VIKOR method are explained in-detail as this research found VIKOR more feasible for the Energy storage system selection. Chapter 8 concludes the thesis, followed by references.

DEDICATION

I would like to dedicate this thesis to my family, advisor and teachers who have been extremely helpful and supportive throughout my journey.

ACKNOWLEDGEMENTS

Firstly, I would like to express my sincere gratitude to my advisor Dr. Linquan Bai for his constant support, patience and encouragement. His suggestions and guidance motivated me to write this thesis. I feel privileged to be guided by him, I could not ask for a better advisor. I would like to thank my thesis committee: Dr. Churzlu Lim and Dr. Tao Hong, for their encouragement. I would also like to thank my friend Naveen Kumar Kodandapani who has helped me during my research. Last but not the least, I would like to thank my beloved family: Vishveshwara Babu Chitturi, Ravindra Konka and Hema Latha Konka .

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ESS Energy Storage System

MCDM Multiple-Criteria Decision-Making

MRE Marine Renewable Energy

PROMETHEE Preference Ranking Organization Method for Enrichment Evaluation

RES Renewable Energy Sources

TOPSIS Technique for Order of Preference by Similarity to Ideal Solution

VIKOR Vlse Kriterijumska Optimizacija Kompromisno Resenje

CHAPTER 1: INTRODUCTION

Oceans covering around 71% of the earth has abundant potential for electric power generation. Ocean energy is environment-friendly and can be tapped out using MRE technology. MRE is a renewable power source that is harnessed from the natural movement of water, including waves, tides, river and ocean currents. Wave energy, Tidal, Solar and Wind are a few energy sources that can generate ocean electricity. The types and the process of power generation are detailed below.

1.1 Tidal Power Generation

Tidal energy at sea is generated due to the gravitational pull of the earth, moon, and sun. Usually installed at the coastlines, tidal power is generated from barrages, turbines, and fences that rotate due to the tide's rise and fall.

1.1.1 Tidal Barrage

Tidal Barrage is a dam-like structure near the coastline between the high tidal level and the tidal basin.

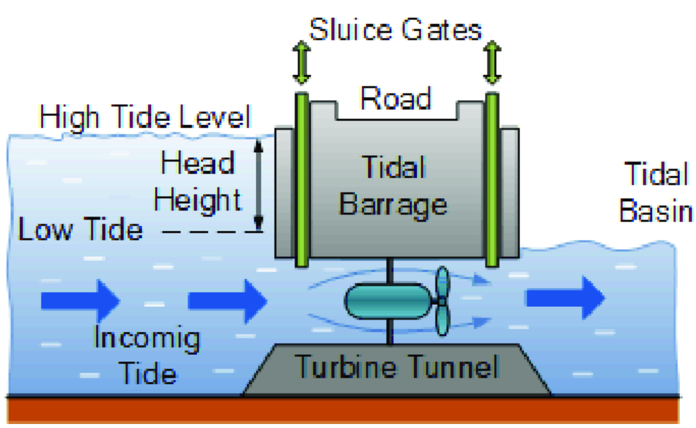


Figure 1.1: Tidal Barrage[1]

The tidal power generation setup is as shown in Figure 1.1[1]. The tide flows from the high tide to the tidal basin and backward. The turbine rotates due to the lift created by the tide flow. The turbine is connected to the generator that generates electricity.

1.1.2 Tidal Turbine

Tidal turbines are similar to wind turbines fixed underwater. Turbines have blades similar to wind turbines that rotate the generator rotor. Tidal turbines exploit the solid tidal flow on the sea floor. Water is 800 times denser than air, so tidal turbines must be heavier and sturdier. Compared to wind turbines, tidal turbines are more expensive.

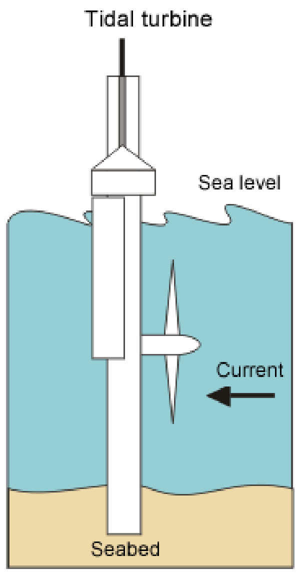


Figure 1.2: Tidal Turbine[2]

Tidal turbine blades can generate more power than wind turbines, given the size of the turbines is the same. Tidal fences are horizontal-axis turbines instead of the vertical-axis turbines in tidal turbines. The tidal turbine setup is as shown in the Figure 1.2[2]. These turbines are installed in the sea bed as shown.

1.1.3 Tidal Fences

Tidal fences are horizontal-axis turbines instead of the vertical-axis turbines in tidal turbines.The tidal fence setup is as shown in Figure 1.3[3].

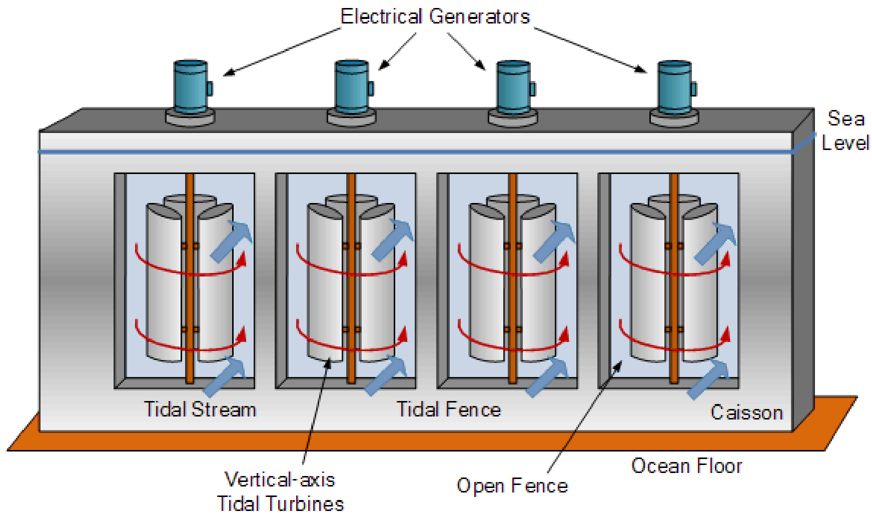


Figure 1.3: Tidal Fences[3]

In a single structure called a "Fence," many turbines are connected. The turbines are placed on the sea bed by the generator on the top. Tidal energy comes under the category of ocean current energy, and it is different from wave energy. The following section discusses the electricity generation process from wave energy.

1.2 Wave Energy

Unlike tidal energy, which exploits the high and low tides of the ocean to generate power, wave energy exploits the motion of the waves to generate power. Wave energy is also a type of renewable energy and is the most significant estimated global resource form of ocean energy. Three well-known wave energy conversion devices are [4], 1. Wave profile device 2. Oscillating Water Columns 3. Wave Capture Devices The description of each of these wave conversion devices is in the following section.

1.2.1 Wave Profile Device

The wave profile device floats on the sea's surface and follows the incident wave shape. The rotary or linear generator uses the toggling movement of the wave to generate power. If the wave profile device is smaller than the periodic length of the wave, it is called the "point observer." If the size is larger, it is called the "linear observer". Wave profile device is applied practically in limited places. Both observers are depicted in the figure .

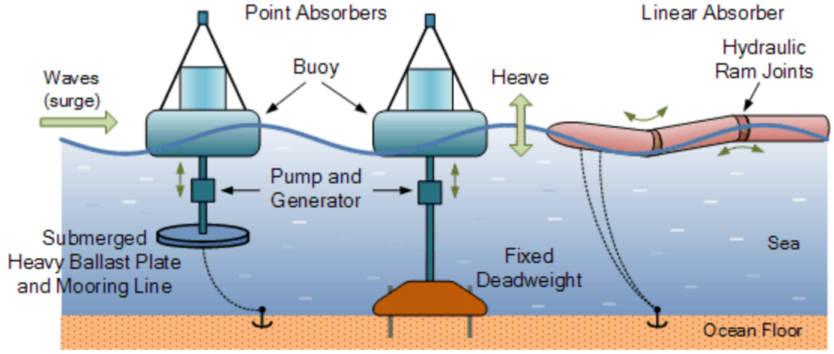


Figure 1.4: Wave Profile Device[4]

Two devices on the left with the buoys are point observers, as shown in the Figure 1.4[4]. The vertical movement of the wave is called heave. Heave facilitates the vertical movement of the buoy. Vertical movement of the buoy, lighter than the heavy fixed dead weight or the ballast plate, pumps water to the generator causing electricity generation. The third device on the right is the Linear Observer. As the waves pass along the length of this snake-like wave energy device, they cause the long cylindrical body to sag downwards into the troughs of the waves and arch upwards when the wave's crest is passing. Connecting joints along the body of the device flex in the waves exerting a great deal of force which is used to power a hydraulic ram at each joint. The hydraulic ram drives oil through a hydraulic motor which drives a generator, producing electricity.

1.2.2 Oscillating Water Columns

An oscillatory water column can be set up where cliffs or caves are near the deep-sea bottom. A hollow chamber submerged partly in the shoreline is used to convert the wave energy to air pressure. The wind turbine generator inside the chamber generates electricity by receiving the high-pressure air. Wave flows into the chamber, resulting in the vertical up-down movement of water that causes air pressure as depicted in Figure1.5[4].

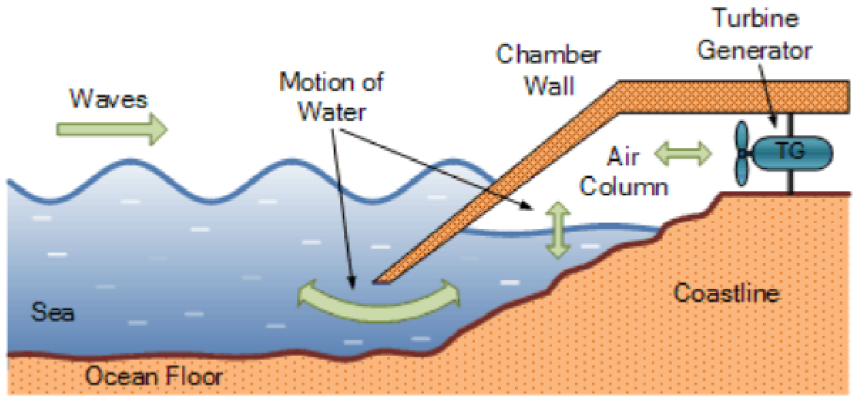


Figure 1.5: Oscillating Water Column[4]

The wind turbine in this application is called the "Wells" turbine. The conversion efficiency of this wave generation technology depends on the type of wind turbine used.

1.2.3 Wave Capture Energy Device

Also known as the overtopping wave power device, the wave capture device elevates the wave to a reservoir above sea level. The potential energy of the water stored in the reservoir is used to generate power.

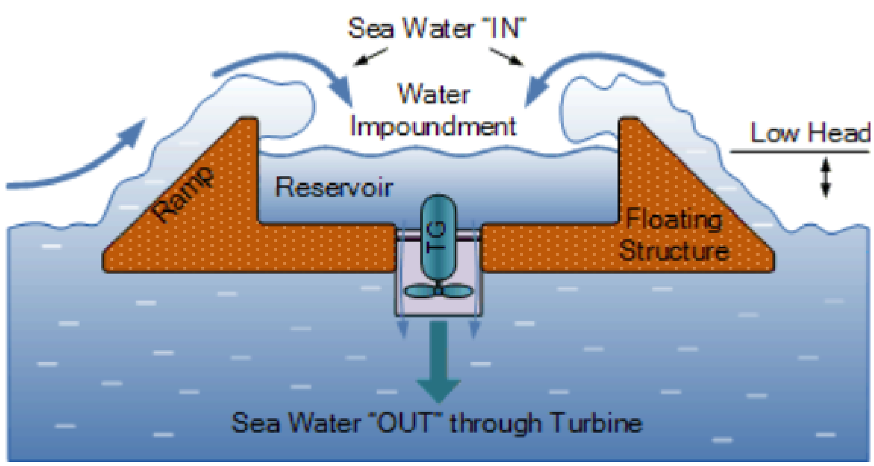


Figure 1.6: Wave Capture Energy Device[5]

The ramp in the floating structure elevates the water to the reservoir. Water stored in the reservoir moves down through the turbine connected to the generator, as shown in the Figure 1.6.This wave energy generator is also a shoreline generator.

1.3 Wind Energy

Wind generators at sea are called offshore wind generators. The wind's kinetic energy falling on the rotor converts it to mechanical energy. The rotor is coupled to the generator through the gear system. A generator that gets the mechanical input from the gear system would convert the mechanical energy into electrical energy. The complete structure of the wind turbine is shown in Figure 1.7. The aerodynamic design of the rotor blades is articulated to enhance power conversion capability from kinetic energy in the air to the rotor mechanical energy. Power energy coefficient is the ratio of actual electric power produced to the total wind power flowing into the turbine blades at a specific speed. The wind turbine construction is categorized according to the following wind turbine-based parameter.

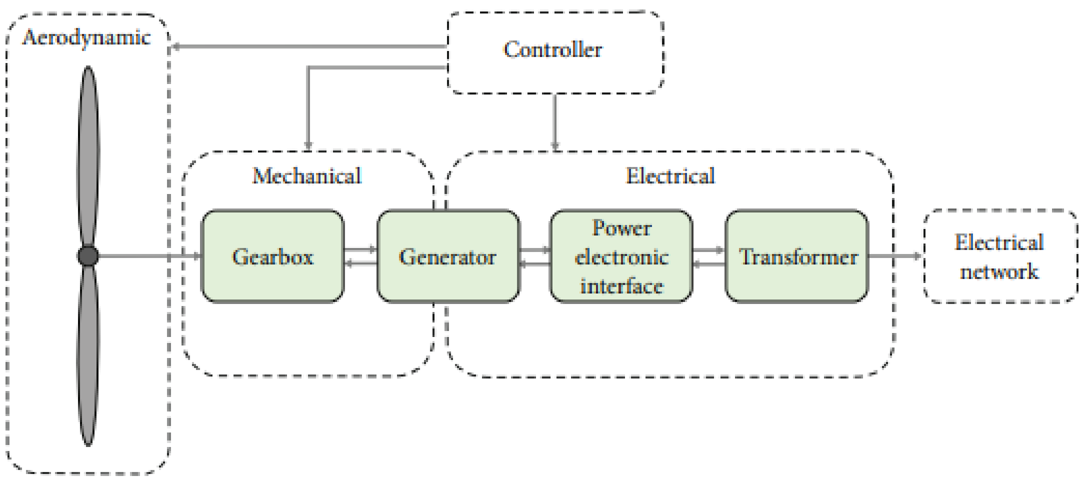


Figure 1.7: Wind Energy Conversion System[6]

1. Speed Parameter: Wind turbines that work near a specific rotor speed in a narrow range are called fixed-speed wind turbines. The rotational speed is adjusted to the incoming wind speed in the variable speed wind turbine to maintain better aerodynamic efficiency.

2. Pitch angle: Both the fixed pitch angle and variable pitch angle setup for WECS.

3. Direct or Indirect: Indirect drive is a doubly-fed squirrel cage induction motor

topology with both the gear system and the frequency converter. Direct drive synchronous generator has the frequency converter without a gearbox. Pitch control in both these drives is relevant, and also, both are variable speed drives.

1.4 Need for Energy Storage System in MRE

Improving human livelihood and economic growth using ocean resources is termed the "Blue Economy." MRE provides power support to blue economy opportunities. Ocean-based activities like ocean observation and navigation, underwater vehicle charging, marine aquaculture, marine algae farming, and seawater mining need MRE to power the activity. These activities should incorporate off-grid or offshore MRE topology. Consistent power supply [17] in this topology is supported using Energy Storage Systems. Absorbing the excess energy from the power system during lower load demand and delivering it during a higher load demand leads to consistent power delivery in off-grid operation. Also, MRE such as wave energy is highly dependent on meteorological conditions hence the power produced from Wave energy conversion (WEC) devices is highly fluctuating and integrating this variable and fluctuating renewable energy resources into power grids complicates the tasks such as power stabilization and power balancing. To smoothen the power fluctuations, improve the system reliability, energy shifting and load leveling, Energy Storage Systems (ESS) have been widely used. 8 different alternatives of energy storage systems are considered for evaluation in this thesis.

1.5 Energy Storage Types

Few of the critical ESS feasible for Marine Renewable Energy storage are discussed below.

1.5.1 Pumped Hydro storage

Pumped Hydro Storage(PHS) is a hydroelectric energy storage system. Two water reservoirs with different elevations are a giant battery in a PHS setup. The reservoir at the higher elevation releases water to the reservoir at the lower elevation through a turbine. Penstock /tunnel regulates the water pressure reaching the generator turbine. Rotation of turbine generates electricity in the coupled generator. The PHS is set up as shown in Figure 1.8[7]. When excess power is available, water is pumped back to the reservoir at a higher elevation. PHS is a well-developed, inexpensive, and reliable ESS technology. Although efficient, it needs the power to pump the water to the reservoir.

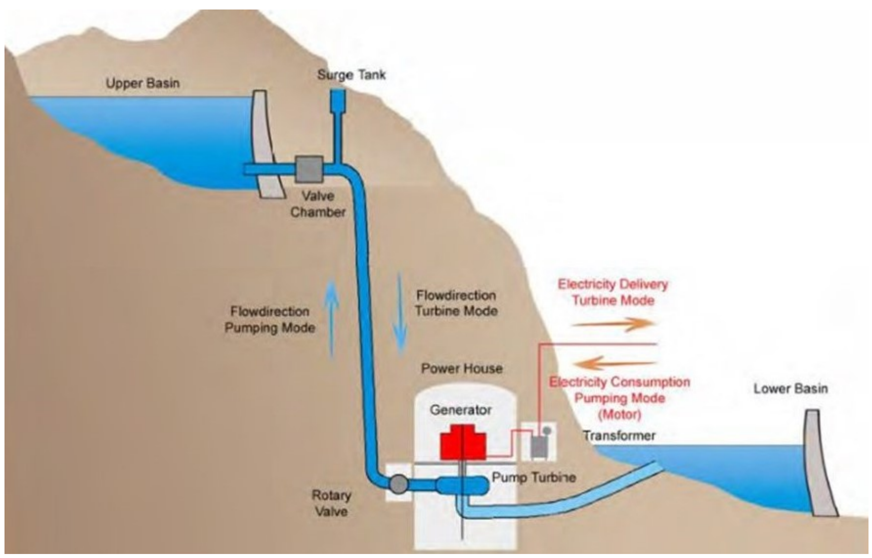


Figure 1.8: Pumped Hydro Storage[7]

PHS has a longer life since an endless loop of water circulation is possible with minor wear and tear in the equipment. Finding a suitable reservoir site is a challenge. Besides the environmental and ecological impacts of PHS installation, the capital cost of setting up the PHS is high.

1.5.2 Super capacitors

The construction of the supercapacitor is similar to a regular electrolytic capacitor. Two metal electrodes soaked in the electrolyte are separated by a thin insulation layer that comprises the supercapacitor. The supercapacitors store electrical energy in between two electrostatic double layers. Double layers are formed by depositing a thin charge layer at the electrolyte interface and the capacitor electrode's inner layer. Supercapacitor uses conduction plates kept closer than those used in electrolytic capacitors. Although the electrochemical device, supercapacitors do not generate power by chemical reaction. Metal plates used for supercapacitor electrodes are coated with either porous carbon or activated charcoal. Supercapacitor uses static electricity to store energy. When powered with the voltage, one of the metal plates develops a positive charge while the other plate develops a negative charge. From the electrolytic solution, positive ions move to the negatively charged plates and negative ions to positive charge plates. A thin layer of ions gets deposited on the inner side of both the plates creating the electrostatic double layer as shown in Figure 1.9.

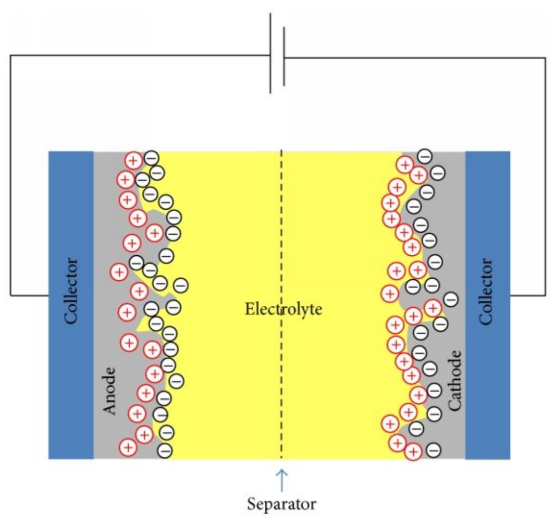


Figure 1.9: Supercapacitor[8]

Supercapacitors have specialized applications, including quenching peak power demand, regulating output power fluctuation, Low voltage Ride Through(LVRT), and engine starting sequence. Supercapacitors inherit a higher lifetime, stable and power-efficient operation, and a higher operating temperature range, including cold temperatures.[18],[8]. The disadvantage of using a supercapacitor is that it needs overcharge and over-discharge protection.

1.5.3 Flywheel Battery

The flywheel conserves the angular momentum to store rotational energy, thus acting as a mass rotating mechanical battery. It accelerates the rotor at a very high speed while releasing kinetic energy [19],[20]. The flywheel energy storage system is shown in Figure reftab:fw[9]. The flywheel rotor coupled with the motor/generator fits on the magnetic bearing to facilitate rotation. The motor/generator is interfaced with the RES through a power electronics device. Power transfer between RES and the flywheel is controlled using the power electronics device. Low-speed flywheels provide an energy density of 5-30Wh/kg; high rotational speed flywheels achieve high energy density up to 100Wh/kg.[19],[20].

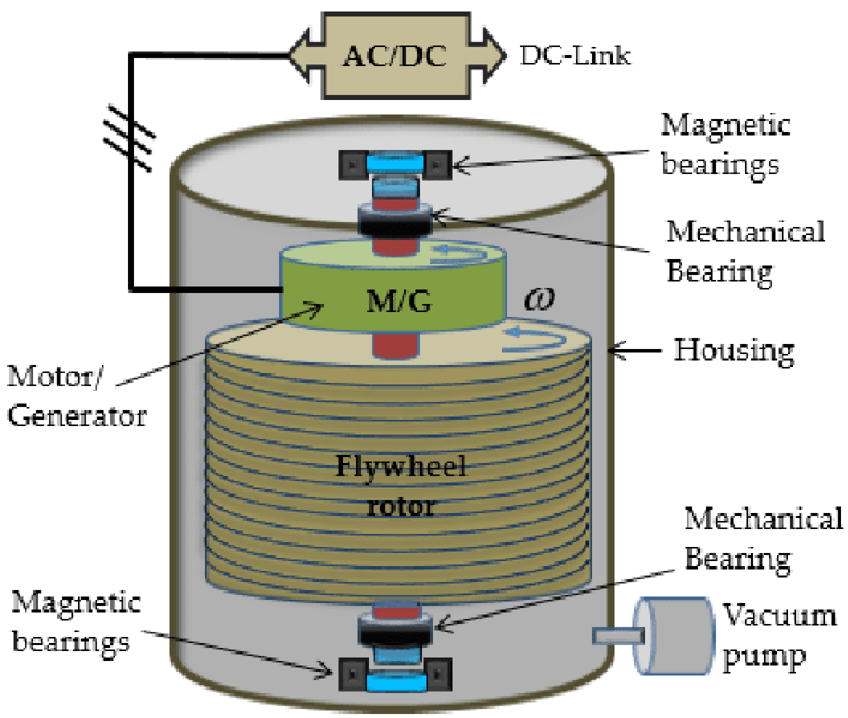


Figure 1.10: Flywheel [9]

Like supercapacitors, flywheel also has a long lifetime. Flywheel features higher specific energy, fast power response, high cycle efficiency, and a short recharge time. The amount of energy stored in a flywheel depends on the square of the rotational speed, making high-speed flywheels highly desirable for Energy/mass ratio optimization. Mechanical stress limits, hazardous failure modes, and short discharge times are the disadvantages of the flywheel energy system.

1.5.4 Lithium Battery

Batteries with Lithium as the anode electrode is called Lithium batteries. Lithium batteries comprise an anode, cathode, positive and negative current collectors, electrolyte, and separator. Both anode and cathode stores lithium. The movement of lithium ions in the anode creates free electrons, thus charging the positive current collector. The electrolyte carries positive lithium ions from the anode to the cathode and vice versa through the separator. The anode discharges current to the external circuit or equipment. High charge density, high cost per unit, reasonable energy density, and small size are a few essential features of Lithium-ion batteries.

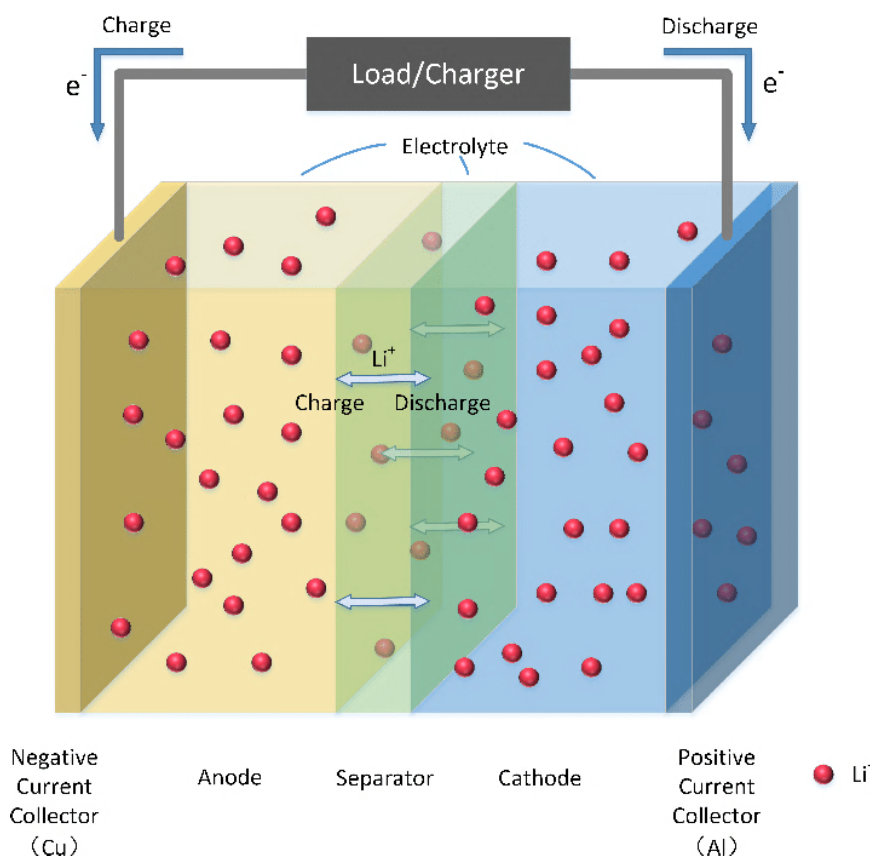


Figure 1.11: Lithium Battery[10]

Although around 3000 charge /discharge cycles are estimated for Lithium-Ion batteries, they are not robust and sometimes fragile. The lifetime of Lithium batteries is affected by temperature and deep discharges. Special protection circuits are required to avoid overloading faults. Higher rating batteries are costly in lithium-ion batteries[10].

1.5.5 Compressed Air Energy Storage

An energy storage system that uses the energy of compressed air stored as the storage source is called Compressed Air Energy Storage(CAES).CAES is the peak power quenching ESS like the supercapacitor. Energy stored in the form of compressed air during the low energy demand stage is used during the high energy demand stage. Electric Energy is converted to compressed air to run the turbine, using the pressure generated from the air while high power demand . Structure of CAES is as shown in Figure 1.12[12]. CAES is known to have a solid potential to deliver high-performance energy storage at large scales for relatively low costs compared with any other solution. In the off-peak scenario, excess power is used to operate a compressor that stores compressed air in an underground reservoir. During the peak power demand scenario, compressed air is used to run the turbine that generates electricity.

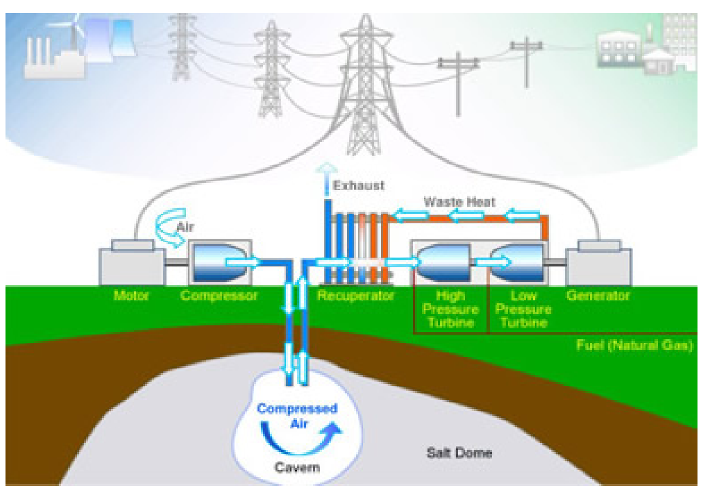


Figure 1.12: Compressed Air Energy Storage[11][12]

CAES is an efficient peak demand quenching ESS that significantly improves the power grid efficiency. With a low maintenance cost, good lifetime CAES is an advantageous ESS. Lower efficiency than the pumped hydro system, slow response time, and risk of using underground reservoirs are a few drawbacks while using CAES[11].

1.5.6 Sodium Sulphur Battery

Sodium sulphur batteries combine liquid states of negative sodium and positive sulphur electrodes. Molten Sodium(Na), liquid Sulphur, and beta alumina tubes are used to develop the sodium-sulphur battery. Sodium metal atoms release electrons, generating sodium ions. These sodium ions move to the positive electrode through the alumina electrolyte. This discharge generates electricity in the battery setup as shown in Figure1.13[13]. Sodium Sulphur battery is equipped with higher energy density (5 times of lead acid battery), high charge/discharge efficiency, and a long life cycle. It has a working temperature range of 350 degrees celsius, and the chemicals used are nontoxic. The larger the size of the cell, the cheaper the battery with very high efficiency (about 90%), high power density, a longer lifetime (4500 cycles), and 80% discharge depth.

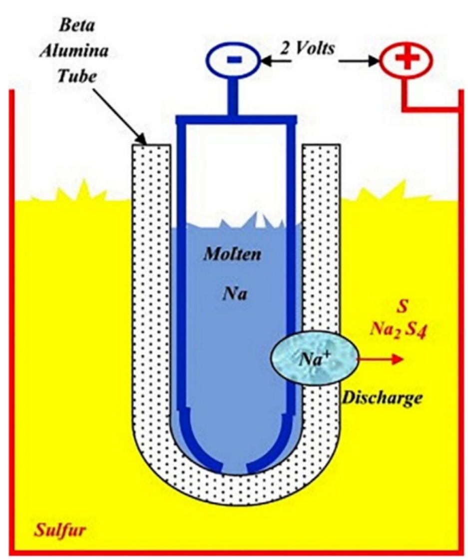


Figure 1.13: Sodium Sulphur Storage [13]

The operation of sodium-sulfur batteries requires a high temperature to liquefy the sodium, which is very difficult to operate and increases the cost of operation. [21]

1.5.7 Lead Acid Battery

Lead-acid batteries are rechargeable batteries with spongy or porous lead as negative electrodes and lead oxide as the positive electrode, as shown in Figure 1.14[14]. The electrolyte used for a lead-acid battery is a combination of sulphuric acid and water. Charging the battery produces free electrons, phosphate, and hydrogen ions. Battery, while discharging, combines these elements to form sulphuric acid and water. Immersing both electrodes in the electrolyte starts the chemical process. Invented in 1859 by French physicist Gaston PlantÃ©, lead-acid battery exhibits is a widely used battery topology [22].

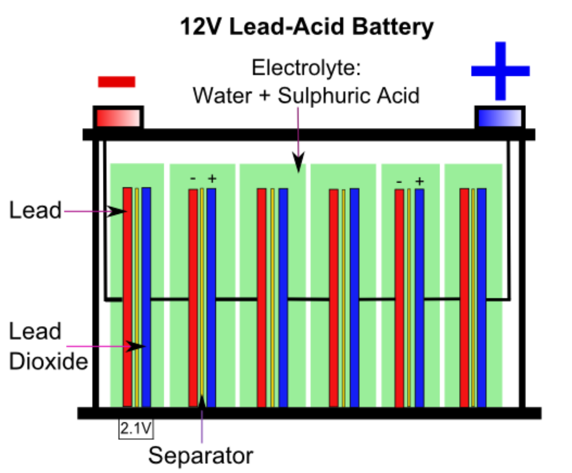


Figure 1.14: Lead Acid Battery[14]

The lead-acid battery is inexpensive and straightforward to manufacture; broadly used technology, high discharge capability, and lowest self-discharge rate are unique features of lead-acid batteries. Low energy density, low cost, and sizeable power-to-weight ratio are a few disadvantages of lead-acid batteries.

1.5.8 Redox Flow Battery

Flow battery or Redox flow battery pumps two chemical elements(electrolytes) along both sides of the ion-selective membrane. Electrode plates cover this setup. They collect the charges from the ion transfer through the membrane. Figure 1.15 [15]depicts the redox battery connection through the power electronic device. The bidirectional nature of the converter facilitates the flow of power from the power system to the battery and vice-versa. Size of the tanks that store anolyte and catholyte determines the battery's capacity.

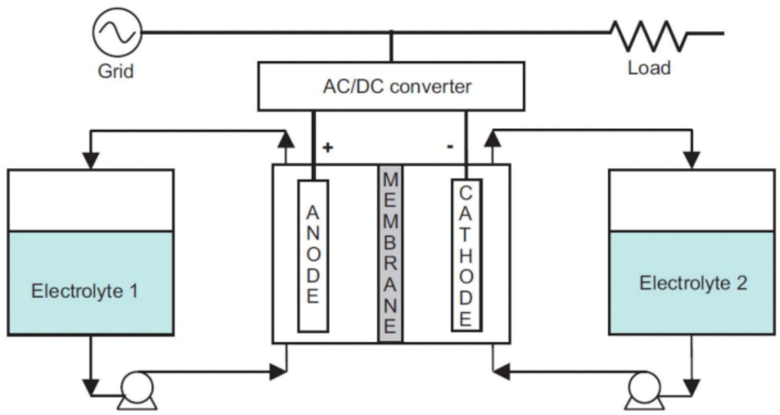


Figure 1.15: Redox Battery[15]

The flow battery design is more accessible considering that the capacity and rating of the battery depending on the electrolyte tank size. Thus, redox batteries are used in multiple types of applications. Another significant advantage is the long service life of about 10,000 cycles at 75% depth of discharge. Other advantages include high safety, negligible degradation for deep discharge, and negligible self-discharge. The drawback of using a redox battery is that it uses expensive fluids that are also toxic. Redox batteries also have low energy density and charge /discharge rate.

1.5.9 Nickel Cadmium Battery

Nickel Cadmium batteries are electrochemical batteries that use Nickel hydroxide as anode and Cadmium hydroxide as the cathode. Potassium Hydroxide is used as the electrolyte. While charging, the Nickel hydroxide converts to Nickel oxyhydroxide while Cadmium hydroxide converts to cadmium. While discharging, the Nickel and Cadmium hydroxides are restored. It is small, compact, and easily transported from one place to another. Generally, each voltage for a Nickel-cadmium battery would be approximately 1.2 V. Number of cells are connected in series or parallel to get the required voltage. Apart from the voltage, its specific energy is around 50-60 Wh per Kg. The Nickel Cadmium battery structure is as shown in Figure 1.16.

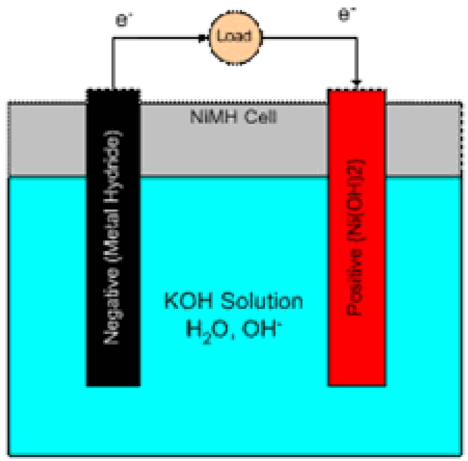


Figure 1.16: Nickel Cadmium[16]

The specific power is 200 W per kg. The energy efficiency is around 70-75%. The temperature range for nickel batteries is 0 to 45-degree centigrade during charging and -20 to 65 degrees centigrade during discharging. Beyond this temperature range, the battery fails to operate, and even chances of explosion exist [16].

1.6 Motivation

Since 97% of the Earth is covered with water out of which 71% is from the oceans. Hence Oceans can constitute to the largest source of renewable energy. Power generation from renewable energy sources(RES) is preferred worldwide. Unlike the land-based power system, the ocean-based power system is isolated, basically a distribution system with a shorter distance. Isolated distributed power systems are bound to have energy storage systems. [23]. Energy Storage System in an MRE environment has various options. Contradictory aspects of energy storage system alternatives introduce a challenging situation while making choices. It can be argued that environment-friendly and reliable alternatives may not always be cost-effective. Installation cost and payback may not correlate with reliability. Hence, these contradictions direct the choice of energy storage system as a Multi-criteria decision-making (MCDM) problem. Choosing the best alternatives among the ESS with different criteria should be addressed. MCDM evaluates different alternatives on the basis of their criteria and chooses a suitable alternative for marine energy storage. This research reviews various scientific literature on MCDM methods that are applied to evaluate ESS alternatives with suitable criteria. Various MCDM methods and their advantages and disadvantages are evaluated to select a standard method for the future studies and decision making.

Multi-Criteria Decision-making problems are solved using various decision-making methods. Decision-making methods are regulated using the stakeholder's preferences on the criteria. If the stakeholder is uncertain about the preference, Analytic Hierarchy Process (AHP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) methods are used for decision making[24].
Although this implementation discusses the advantages of the TOPSIS method, it has not been implemented for ESS selection.

Renewable energy sources are chosen using the MCDM methods considering the economic and environmental criteria while integrating into the distributed system[25]. Numerous MCDM techniques are applied to the renewable energy resources selection. The grid environment supported by using the energy storage system is efficient in energy management. Analytic Hierarchy Process (AHP) is applied using the Preference ranking organization method for enrichment evaluation(PROMETHEE) algorithm to prioritize the energy storage devices. Then the sensitivity of the criteria is analyzed using the Geometrical Analysis for Interactive Assistance (GAIA) method[26].
Although its implemented on the grid system it has not considered the ocean power generation sources.

Photovoltaic PV system investment decision-making problem comprises economical, and system efficiency criteria in the publication [27]. Both of these criterias are applied to different alternatives of the financial support schemes. For the purpose of Identification of the investment screen using multicriteria analysis method ELECTRE III is applied. PV owners can get benefited from deciding on the investment plans. Only a single MCDM method is applied. The trade-off between various MCDM methods is not developed for robustness check.

Conflicting objectives in choosing the best renewable energy resource for sustainable energy management are sorted out using the MCDM methods in different publications

[28]. Analytical Hierarchy Process is followed by the PROMETHEE method and Elimination Choice Translating Reality(ELECTRE) for ranking. FUZZY methods are used to sort out the uncertainties in the data used. This implementation is not applied to the energy storage system selection but it's applied to choose a better renewable energy resource.

The energy storage devices support the islanded mode of power system operation while renewable energy is integrated. MCDM is applied to choose amongst the energy storage devices used in the renewable energy-based power system[29]. Multiple MCDM methods are not adopted to understand the tradeoff between methods.

Choice of batteries for electrical vehicles using MCDM methods is solved with low cost, long battery life, rapid charging, and long-range driving as criteria[30]. Lithium-Ion batteries with various chemistry are the alternatives to this sorting problem. Lithium as the anode material and various cathode materials are compared for the MCDM method. The analysis is limited to only the Lithium-Ion based chemistry.

Economic, environmental, technological, and social criteria are chosen to decide which battery technology to adopt for the energy storage technology[19]. It is analyzed that lead-acid batteries attained the lowest rank in the MCDM solution. Meanwhile, weight values assigned to different criteria have changed the outputs to a greater extent, depending on the stakeholder's priority.

A comparative analysis of different MCDM methods are discussed that finds the solution for finding the best flow release scenario for a hydropower plant[31]. Among different MCDM algorithms, the VIKOR method is one of the better methods to solve the MCDM problem.

With low carbon economy development as the criteria for MCDM solution on an optimal energy storage system, an assessment to prioritize different battery energy storage systems is developed[32]. Lithium-ion battery is found to be an optimal choice among the different battery technologies.

Decisions are made based on the demands of the stakeholders, and the outputs might contradict; hence, the decision outcome of an MCDM is based on a detailed hierarchical comparison of alternatives that are sometimes contradictory to one another. This complex comparison is usually analyzed by assigning weights to the relative importance of the attributes based on the objective [33]. The main steps involved in MCDM are [34] a) Identify the goals. b) Establish evaluation criteria that relate to goals. c) Identify alternatives for attaining the set goals. d) Evaluate alternatives in terms of criteria (define the values or intervals) e) Apply multicriteria analysis methodology f) Accept an optimal or preferred alternative g) If the final solution is not acceptable, collect more information and perform another iteration till a preferred solution is obtained. This paper aims to select the best ESS for smoothening the power fluctuations, improving the system reliability, and shifting energy and load leveling for WEC. Fig. 2 shows the steps involved in the analysis.

In existing literature, various MCDM methods are developed for almost every technology application. Flexibility in power delivery is improved using the battery storage backup in the power system where penetration of renewable energy is noticeable[35].

Choice of different Battery Energy Storage systems (BESS) is solved using MCDM techniques[36]. Some of the literature considers the environmental, social, and techno-economic criteria for choosing BESS among alternatives while ignoring performance parameters like energy to power ratio(EPR)[37],[38]. There are few publications that do not consider any criteria, which are called context-free decision making[39]. Techno-economic and environmental performance alone are considered to assess the BESS alternatives [40].

Multicriteria problems do not have a single way or a particular way to solve the problem. These complex problems are solved using the MCDM methods since multi-criteria and multiple alternatives are a non-orthogonal problem[19]. In recent years, decision-makers have relied on the multicriteria Decision Making (MCDM) process to choose the best option based on various factors. It is easy to choose the best alternative utilizing existing data such as technical and economic parameters. However, identifying environmental parameters is more difficult because they can vary depending on various interest groups and stakeholder needs and demands[41]. Various methodologies have been developed over the years to assist decision-makers in selecting the best alternatives for a given list of criteria.

This literature survey summarizes different solution methodologies implemented for the Multiple Criteria Decision Making(MCDM) problems in the previous publications. Stakeholders with good technological expertise would like the chance to control their preferences and make a tradeoff between different aspects like the techno-economic and environmental impacts and make a perfect decision. Multiple MCDM methodologies are considered in this research, which will lead to accurate decision-making.

CHAPTER 3: Problem Statement

Various types of energy storage systems have been developed over the last decade with innovations and advancements in technology. Based on the technical and economic criteria of these ESS, selecting the best ESS for MRE is essential for policymakers, analysts, and decision-makers. Each ESS has unique parameters, so the ESS power requirement varies depending on these key parameters. In this research three different MCDM techniques are applied for selecting the best ESS for marine renewable energy and the accuracy of the MCDM methods is to be analyzed by using four normalization techniques and are also tested with variable weight values of criteria(parameters). Choosing an energy storage alternative with good robustness and consistency among the alternatives is the problem to be solved.

CHAPTER 4: Objectives

1. To build the MCDM models that deal with qualitative and quantitative information and illustrate the method's potential in choosing the most feasible option among the multiple energy storage alternatives for marine renewable energy.
2. Build decision making models for VIKOR, TOPSIS and PROMETHEE and compare for their usefulness, and consistency of the results. Also evaluate the computational complexity of all the methods.
3. Evaluate the decisions to make a trade-off and choose the best alternative and eliminate the worst alternative confidently.
4. To test the MCDM methods for their accuracy using different normalization techniques and re-test the models using 3 different cases.
5. Building agile models, meaning these MATLAB models can be altered by adding or deleting the alternatives and criteria without affecting the entire results. They are also flexible to use in decision-making for various applications with multiple alternatives and criterias.
6. To choose the best among the multiple ESS and the next best alternatives in the hierarchical order when there are large set of alternatives and wide range of criteria.

CHAPTER 5: MCDM Methodologies

The decision through MCDM methodologies is based on various factors. MDCM based on Distance, Outranking, Utility are few of the kinds. For the purpose of selecting the best ESS, distance based algorithms VIKOR, TOPSIS and Outranking based algorithm, PROMETHEE are evaluated and compared to make a precise decision.

5.1 TOPSIS

Developed by Ching-Lai Hwang and Yoon in 1981[42] TOPSIS method is further developed by Yoon in 1987,[43] and Hwang, Lai, and Liu in 1993[44]. Solution using TOPSIS method uses two critical terms, Positive Ideal Solution(PIS) and Negative Ideal Solutions(NIS)[45]. Geometrical distance from these two ideal solutions defines the importance of the alternatives. The shortest geometrical distance between the alternative with the PIS and the longest geometrical distance between the alternatives with the NIS is the principle for choosing the alternative. While the benefit criteria are maximized, the cost criteria are minimized. It is called the positive ideal solution. It is called the negative ideal solution when cost criteria are maximized, and the benefit criteria are minimized. Another term that is synonymous with trade-off is called compensability. Compensability is offsetting one disadvantage of criteria with the advantage of another criterion. The term aggregation defines the summary of a combination of indicators. TOPSIS is a method that uses compensatory aggregation to compare the alternatives. Assigning weights to each criterion, then normalizing the criterion score and finding the geometric distance between alternatives produces the best score of each criterion[46],[47]. The poor result from one criterion is negated by a good result from another criterion in the TOPSIS implementation, hence TOPSIS is called compensatory model, as it doesn't exclude the alternative solutions based on hard cut-offs[48].

Considering that there are m alternatives and n criteria for any problem. In this solution, alternatives are different battery chemistry and other energy storage devices that are used in Marine Energy Storage (MES) system. And criteria are the parameters that affect the choice of any of these alternatives. The parameters that act as criteria for choosing the best ESS are Energy density, power rating, discharge time, cycle efficiency, lifetime, and specific cost of different energy storage devices. The TOPSIS process is carried out as follows:

Step 1

Create an evaluation matrix consisting of m alternatives and n criteria, with the intersection of each alternative and criteria given as x_{ij} . This is the evaluation matrix denoted as $(x_{ij})_{mxn}$.

Usually, deciding the weights and profit(beneficial) attribute and cost(non-beneficial) attribute from the criteria is the stakeholder's job. The energy consultant gives a vector that decides whether a criterion is a profit or cost attribute. In this research, different weighting methodologies are considered for defining weights to the criteria.

Step 2

Since for different alternatives the criteria values are in different numerical ranges they are normalized to obtain the normalized evaluation matrix denoted by$R = (r_{ij})_{mxn}$. Four types of normalization methods are used in the proposed implementation. Max, min-max, sum and vector are four different normalization methods that are used they are defined in Equation (5.1), (5.2), (5.3) and (5.4) respectively.

$$r_{ij} = \frac{x_{ij}}{max_i(x_{ij})}(profit), r_{ij} = 1 - \frac{x_{ij}}{max_i(x_{ij})}(cost), i = 1,2...m, j = 1,2..n \tag{5.1}$$

$$r_{ij} = \frac{x_{ij} - min_i(x_{ij})}{max_i(x_{ij}) - min_i(x_{ij})}(profit), r_{ij} = \frac{max_i(x_{ij} - x_{ij}}{max_i(x_{ij}) - min_i(x_{ij})}(cost) \tag{5.2}$$

$$r_{ij} = \frac{x_{ij}}{\sum_{(k=1)}^{m} x_{ij}}(profit), r_{ij} = 1 - \frac{x_{ij}}{\sum_{(k=1)}^{m} x_{ij}}(cost) \tag{5.3}$$

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{(k=1)}^{m} x_{ij}^2}}(profit), r_{ij} = 1 - \frac{x_{ij}}{\sqrt{\sum_{(k=1)}^{m} x_{ij}^2}}(cost) \tag{5.4}$$

All four types of normalization techniques are used to aggregate the best choice.

Step 3

After calculating the normalized evaluation matrix weighted normalized matrix should be calculated for further calculation.

$$t_{ij} = r_{ij}.w_j, i = 1, 2, m, j = 1, 2..n \tag{5.5}$$

where w_j is the weight value and can be calculated using the formula,

$$w_j = \frac{W_j}{\sum_{(k=1)}^{m} w_k}, j = 1, 2, n \tag{5.6}$$

where W_j is the original weight given to the criteria by the stakeholder.

Step 4

Worst (A_w) and the best alternative $(A_b)$are calculated using the formula:

$$A_w = max((t_{ij}|i = 1, 2, ., m)|j{\in}J_-, min(t_{ij}|i = 1, 2, m)|j{\in}J_+ \equiv (t_{wj}|i = 1, 2., n) \tag{5.7}$$

A$_b = min((t_{ij}|i = 1, 2, ., m)j{\in}J_-, max(t_{ij}i = 1, 2, , m)j{\in}J_+ \equiv(t_{bj|}i = 1, 2, .m)$ (5.8)

$J_+ = j = 1, 2.n$ j associated with the criteria having a positive impact,and $J_- = j = 1, 2.n$ j associated with the criteria having a negative impact,

Step 5

Distance between target alternative "i" and the worst condition A_w is calculated using L2-distance between them.

$$d_{iw} = \sqrt{(\sum_{(j=1)}^{n} (t_{ij} - t_{wj})^2)}, i = 1, 2, .., m. \tag{5.9}$$

Similarly distance between alternative "i" and the best condition A_b is calculated using the following equation.

$$d_{ib} = \sqrt{(\sum_{(j=1)}^{n} (t_{ij} - t_{bj})^2)}, i = 1, 2, .., m. \quad (5.10)$$

where $d_i w$ and $d_i b$ are L2-norm distances from the target alternative i to the worst

and best conditions,respectively.

Step 6

Similarity with the worst condition is calculated using the following equation.

$$s_i w = \frac{d_i w}{((d_i w + d_i b))}, 0 \geq s_i w \leq 1, i = 1, 2, .m. \quad (5.11)$$

$s_i w = 1$ if and only if the alternative solution has the best condition; and

$s_i w = 0$ if and only if the alternative solution has the worst condition.

Step 7

Rank the alternatives according to $s_i w, i = 1, 2, .m$. This output is given as "Q" for intensity calculation "Qi".

5.2 PROMETHEE

Several applications have successfully incorporated PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluations) [49]. PROMETHEE compares alternatives rank-wise. The strength of one alternative on the other is compared pairwise. A better alternative in a pair is chosen. Criteria that are chosen for comparison can have either maximization or minimization conditions. Two important things that control the PROMETHEE algorithm are the weight and preference function for each criterion. Two possible decisions are brought into the range of 0 to 1, which is called the preference degree[50]. Steps involved in solving the PROMETHEE implementation are follows, Step 1

Value for each pair of decisions and the criterion is observed. $g_j(a)$ is the value of criterion j for a decision "a".The input data is normalized using the four methods mentioned in the TOPSIS algorithm. The difference value of a criterion j for two decisions a and b are termed $d_j(a,b)$.

$$d_j(a,b) = g_j(a) - g_j(b) \tag{5.12}$$

Preference degree function is used to find the preference degree value $P_j(a,b)$. The preference degree is dependent on the preference degree function as given in the equation below.

$$P_j(a,b) = F(d_j(a,b)) \tag{5.13}$$

Different preference functions are available. In this implementation V shape preference function is adopted.

Step 2

The preference degree of all the criteria is aggregated in this step for each possible decision pair. This aggregation is to compute the global preference index. Considering the C set of considered criteria and w_j the weight of criterion j global preference index of decisions "a" and "b" is calculated as given in the equation.

$$\pi(a,b) = \sum_{j \in C} w_j P_j(a,b) \tag{5.14}$$

Step 3

The ranking of the alternatives are calculated. The positive and negative outranking flow is calculated to calculate the alternatives' rank. Computation of the positive outranking flow $\phi^+(a)$ and the negative outranking flow $\phi^-(a)$ is done using the set of possible decisions " A." Formula to find positive outranking flow is given in the following.

$$\phi^{+}(a) = \frac{1}{n-1} \sum_{x \in A} \pi(a, x) \tag{5.15}$$

Formula for negative outranking flow is,

$$\phi^{-}(a) = \frac{1}{n-1} \sum_{x \in A} \pi(x, a) \tag{5.16}$$

Step 4

The overall ranking is dependent on both the positive and negative outranking flows. First the net outranking flow is calculated using the formula given below.

$$\phi(a) = \phi^{+}(a) - \phi^{-}(a) \tag{5.17}$$

Decision that increases the net outranking flow is chosen as the best decision. Ranking is decided based on the net outranking flow. PROMETHEE method decides the best ranking by checking the pairing of decisions.

5.3 VIKOR

VIKOR method is one of the most essential multi-criteria decision-making algorithm used in various fields where optimization is necessary. The compromise ranking list of alternatives and the compromise solution with the advantage rate comprise the primary ranking outcome. The reached compromise solution offers a maximum "group utility" (represented by min S) for the majority and a minimal "individual regret" (expressed by min R) for the opponent, hence the decision-makers can accept it confidently. After all the steps are implemented the results are tabulated as Q and iQi to decide the intensity of the alternative to a particular rank. The alternative corresponding to the lower iQi value is the best alternative. Negotiations that consider the decision maker's choice according to the criteria weights could start with the compromise options. VIKOR is a valuable tool in multi-criteria decision-making, primarily when the decision maker cannot communicate their choice at the outset of system design or is unsure of how to do so. The matrix is formed with "i" alternatives and "j" criteria. Performance measures of each alternative on different criteria are defined by the term pm_{ij}. Where "pm" indicates performance measure "i" indicates the i^{th} alternative and " j " indicates the j^{th} criteria. Compromise programming is applied to these alternatives and criteria to choose the best ESS in the MES system. Lp norm is used as the aggregating function to obtain the compromise among the alternatives. VIKOR method can introduce the L_1 to L_∞ norm in defining the aggregation function. The aggregation function for the compromise is as given in Equation according to (Zeleny, 1982),

$$L_{p,i} = \{\sum_{(j=1)}^{M} \{(\frac{w_j[pm_{ij_{max}} - p_{ij}]}{[pm_{ij_{max}} - p_{ij_{min}}]})^p\}^{\frac{1}{p}}, 1 \leq p \geq \infty; i = 1, 2....N \qquad (5.18)$$

The equation indicates M as number of criteria and N as the number of alternatives, and the equation is an Lp norm equation that acts as an aggregation equation. pm_{ij} is the element of the decision matrix derived using the *alternatives* and *criteria*. The steps involved in the VIKOR method are as follows.

Step 1

From the decision matrix, identification of the best element $pm_{ij_{max}}$ and the worst element $pm_{ij_{min}}$ are determined by evaluating the lowest and the highest from all the criteria.

Step 2

Equal Weight Method and entropy method is used to find the weight values for each criteria.

Step 3

The input data is normalized using the four methods similar to the TOPSIS algorithm.

Utility measure (S_i) and regret measure (R_i) are found using the equation (5.19) and (5.20).

$$S_i = L_{1,i} = \{\sum_{(j=1)}^{M} \{(\frac{w_j[pm_{ij_{max}} - p_{ij}]}{[pm_{ij_{max}} - p_{ij_{min}}]}\} \tag{5.19}$$

$$R_i = L_{\infty,i} = \{max\frac{w_j[pm_{ij_{max}} - p_{ij}]}{[pm_{ij_{max}} - p_{ij_{min}}]}\}, j = 1, 2, ...M \tag{5.20}$$

For beneficial criteria the equation (5.19) is used, while for non-beneficial criteria equation (5.21) needs modification. The term $pm_{ij_{max}} - pm_{ij}$ is replaced by $pm_{ij} - pm_{ij_{min}}$ and it can be rewritten as in Equation

$$S_i = L_{1,i} = \{\sum_{(j=1)}^{M} \{(\frac{w_j[p_{ij} - pm_{ij_{min}}]}{[pm_{ij_{max}} - p_{ij_{min}}]}\} \tag{5.21}$$

Step 4

The next step is to find the Vikor index (Q_i) value. To find Q_i from equation (5.19) and (5.21) $S_(imax)$ and $S_(imin)$ needs to be found. Equation is used to find Q_i

$$Q_i = v\frac{S_i - S_{imin}}{(S_{imax} - S_{imin})} + (1 - v)\frac{(R_i - R_{imin})}{(R_{imax} - R_{imin})} \tag{5.22}$$

In equation S_{imin} and S_{imax} are minimum and maximum values of S_i while R_{imin} and R_{imax} are minimum and maximum values of R_i. The term v is a variable having values between 0 and 1. It is defined as the weight of the strategy. The usual value of v is chosen as 0.5 as a moderate compromise for the strategy.

Step 5

All the alternatives should be arranged in the ascending order of the values obtained for Vikor index Q. There are three ranking lists ready. The decision-making starts from the Q ranking. Ascending order of Q is used to find the minimum value. The compromise solution "a" corresponding to this minimum value of Q is to be considered as the solution if two conditions are satisfied. First condition is C1:"Acceptable Advantage" the condition is that

$Q(a'') - Q(a') \geq DQ$

Where a'' is the second best alternative and a' is the best alternative in the Q ranking list. While DQ is defined as $DQ = \frac{1}{(N-1)}$

Second Condition is C2: "Acceptable stability in decision making." a' is the best alternative in the Q ranking list while, at the same time, it must be best ranked in S or/and R. If any one of the two conditions fail, that is if condition 2 does not satisfy then the solution is both a' and a''. If condition 1 is not satisfied then $a', a'' a^N$ should be considered. Where a^N is calculated using the relation $Q(a^N) - Q(a') < DQ$. The VIKOR method and its variants are defined in [51].

5.4 Summary

Three important MCDM algorithms of TOPSIS, PROMETHEE, and VIKOR method are detailed. In this solution, alternatives are different battery chemistry and other ESS alternatives that are used in the Marine Energy Storage (MES) system. And criteria are the parameters that affect the choice of any of these alternatives. The parameters that act as criteria for choosing the best ESS are Energy density, power rating, discharge time, cycle efficiency, lifetime, and specific cost of different energy storage devices. Decision making implementation using these algorithms for ESS selection are applied in the next chapter.

CHAPTER 6: MCDM Formulations

Energy density, power rating, discharge time, cycle efficiency, lifetime, and specific cost of different energy storage devices act as the criteria for MCDM solutions. Various energy storage sources are used as alternatives in the MCDM problem are explained in the Chapter 1. Below are the alternatives and their standard representation (A1-A8) that has been used for the corresponding alternatives throughout the thesis.

A1. Pumped Hydro storage

A2. Flywheel Battery

A3. Lithium Battery

A4. Sodium Sulphur Battery

A5. Lead Acid Battery

A6. Compressed Air Storage

A7. Redox Flow Battery

A8. Nickel Cadmium Battery

Criteria that influences these alternatives are collected from previous publications and internet sources. The decision matrix is generated from the collected criteria and alternatives. The problem formulation of the MCDM method starts with the decision matrix, which uses both the criteria and the alternatives. Here $N = 8$, which is the number of alternatives, and $M = 6$ is the number of criteria chosen for MCDM analysis. Techno-economic criteria are considered for the solution of this MCDM solution. Among the six criteria, five are technical, while one(Specific Cost) of the criteria is economical. Table 6.1 defines the criteria considered for the MCDM solution for all the chosen alternatives along with the category details, such as a technical or economic criterion.

Table 6.1: Criteria chosen for Energy Storage Device Selection

Criterion	Definition	Units	Category
Energy Density	Energy Accumulated per unit volume	WhL^{-1}	Technical
Power Rating	Maximum Power of the ESS alternative	MW	Technical
Discharge Time	Theoritical discharge time of ESS	Time (Years/Hours /Mins)	Technical
Cycle Efficiency	Ratio of charging capacity to discharge capacity	Percentage	Technical
Lifetime	Tenure till which the ESS can efficiently deliver	Period of Time or Number of Charge discharge cylces	Technical
Specific Cost	Cost for unit Energy Unit delivered	$ per KWh	Economic

A generator matrix is developed with parameters of all alternatives. The size of the matrix is MXN with "M" alternatives and "N" criteria(parameters). Table 6.2 and Table 6.3 depicts the vector values of decision matrix, developed for ESS selection.

Table 6.2: Parameters Used for Energy Storage Device Selection using MCDM method

Alternatives	Energy density WhL^{-1}	Power Rating MW	Discharge time
Pumped Hydro storage	2.028 [24]	3,000 [24]	4h to 16h[24]
Flywheel Battery	20-80[30],[31]	1[31]	secs to mins[31]
Lithium Battery	250 to 670[27]	100MW[33]	1 min to 8h[36]
Sodium Sulphur Battery	75Wh/L[37]	300[37]	4-8hr[37]
Lead Acid Battery	30-50[39]	100 [31-39]	1 min to 8h[36],[37]
Compressed Air Storage	3-6[25]	1000 [25]	2-30hrs [25]
Redox Flow Battery	20-70[41]	100 [41]	8[41]
Nickel Cadmium Battery	50-150 [42]	100[42]	1 min to 8h[42]

Columns in Table 6.2 and Table 6.3 define different criteria and rows define the number of alternatives. Energy storage systems used in the MES domain are considered as alternatives for the MCDM analysis. Different criteria for this analysis include "Energy Density," in Watt-hour per liter. Energy density for any energy storage system is the unit of wattage delivered for an hour per liter. Power rating of equipment is the highest power input allowed to flow through particular equipment as "Power Rating." The "Discharge time" of each energy storage device which varies from a few minutes to many hours.

Table 6.3: Parameters Used for Energy Storage Device Selection using MCDM method

Alternatives	Cycle efficiency (percentage),	Lifetime (Years cycles)	Specific cost $ per KWh
Pumped Hydro storage	70-85[24]	50 to 150 years[29]	165[26]
Flywheel Battery	70-95[21]	20,000 to 100,000[21]	150-250[22]
Lithium Battery	80-90[28]	1,000 to 10,000[25]	356[24]
Sodium Sulphur Battery	80-90[26],[27]	4500 cycles [37]	500 [38]
Lead Acid Battery	80-90[36],[37]	1000 cycles [36,37]	100[40]
Compressed Air Storage	40-70[25]	20 to 40years[25]	105[26]
Redox Flow Battery	60-85[41]	12000 to 14000[41]	25 [41]
Nickel Cadmium Battery	70-90[42]	2000[42]	400[42]

"Cycle Efficiency" is the ratio of discharge capacity to charge capacity in a single cycle, regardless of the self- discharge loss. The range of cycle efficiency for the energy storage devices is as considered in Table 6.2 and Table 6.3. A period for which the ESS can work efficiently is defined as "lifetime". The number of charge-discharge cycles or years refers to the lifetime of the energy storage device. The specific cost of each energy storage device is the cost in dollars per kilowatt hour. The parameters ranges used for the MCDM method are taken from publications[52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 70]. The Coulomb efficiency, also called as the "cycle efficiency", is usually used to describe the released battery capacity. It refers to the discharge capacity ratio after the full charge and the charging capacity of the same cycle. It is usually a fraction, less than 1. The data is ready for the solution implementation after generating a matrix with all the alternatives and criteria. This matrix is evaluated with 3 different MCDM methodologies for decision making.

CHAPTER 7: MCDM Results and Discussion

A comparison of three different MCDM methods is intended in the research to make an accurate decision on selecting the ESS that satisfies the preferences stated and building the models that are feasible to add or remove the alternatives and criteria according to the requirement during various stages of the decision making .

7.1 Prerequisites for MCDM implementation

By observing Table 6.2 and Table 6.3, it can be observed that the lifetime of the energy storage device is mentioned in both the number of years and the number of charge-discharge cycles. In-order to represent in a common unit; the lifetime is converted to a charge-discharge cycle. Both pumped hydro and compressed air-based energy storage has lifetime in terms of years, it has been converted into charge-discharge cycles; it is considered that there is one charge and discharge occuring every day. By estimating the number of days in the total number of years, the number of cycles measure is found. And also, the Energy density, discharge time, efficiency, lifetime, and specific cost are in the specific range. In this, the maximum value is considered for further calculation. After refining the values from the Table 6.2 and Table 6.3 the Table 7.1 and Table 7.2 are obtained by considering the assumptions stated above. The lifetime of each alternative is changed to a number of cycles by converting from years and other times to have a common unit. A spider graph is drawn to visualize the data to understand the different alternatives and their criteria. After the values are normalised their distance measure is represented in the graph and Figure 7.1 shows the distance measure through spider graph drawn for all eight alternatives.

Table 7.1: Refined Parameters Used for Energy Storage Device Selection using MCDM method

Alternatives	Energy density WhL^{-1}	Power Rating MW	Discharge time ours
Pumped Hydro storage	1.5	3,000	16
Flywheel Battery	80	20	0.0833
Lithium Battery	400	100	8
Sodium Sulphur Battery	75	300	8
Lead Acid Battery	80	100	8
Compressed Air Storage	6	1000	30
Redox Flow Battery	70	100	8
Nickel Cadmium Battery	150	100	8

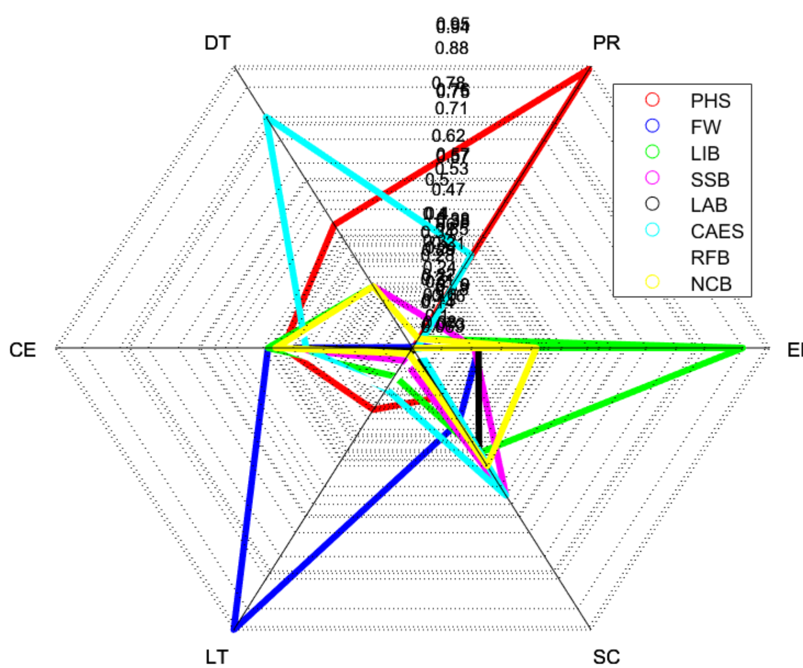


Figure 7.1: Spider Graph

Pumped Hydro Storage(PHS),Flywheel Battery(FW),Lithium-Ion Battery(LIB),Sodium

Sulphur Battery(SSB),Lead Acid Battery(LAB),Compressed Air Energy Storage(CAES), Redox Flow Battery(RFB) and Nickel Cadmium Battery(NCB) are used as alternatives for the MCDM problem. Energy Density(ED),Power Rating(PR),Discharge Time(DT), Lifetime(LT),Cycle Efficiency(CE) and Specific Cost (SC) are the criteria for alternative selection algorithm. Figure 7.1 displays the Radar Chart of criteria weights. This is the pictorial representation of evaluation matrix.

Table 7.2: Parameters Used for Energy Storage Device Selection using MCDM method

Alternatives	Cycle Efficiency (Percentage)	Lifetime (Cycles)	Specific cost $ per KWh
Pumped Hydro storage	85	21900	165
Flywheel Battery	95	100,000	250
Lithium Battery	95	10,000	356
Sodium Sulphur Battery	85	4500	500
Lead Acid Battery	90	1000	356
Compressed Air Storage	70	14600	500
Redox Flow Battery	85	14000	25
Nickel Cadmium Battery	150	2000	400

Three cases are defined for MCDM solutions using TOPSIS, PROMETHEE, and VIKOR algorithms by using the different weighting methodologies and assigning the beneficial and non-beneficial according to the relevant criteria. These three tabulations are developed in order to assess the algorithm's accuracy and consistency. Tabulation for three different cases is as follows.

Weights play a critical role in decision making as the outcome is dependent on the choice of the stakeholder. Determining criteria weights is a wicked problem faced by many MCDM methods. The weighting methods can be classified as Subjective and Objective weighting methods

Subjective weighting methods: Criterion weights are set based on decision-makers preferences. The most common type of subjective weighting methods used are Entropy Weighing Method and Pairwise Comparison Analysis (PCA) method where each criterion is compared with other on a scale of 1 to 9 (least significant to most significant). Some of the drawbacks of these methods include time consuming, problem with consistency and becomes complex when there are large number of criterions. To over come these issues, scales have been introduced.

Table 7.3: Weight and Preference (Beneficial/ Non-Beneficial)- Technical Parameters (Equal Weight Values)

SL No.	Parameter /Criteria	Weight	Beneficial/Non-Beneficial
1	Energy Density	.1667	1
2	Power Rating	.1667	1
3	Discharge Time	.1667	1
4	Cycle Efficiency	.1667	1
5	Lifetime	.1667	1
6	Specific Cost	.1667	-1

Objective weighting methods: Criterion weights are set based on mathematical methods and are used when the number of criteria is large or when there is no information from the decision maker, or the information is insufficient to make a judgement. The most common objective weighting method is Mean Weight method. The mean weight method distributes weights equally among all criterions.

Case 1: Mean weight method is used for determining the weight of the criterion and the weights are assigned as shown in the table 7.3. Equal weight values are assigned and preference(beneficiary/non-beneficiary) are assessed. The cost is minimised by considering -1 and the other criteria are maximised by considering 1.

Table 7.4: Weight and Preference (Beneficial/ Non-Beneficial)- Technical Parameters (Random Weight Values)

SL No.	Parameter /Criteria	Weight	Beneficial/Non-Beneficial
1	Energy Density	0.1697	1
2	Power Rating	0.1718	1
3	Discharge Time	0.1498	1
4	Cycle Efficiency	0.1660	1
5	Lifetime	0.1722	1
6	Specific Cost	0.1705	-1

Case 2: The entropy weighing method, a subjective weightage method, is used for determining the weights for case 2. The weight values are obtained using the methodology below, and the results are tabulated in 7.4. A standardized value of the ith index is given as,

$$p_{ij} = \frac{r_{ij}}{\sum(r_{ij})}, j = 1, 2..n \tag{7.1}$$

Entropy value is given as,

$$E_i = \frac{\sum_{j=1}^{n} p_{ij}.lnp_{ij}}{lnn}, j = 1, 2..n \tag{7.2}$$

From the entropy value the weight value is calculated given in the previous equation weight values are calculated as follows,

$$w_i = \frac{1 - E_i}{\sum_{i=1}^{m} 1 - E_i}, i = 1, 2..m \tag{7.3}$$

Case 3: Considering choosing the ESS without compromising on the cost, the weightage for the cost is considered as zero and other criteria are given equal weightage as shown in the table 7.5.

Table 7.5: Weight and Preference (Beneficial/ Non-Beneficial)- Technical Parameters (Unequal Weight Values)

SL No.	Parameter /Criteria	Weight	Beneficial/Non-Beneficial
1	Energy Density	.2	1
2	Power Rating	.2	1
3	Discharge Time	.2	1
4	Cycle Efficiency	.2	1
5	Lifetime	.2	1
6	Specific Cost	0	- 1

4 kinds of normalization algorithms are used to test the accuracy of the results and 3 cases with weight variations are used to test the result variations of the MCDM methods. MATLAB based models are developed for the formulated problem. The weights and the MM(Beneficial or Non-beneficial) values for the implementation are

considered as stated in the three cases above. The first step is to normalize with 4 different techniques. Min-max normalization is one of the most common ways to normalize the data. For every feature, the minimum value of that feature gets transformed into a 0, the maximum value gets transformed into 1, and every other value gets transformed into a decimal between 0 and 1. In Sum normalisation, each value in a row is divided by the total sum of the row and multiplied by 100. Vector Normalisation is to take a vector of any length and, keeping it pointing in the same direction, change its length to 1, turning it into what is called a unit vector.

7.2 Energy Storage System Selection using TOPSIS

All the steps defined for TOPSIS algorithm are applied and the output of the TOPSIS algorithm is obtained in the form of "Q" values tabulated in Table 7.6. Then intensity values are obtained from the "iQi" values, which defines the participation of the alternative to a particular rank. These values are used to find the percentage contribution of alternatives towards the ranks and drawn as percentage contribution graphs. The procedure is standard for all three algorithms. Table 7.7 shows the intensity of alternatives for all the normalization methods in the TOPSIS method. It can be observed that both Q and the intensity values are sorted in descending order. Higher the values in iQi table more is the affiliation of the alternative towards higher rank. Rank values are obtained according to the intensity values. The tables tabulate the values obtained from all the four normalization methods. The cumulative intensity value is the ratio of individual "iQi" value to the sum of "iQi" values of all alternatives in that specific rows. This ratio is converted to a percentage value by multiplying with 100. Alternatives and their ranks are represented in the Table 7.9 considering 3 different cases. The graphs show only the first three ranks since the importance of other ranks will be residual. MCDM methods provide the percentage contribution of each alternative to the specific rank.

Table 7.6: Q Value with tuned beneficial non beneficial criteria

	Max	Sum	Max-Min	Vector
Case1	0.4965	0.4317	0.4513	0.5648
Case2	0.4974	0.4311	0.4518	0.5656
Case3	0.4435	0.4556	0.4390	0.5315
Case1	0.3971	0.4129	0.4353	0.4291
Case2	0.3978	0.4128	0.4252	0.4347
Case3	0.4079	0.3656	0.4017	0.4609
Case1	0.3331	0.4034	0.4144	0.4279
Case2	0.3331	0.3940	0.4135	0.4281
Case3	0.4047	0.2852	0.2932	0.4159
Case1	0.2888	0.3128	0.3183	0.3992
Case2	0.2878	0.3196	0.3256	0.3909
Case3	0.3940	0.2834	0.2868	0.2387
Case1	0.2709	0.2438	0.2758	0.3554
Case2	0.2626	0.2429	0.2752	0.3554
Case3	0.2967	0.1473	0.1621	0.2309
Case1	0.2051	0.2092	0.2399	0.3283
Case2	0.2051	0.2076	0.2385	0.3273
Case3	0.2677	0.1445	0.1596	0.2105
Case1	0.1540	0.1519	0.1790	0.2659
Case2	0.1624	0.1499	0.1770	0.2641
Case3	0.1375	0.1434	0.1561	0.2073
Case1	0.1214	0.1143	0.1187	0.1495
Case2	0.1194	0.1126	0.1168	0.1475
Case3	0.1373	0.0976	0.1138	0.1883

Table 7.7: Intensity of Alternatives (iQ(i))

	Max	Sum	Max-Min	Vector
Case1	21.9028	18.9324	18.5516	19.3433
Case2	21.9539	18.9876	18.6429	19.4132
Case3	17.8181	23.6972	21.8155	21.3975
Case1	17.5185	18.1100	17.8919	14.6942
Case2	17.5577	18.1819	17.5443	14.9204
Case3	16.3876	19.0138	19.9619	18.5564
Case1	14.6945	17.6932	17.0366	14.6535
Case2	14.7026	17.3551	17.0606	14.6924
Case3	16.2598	14.8338	14.5721	16.7432
Case1	12.7403	13.7186	13.0852	13.6698
Case2	12.7013	14.0759	13.4350	13.4158
Case3	15.8266	14.7391	14.2511	9.6096
Case1	11.9504	10.6942	11.3386	12.1709
Case2	11.5905	10.6970	11.3554	12.1983
Case3	11.9177	7.6632	8.0569	9.2943
Case1	9.0480	9.1765	9.8614	11.2438
Case2	9.0545	9.1428	9.8393	11.2331
Case3	10.7534	7.5153	7.9313	8.4737
Case1	6.7917	6.6633	7.3567	9.1049
Case2	7.1690	6.6026	7.3030	9.0655
Case3	5.5228	7.4605	7.7560	8.3467
Case1	5.3538	5.0118	4.8781	5.1196
Case2	5.2704	4.9571	4.8195	5.0613
Case3	5.5140	5.0772	5.6552	7.5786

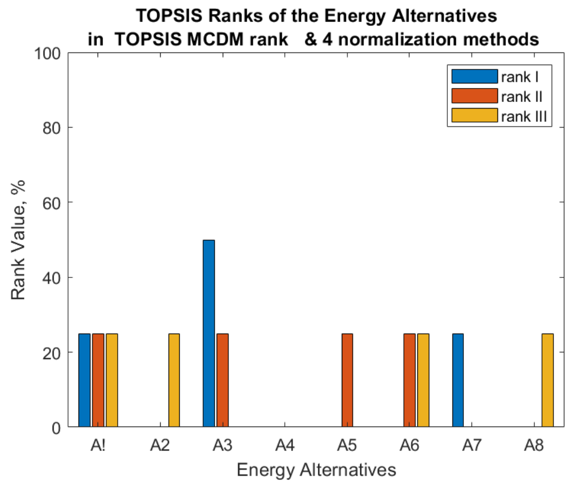
Table 7.8: Alternatives Obtained for each rank with Different Normalization Algorithm for tuned criteria

	Max	Sum	Max-Min	Vector
Case1	7	1	3	3
Case2	7	1	3	3
Case3	5	1	1	3
Case1	5	3	6	1
Case2	5	3	6	2
Case3	4	3	3	1
Case1	8	6	1	2
Case2	8	6	1	1
Case3	7	2	6	2
Case1	4	2	2	6
Case2	4	2	2	6
Case3	8	6	2	8
Case1	2	4	4	4
Case2	2	4	4	4
Case3	6	7	8	6
Case1	1	8	8	8
Case2	1	8	8	8
Case3	2	4	7	7
Case1	6	5	5	5
Case2	6	5	5	5
Case3	3	8	4	4
Case1	3	7	7	7
Case2	3	7	7	7
Case3	1	5	5	5

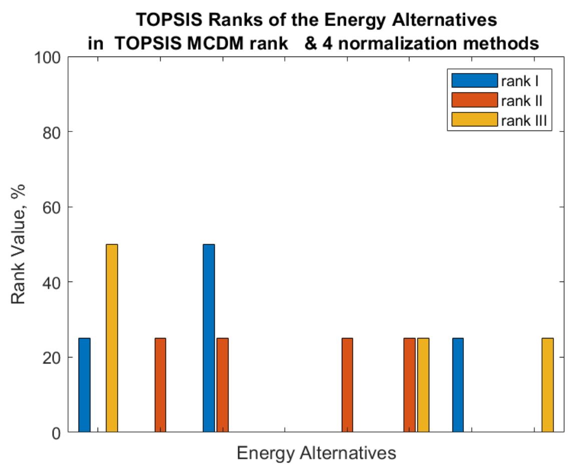
Table 7.9: TOPSIS method results

Rank	Case1	Case2	Case3
Rank1	A3	A3	A1
Rank2	A1	A2	A3
Rank3	A1	A1	A2
Rank4	A2	A2	A8
Rank5	A4	A4	A6
Rank6	A8	A8	A7
Rank7	A5	A5	A4
Rank8	A7	A7	A5

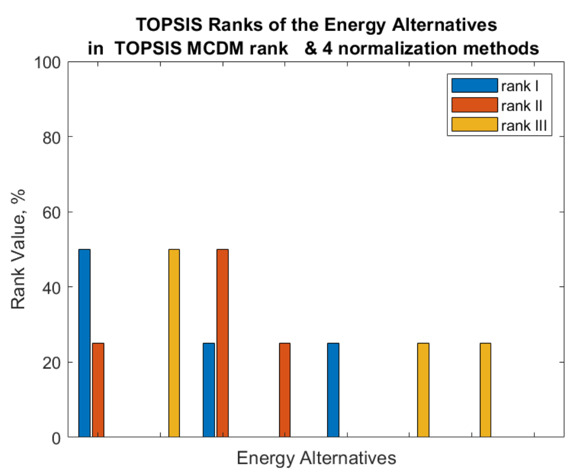
The ranks are represented in the form of Bar charts. Rank1 is the "Blue" bar, "Red" is Rank2, and "Yellow" is Rank3. The amplitude of these bars is higher for the alternatives corresponding to the higher rank. Figure 7.2 depicts the percentage contribution graphs for each alternative towards the top three ranks. It can be observed that the alternative "A3", which is Lithium battery is assigned with the first rank for all three cases. Although the first alternative is chosen unanimously from the different normalization techniques for other alternatives, the decision is not distributed accurately for subsequent ranks. It can be inferred from the analysis that the alternatives vary for each criteria change and weight change for the TOPSIS-based implementation. TOPSIS method output infers that the contribution of the alternatives to the individual rank is not distinguishable from the rank table. Except for the top ranks, the alternative's contribution to the following rank is not distinct. Although the first rank alternative is getting the unambiguous mandate, the preceding ranks are not getting the precise mandate. While different normalization methods are used they did not provide consistent outputs hence TOPSIS method is less confident in decision making for the lower ranks in this particular analysis.



(a) Percentage contribution of alternatives Case1



(b) Percentage contribution of alternatives Case2



(c) Percentage contribution of alternatives Case3

Figure 7.2: TOPSIS Results

Figure 7.2 shows the results obtained for the TOPSIS implementation for all the three cases considered data. It can be observed that the same rank is given to more than one alternative, which is calculated by finding the percentage of a particular alternative's intensity values from the total intensity of all the alternatives. TOPSIS gives consistent output for top ranks, but for lower rank alternatives, the output is not completely distinguished towards a particular alternative.

7.3 Energy Storage System Selection Using PROMETHEE

PROMETHEE algorithm is based on outranking. By varying the weights of the criteria as defined in 3 cases, the outputs obtained from the PROMETHEE method are shown in the following tables for all the normalization methods. The steps defined for PROMETHEE in the previous chapter are applied and the output values of Q are calculated which are tabulated in Table 7.10. The output value from the PROMETHEE algorithm is termed "Q,". Intensity values are again found from the iQi values as shown in the Table 7.11. Percentage contribution graphs for all the three cases are given in Figure 7.3.

From the above Table 7.12 it can be observed that the decision-making from the PROMETHEE algorithm either produces the complete mandate or a mandate which is a tie between two alternatives when assessed from the different normalization techniques. All the three cases that are discussed in Section 7.1 are repeated for the PROMETHEE method, and the results are obtained. The percentage contribution of alternatives to the highest three ranks is shown in the bar charts. It can be observed that the PROMETHEE method provides a clear mandate to the first alternative from Table 7.12. The rest of the alternatives do not have a clear mandate for the particular rank.

The rank values obtained for the top alternatives are "one-sided" in nature, while the decision on the lower ranks is not giving a clear mandate for all the three cases considered.

Table 7.10: Q Value with tuned beneficial non beneficial criteria

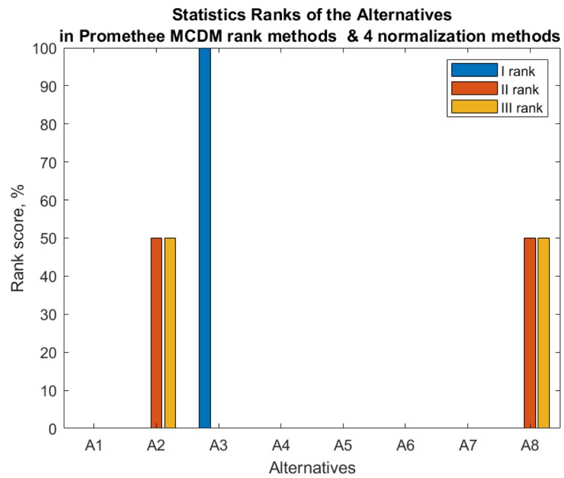
	Max	Sum	Max-Min	Vector
Case1	3.3177	3.4000	3.0701	3.0687
Case2	1.9941	1.6508	1.7538	1.7872
Case3	1.7680	1.8000	1.5455	1.5447
Case1	2.7817	2.4095	1.8766	2.2586
Case2	1.4454	1.3478	1.1827	1.1818
Case3	1.4200	1.0219	1.2012	1.2707
Case1	2.5577	2.1810	1.8589	2.2302
Case2	1.0953	1.3288	1.1760	1.0330
Case3	0.5383	0.8095	0.7159	0.5137
Case1	1.1777	1.2095	1.0414	1.1288
Case2	0.2985	0.1484	0.2143	0.1635
Case3	0.1473	0.3721	-0.0113	0.2754
Case1	0.6009	1.1810	0.9538	1.0369
Case2	-0.6045	-0.0257	-0.4719	-0.0993
Case3	-0.2118	-0.2571	-0.1631	-0.4406
Case1	-1.4357	-1.4905	-1.2715	-1.2211
Case2	-0.9968	-0.7310	-0.8576	-0.7653
Case3	-1.0896	-0.6634	-0.8687	-0.7600
Case1	-3.7820	-3.7143	-3.3183	-3.6570
Case2	-1.0879	-1.3459	-1.0260	-1.3920
Case3	-1.2225	-1.4658	-1.1477	-1.1981
Case1	-5.2180	-5.1762	-4.2109	-4.8451
Case2	-2.1441	-2.3733	-1.9712	-1.9090
Case3	-1.3496	-1.6171	-1.2718	-1.2057

Table 7.11: Intensity of Alternatives (iQ(i))

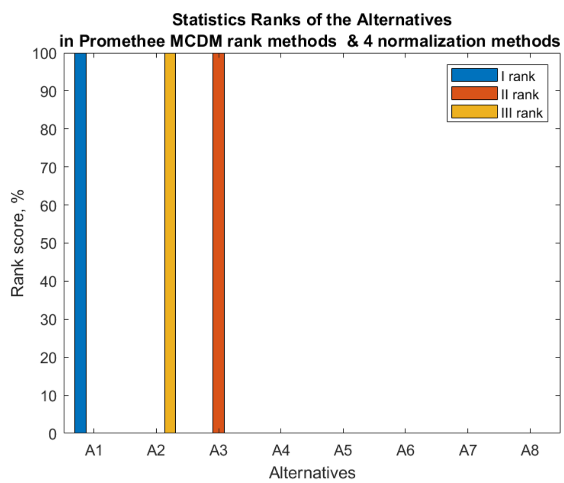
	Max	Sum	Max-Min	Vector
Case1	20.4477	20.7107	21.6136	20.4170
Case2	24.1256	21.1949	23.6211	24.2025
Case3	28.8751	26.4137	27.6903	28.5138
Case1	19.1638	18.3188	18.0706	18.3271
Case2	20.9265	19.5988	20.0001	20.2385
Case3	25.6519	20.3989	24.3062	25.6736
Case1	18.6271	17.7668	18.0181	18.2538
Case2	18.8853	19.4986	19.9573	19.2636
Case3	17.4856	18.7575	19.5363	17.8255
Case1	15.3212	15.4209	15.5914	15.4122
Case2	14.2404	13.2816	13.8588	13.5706
Case3	13.8642	15.3761	12.3893	15.3554
Case1	13.9395	15.3519	15.3313	15.1750
Case2	8.9757	12.3649	9.5076	11.8501
Case3	10.5381	10.5124	10.8968	7.9320
Case1	9.0608	8.9006	8.7256	9.3495
Case2	6.6887	8.6499	7.0616	7.4892
Case3	2.4081	7.3721	3.9615	4.6206
Case1	3.4400	3.5304	2.6496	3.0652
Case2	6.1577	5.4114	5.9935	3.3855
Case3	1.1770	1.1693	1.2196	0.0792
Case1	0	0	0	0
Case2	0	0	0	0
Case3	0	0	0	0

Table 7.12: Alternatives Obtained for each rank with Different Normalization Algorithm for tuned criteria

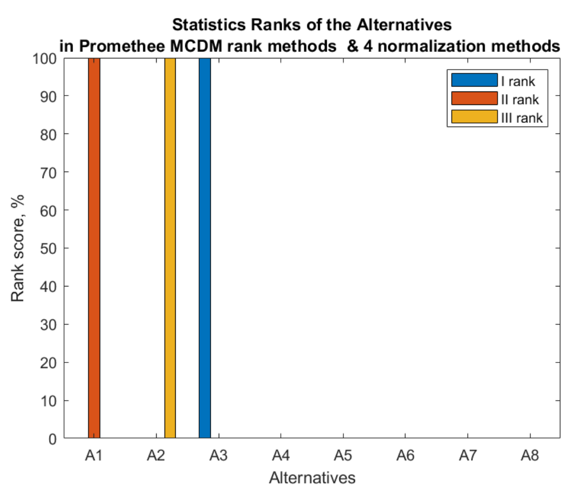
	Max	Sum	Max-Min	Vector
Case1	3	3	3	3
Case2	1	1	1	1
Case3	3	3	3	3
Case1	2	2	8	8
Case2	3	3	3	3
Case3	1	1	1	1
Case1	8	8	2	2
Case2	2	2	2	2
Case3	2	2	2	2
Case1	5	5	4	4
Case2	7	8	7	7
Case3	6	8	6	8
Case1	4	4	5	5
Case2	8	7	8	8
Case3	8	6	8	6
Case1	7	7	7	7
Case2	6	5	5	5
Case3	7	5	5	5
Case1	6	6	6	6
Case2	5	6	6	6
Case3	5	7	7	4
Case1	1	1	1	1
Case2	4	4	4	4
Case3	4	4	4	7



(a) Percentage contribution of alternatives for Case1



(b) Percentage contribution of alternatives for Case2



(c) Percentage contribution of alternatives for Case3

Figure 7.3: PROMETHEE Results

Attributes and its ranks are as given in the Table 7.12 for weight values given equally to all alternatives.

Table 7.13: PROMETHEE method results

Rank	Case1	Case2	Case3
Rank1	A3	A1	A3
Rank2	A2	A3	A2
Rank3	A2	A2	A2
Rank4	A4	A7	A4
Rank5	A4	A8	A4
Rank6	A7	A5	A7
Rank7	A6	A6	A6
Rank8	A1	A4	A1

PROMETHEE algorithm seems to be working better for choosing the top alternatives, while for the lower ranks, their results are not-satisfactory. Although consistency is found for the alternative selection, the consistency to give the same output for all normalization techniques is less. This nature of both TOPSIS and PROMETHEE methods reckons a new progressive algorithm to be considered for the ESS selection MCDM solution.

7.4 Energy Storage System Selection using VIKOR

VIKOR method is implemented for all the three cases that are defined in the Section 7.1. With the defined parameter values the VIKOR method is implemented to determine the best alternative from the set of 8 alternatives chosen for MCDM analysis. The iterative process of finding the aggregation function and finding the S, R and Q values to decide the hierarchy of the alternatives is applied and the values of S,R,Q are arranged in the increasing order. The methodology of the VIKOR is shown in the flowchart Figure 7.4.

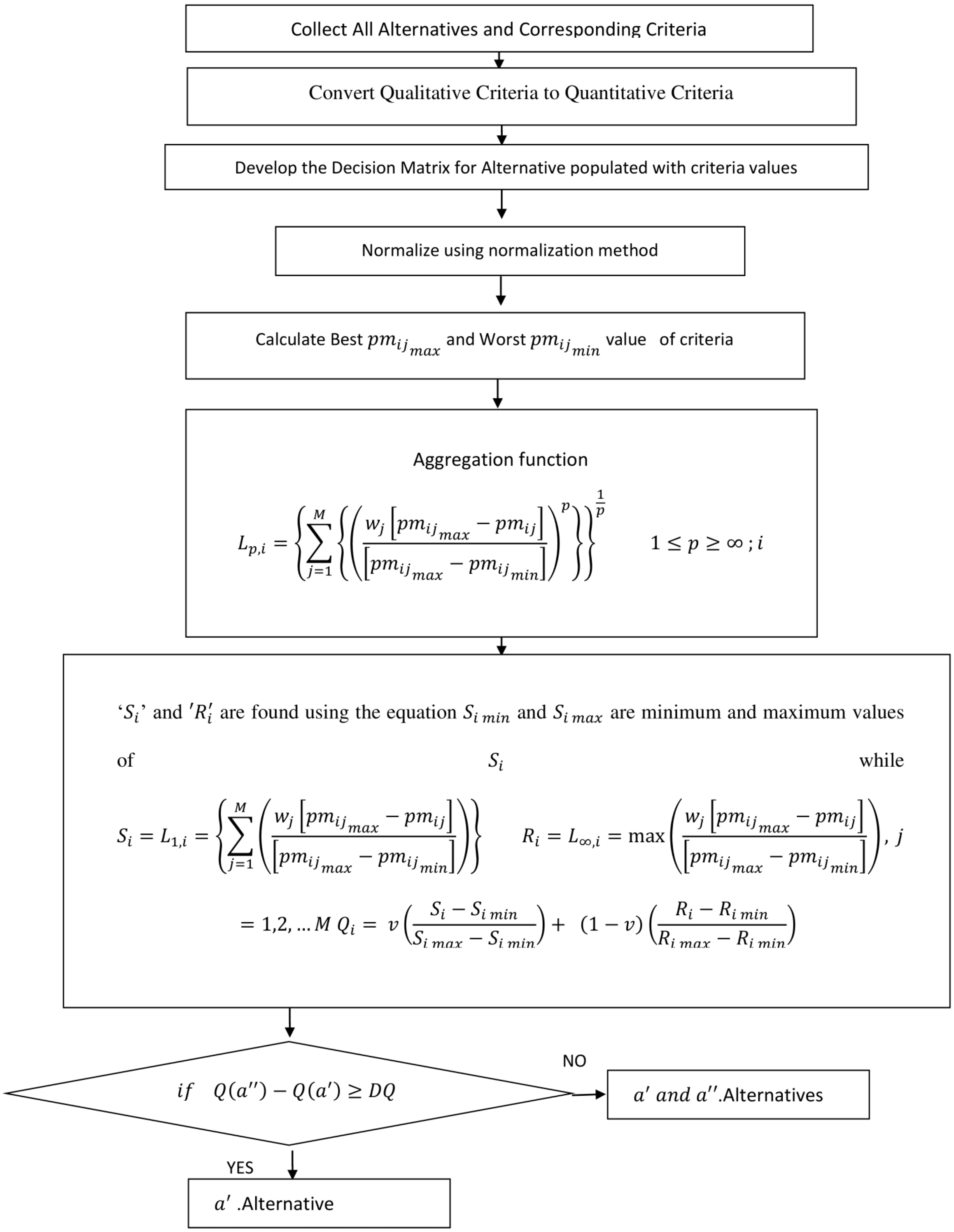


Figure 7.4: VIKOR flowchart

Table 7.14: Q Value with tuned beneficial non beneficial criteria

0.1203	0.1203	0.1203	0.1203
0.2390	0.2390	0.2390	0.2390
0.5735	0.5735	0.5735	0.5735
0.6084	0.6084	0.6084	0.6084
0.6171	0.6171	0.6171	0.6171
0.6596	0.6596	0.6596	0.6596
0.7902	0.7902	0.7902	0.7902
1.0000	1.0000	1.0000	1.0000

Implementation of the VIKOR method for all the cases with different weight values of the criteria is repeated using the methodology represented in the flowchart. Output obtained from all the four normalization methods are analysed and final alternative is selected by voting. The Q values obtained from the Case1 are shown in the Table 7.14. Table 7.15 shows their corresponding intensity values of the alternatives for all the normalization methods in the VIKOR method. The rank obtained from the two conditions of VIKOR method C1: "Acceptable Advantage" and C2: "Acceptable stability in decision making" as given in the formulation section is tabulated in Table 7.16 for Case1. Alternatives and their ranks are given in Table 7.16 for Case1. A consistent rank of each alternative from the different normalization algorithms is found by analyzing the Table 7.16. The cumulative values are calculated for each rank, from the intensity table, to measure the percentage of contribution of each alternative to a specific rank.

Table 7.15: Intensity of Alternatives (iQ(i)) for Equal weight values

Max	Sum	max-Min	Vector
2.6111	2.6111	2.6111	2.6111
5.1866	5.1866	5.1866	5.1866
12.4455	12.4455	12.4455	12.4455
13.2024	13.2024	13.2024	13.2024
13.3912	13.3912	13.3912	13.3912
14.3144	14.3144	14.3144	14.3144
17.1484	17.1484	17.1484	17.1484
21.7004	21.7004	21.7004	21.7004

Table 7.16: Alternatives Obtained for each rank with Different Normalization Algorithm for tuned criteria

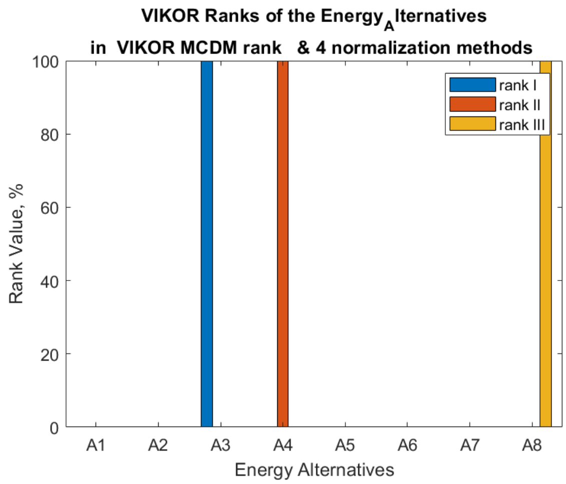
Rank	Max	Sum	max-Min	Vector
1	3	3	3	3
2	4	4	4	4
3	8	8	8	8
4	2	2	2	2
5	1	1	1	1
6	6	6	6	6
7	5	5	5	5
8	7	7	7	7

The graphs obtained are drawn only to the first three ranks since the importance of other ranks will be residual. The results obtained from all the normalisation methods indicate that most of the results have obtained the alternatives A3, A4, and A8 as the best alternatives.

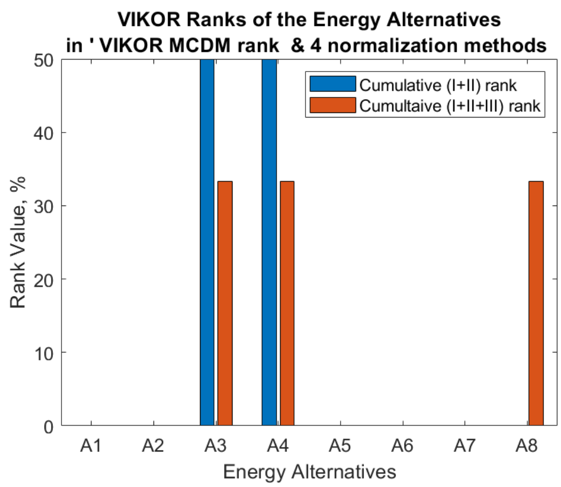
Table 7.17: VIKOR method results

SL No.	Final Best Alternatives(A_i)
1	A3
2	A4
3	A8
4	A2
5	A1
6	A6
7	A5
8	A7

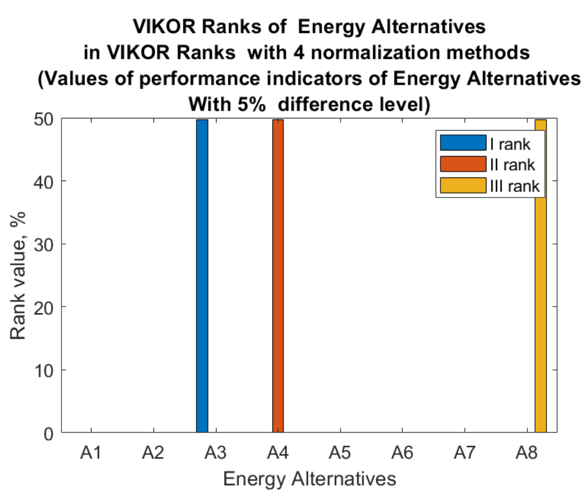
The best ranking hierarchy for the VIKOR method with equal weight values for criteria is shown in the Table 7.17. Since there are multiple occurrences of ranks in Figure 7.5(a), refining of a rank is done by removing the alternatives with less than 5% affiliation in the intensity values, and the refined ranks are as given in Figure 7.5(c), if there is 5% or less variation in the intensity values the ranks are rounded to a same rank. Figure 7.5(b) shows the cumulative rank contribution, which defines an alternative's contribution to the top two ranks accumulated. A similar implementation is applied for all three cases. The output from Case1 clearly indicates that the VIKOR algorithm is accurate in all the normalization algorithms. Unlike the TOPSIS and PROMETHEE algorithms, where the lower ranks did not provide one-sided output, the VIKOR method maps different alternatives for different rank.



(a) Percentage contribution of alternatives (Case1)



(b) Cumulative Rank Contribution percentage



(c) Ranks after refining (5 percent difference values)

Figure 7.5: VIKOR Results(with Equal Weights)

Case 2: Weights are assigned based on Entropy Method : The results for case 2 are as follows

Table 7.18: Q Value with tuned beneficial non beneficial criteria(Entropy Method)

Max	Sum	max-Min	Vector
0.0884	0.0884	0.0884	0.0884
0.2371	0.2371	0.2371	0.2371
0.3130	0.3130	0.3130	0.3130
0.4150	0.4150	0.4150	0.4150
0.5644	0.5644	0.5644	0.5644
0.5733	0.5733	0.5733	0.5733
0.7904	0.7904	0.7904	0.7904
0.8604	0.8604	0.8604	0.8604

Table 7.19: Intensity of Alternatives (iQ(i)) for Entropy Weight values

Max	Sum	max-Min	Vector
2.2998	2.2998	2.2998	2.2998
6.1707	6.1707	6.1707	6.1707
8.1479	8.1479	8.1479	8.1479
10.8019	10.8019	10.8019	10.8019
14.6916	14.6916	14.6916	14.6916
14.9211	14.9211	14.9211	14.9211
20.5723	20.5723	20.5723	20.5723
22.3947	22.3947	22.3947	22.3947

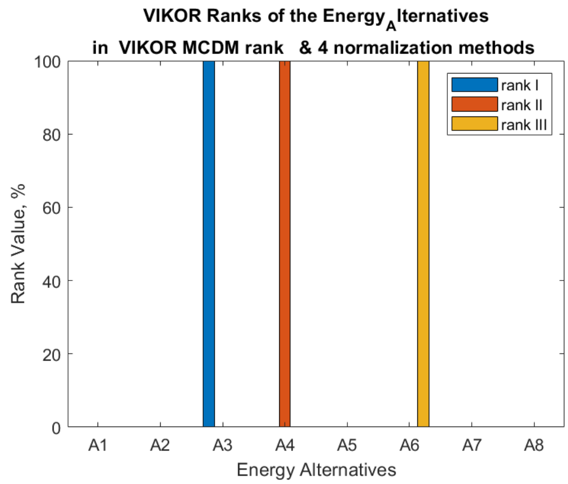
The rank obtained from the VIKOR method is given the formulation section is tabulated in Table 7.20 for "Case2" given to each alternative.

Table 7.20: Alternatives Obtained for each rank with Different Normalization Algorithm for tuned criteria

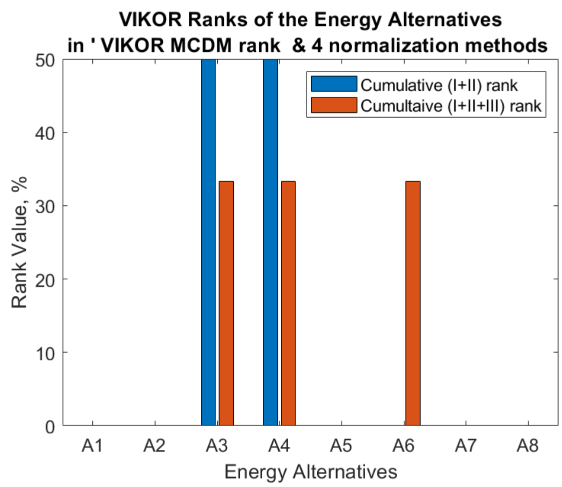
Rank	Max	Sum	max-Min	Vector
1	3	3	3	3
2	4	4	4	4
3	6	6	6	6
4	1	1	1	1
5	2	2	2	2
6	8	8	8	8
7	5	5	5	5
8	7	7	7	7

Table 7.21: VIKOR method results

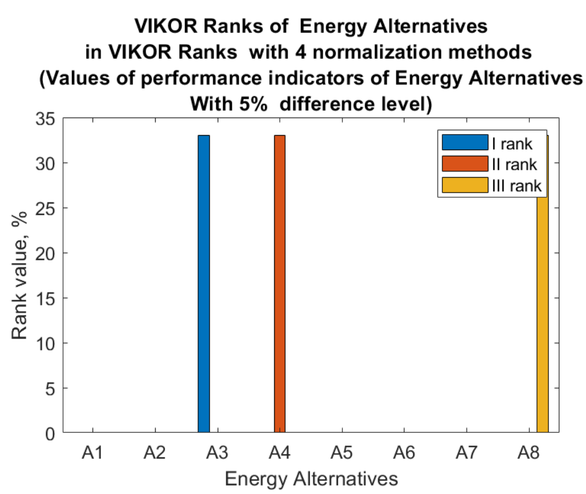
SL No.	Final Best Alternatives(A_i)
1	A3
2	A4
3	A6
4	A1
5	A2
6	A8
7	A5
8	A7



(a) Percentage contribution of alternatives in Ranks(1,2,3)



(b) Cumulative Rank Contribution percentage of alternatives



(c) Ranks after refining (5 percent difference values)

Figure 7.6: VIKOR Results with Entropy based Weights

Results obtained from the VIKOR algorithm for "Case2" are shown in Figure 7.6 with Percentage contributions, cumulative contribution and 5% refined contributions. Following are the outputs obtained for Case 3 of VIKOR method.

Table 7.22: Q Value with tuned beneficial non beneficial criteria

Max	Sum	max-Min	Vector
0.1203	0.1203	0.1203	0.1203
0.5000	0.5000	0.5000	0.5000
0.5163	0.5163	0.5163	0.5163
0.5770	0.5770	0.5770	0.5770
0.6136	0.6136	0.6136	0.6136
0.7343	0.7343	0.7343	0.7343
0.8758	0.8758	0.8758	0.8758
0.9543	0.9543	0.9543	0.9543

Table 7.23: Intensity of Alternatives (iQ(i)) for cost weighting Zero

Max	Sum	max-Min	Vector
2.4599	2.4599	2.4599	2.4599
10.2218	10.2218	10.2218	10.2218
10.5549	10.5549	10.5549	10.5549
11.7957	11.7957	11.7957	11.7957
12.5433	12.5433	12.5433	12.5433
15.0114	15.0114	15.0114	15.0114
17.9039	17.9039	17.9039	17.9039
19.5090	19.5090	19.5090	19.5090

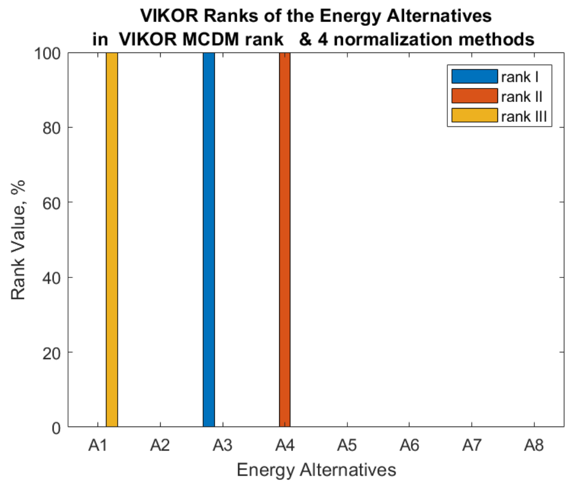
Table 7.23 shows the intensity of alternatives for all the normalization methods in the VIKOR method.

Table 7.24: Alternatives Obtained for each rank with Different Normalization Algorithm for tuned criteria

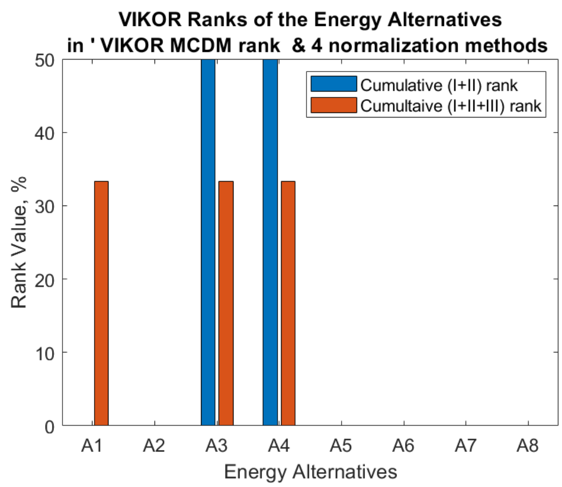
Rank	Max	Sum	max-Min	Vector
1	3	3	3	3
2	4	4	4	4
3	1	1	1	1
4	2	2	2	2
5	7	7	7	7
6	8	8	8	8
7	6	6	6	6
8	5	5	5	5

Table 7.25: VIKOR method results

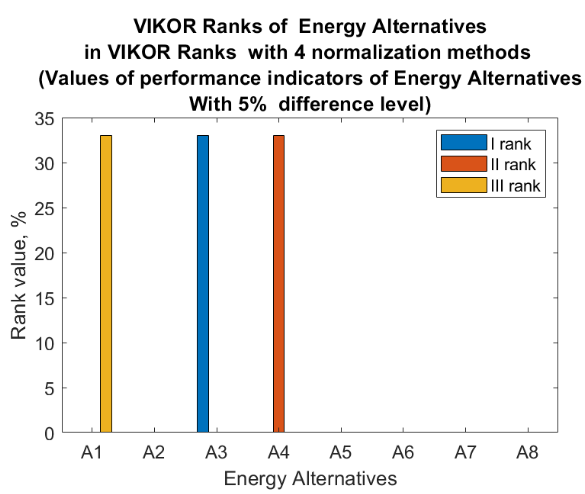
SL No.	Final Best Alternatives(A_i)
1	A3
2	A4
3	A1
4	A2
5	A7
6	A8
7	A6
8	A5



(a) Percentage contribution of alternatives in Ranks(1,2,3)



(b) Cumulative Rank Contribution percentage of alternatives



(c) Ranks after refining (5 percent difference values)

Figure 7.7: VIKOR Results with specific cost weighing zero

VIKOR index values(Q) are obtained from four normalization algorithm for Case3 are shown in the Table 7.22. The ranks obtained from the VIKOR method are shown in Table 7.25. The results obtained from Case3 are shown in Figure 7.7. From the analysis of the results from all the cases it can be observed that "Lithium Battery" is the best ESS alternative.

Table 7.26: VIKOR method results all Cases

Rank	Case1	Case2	Case3
Rank1	A3	A3	A3
Rank2	A4	A4	A4
Rank3	A6	A6	A1
Rank4	A1	A1	A2
Rank5	A2	A2	A7
Rank6	A8	A8	A8
Rank7	A5	A5	A6
Rank8	A7	A7	A5

When different normalization methods are used, the VIKOR method gives a clear mandate with more votes to the relevant rank than the TOPSIS method. Although PROMETHEE methods give the rank output that distinguishes the alternative for top ranks, the outputs for other ranks have oscillations while selecting other ranks.

CHAPTER 8: Conclusion

Marine Renewable Energy installation uses different ESS for energy management. Considering different alternatives of ESS, MCDM selection models are developed. The literature survey of different ESS alternatives and their performance parameters is carried out to obtain the input for the MCDM implementation. Collected data for the alternatives and their criteria researching various publications and are used to generate the decision matrix. MCDM algorithms are evaluated in three different scenarios to validate the variations in the output. Max, sum, min-max, and vector normalization techniques are used on the decision matrix to validate TOPSIS, PROMETHEE, and VIKOR methods.

VIKOR over PROMETHEE: Although each method provided the solution to the problem, upon evaluation of robustness and consistency, the VIKOR method performed the best. PROMETHEE gave a clear mandate to only the first best alternative with different normalization methods but found inconsistency in the selection of other rank alternatives. VIKOR method gave precise results for all the normalization methods compared to other MCDM methods. Irrespective of the ranks, the VIKOR method gave a clear mandate for selecting alternatives for all ranks(A7-A1).

VIKOR over TOPSIS: It is observed that the VIKOR method's outputs are distinguishable compared to the TOPSIS method when each alternative's contribution and its correspondence to each rank is calculated. Also, there is the repetition of alternatives in the results for TOPSIS, which makes it challenging to decide on the least good alternatives. While different sampling methods are used, the VIKOR method gives a clear mandate with more votes to every rank than the TOPSIS method. Decision-making of all the alternatives and deciding their ranks has more confidence through the VIKOR method when compared to the TOPSIS and PROMETHEE methods.

Overall performance of the VIKOR method is found to be dominating and transparent in decision making. Testing for robustness with different normalization method showed that VIKOR method gave a clear mandate to every rank. While PROMETHEE and TOPSIS selected same alternative for more than one ranks. To check consistency of the MCDM algorithm multiple cases are selected which highlighted the economical performance and also that highlighted the technological performance of alternatives. VIKOR performed well for all the cases. The final results obtained by the MCDM technique are the average of the results obtained from all the 3 cases of VIKOR. The final order of importance is A3>A4>A8>A2>A1>A6>A5>A7. Lithium ion battery bearing Rank 1, Rank 2 - Sodium Sulphur battery, Rank 3 - Nickel Cadmium Battery, Rank 4 - Flywheel, Rank 6 - Pumped Hydro, Rank 7 - Lead acid battery Rank 8 - Redox Flow Battery. The ranking holds good even when the criteria are evaluated manually on the basis of the advantages and disadvantages of the alternatives.

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