energies

Article

Multi-Criteria Decision-Making Approach for Optimal Energy Storage System Selection and Applications in Oman

Zayid M. Al-Abri [1], Khaled M. Alawasa [1,2,*], Rashid S. Al-Abri [3], Amer S. Al-Hinai [1] and Ahmed S. A. Awad [1]

[1] Department of Electrical and Computer Engineering, Sultan Qaboos University, P.O. Box 33, Muscat 123, Oman; s66415@student.squ.edu.om (Z.M.A.-A.); hinai@squ.edu.om (A.S.A.-H.); a.awad1@squ.edu.om (A.S.A.A.)
[2] Department of Electrical Engineering, Faculty of Engineering, Mutah University, Mutah, AlKarak 61710, Jordan
[3] Department of Electrical and Computer Engineering, College of Engineering and Architecture, University of Nizwa, P.O. Box 33, Birakat AlMouz 616, Oman; r.alabri@unizwa.edu.om
* Correspondence: k.alawasa@squ.edu.om or kmalawasa@mutah.edu.jo

Abstract: This research aims to support the goals of Oman Vision 2040 by reducing the dependency on non-renewable energy resources and increasing the utilization of the national natural renewable energy resources. Selecting appropriate energy storage systems (ESSs) will play a key role in achieving this vision by enabling a greater integration of solar and other renewable energy. ESSs allow for solar power generated during daylight hours to be stored for use during peak demand periods. Additionally, the proposed framework provides guidance for large-scale ESS infrastructure planning and investments to support Oman's renewable energy goals. As the global renewable energy market grows rapidly and Oman implements economic reforms, the ESS market is expected to flourish in Oman. In the near future, ESS is expected to contribute to lower electricity costs and enhance stability compared to traditional energy systems. While ESS technologies have been studied broadly, there is a lack of comprehensive analysis for optimal ESS selection tailored to Oman's unique geographical, technical, and policy context. The main objective of this study is to provide a comprehensive evaluation of ESS options and identify the type(s) most suitable for integration with Oman's national grid using a multi-criteria decision-making (MCDM) methodology. This study addresses this gap by applying the Hesitate Fuzzy Analytic Hierarchy Process (HF-AHP) and Hesitate Fuzzy VIKOR methods to assess alternative ESS technologies based on technical, economic, environmental, and social criteria specifically for Oman's context. The analysis reveals pumped hydro energy storage (PHES) and compressed air energy storage (CAES) as the most appropriate solutions. The tailored selection framework aims to guide policy and infrastructure planning to determine investments for large-scale ESSs and provide a model for comprehensive ESS assessment in energy transition planning for countries with similar challenges.

Keywords: energy storage systems (ESS); renewable energy; multi-criteria decision making (MCDM); pumped hydro energy storage (PHES); Oman power system

Citation: Al-Abri, Z.M.; Alawasa, K.M.; Al-Abri, R.S.; Al-Hinai, A.S.; Awad, A.S.A. Multi-Criteria Decision-Making Approach for Optimal Energy Storage System Selection and Applications in Oman. *Energies* **2024**, *17*, 5197. https://doi.org/10.3390/en17205197

Academic Editor: Nikolaos Koukouzas

Received: 17 August 2024
Revised: 23 September 2024
Accepted: 30 September 2024
Published: 18 October 2024

1. Introduction

The escalating global energy consumption, driven by economic growth, technological advancements, and increased industrialization [1], poses significant challenges in meeting the rising demand. As projected by a recent survey by the International Energy Agency (IEA), energy demand is expected to surge by 25–30% before the end of this decade by 2030 under the Stated Policies Scenario (STEPS) and Announced Pledges Scenario (APS) [2]. Traditional fossil fuels, already facing multiple financial and environmental hurdles, will be extremely strained if they are to fully cover this dramatic increase in energy consumption worldwide.

To help address this daunting challenge of surging energy demand amidst fossil fuel limitations, the International Energy Agency (IEA) strongly advocates for a widespread global transition towards utilizing more renewable energy resources. In IEA models, renewable resources such as wind and solar photovoltaics are forecasted to account for 75–80% of all new energy generation capacities installed by the year 2050 [2]. This enormous shift would require renewable energy to go from a niche contributor currently to a dominant and mainstream supplier of electricity globally in the coming decades. Additionally, underscoring this urgent need to embrace renewables, an analysis by the International Renewable Energy Agency (IRENA) found that non-fossil fuel-based generation must expand radically to reach at least 57% of the overall share to meet the Paris Agreement's widely publicized target of restricting global temperature rise below 2 °C [3].

However, while renewable energy resources offer sustainability benefits over fossil fuels, utilizing these alternative energy supplies poses substantial technological hurdles. Wind, solar, and other renewable energy sources come with unique challenges associated with large-scale grid integration. Most notably, the highly intermittent and intrinsically stochastic availability of natural renewable resources poses risks in properly balancing and controlling renewable energy generation profiles to maintain stability in electricity grids [4,5]. More specifically, the variable nature of solar and wind poses substantial grid management difficulties. Solar photovoltaic output can fluctuate dramatically due to intermittent cloud cover that severely curtails irradiation levels. Similarly, wind turbine generation often suffers from calm periods and seasonal wind variability that yields markedly lower energy. To truly realize the extensive utilization of solar, wind and other renewable options that agencies like the IEA, IRENA, and European Association for Storage of Energy (EASE) advocate as imperative, effective and reliable energy storage systems (ESSs) are crucial to ensure the delicate balance between dynamic renewable power generation and electricity demand can be preserved at all times [6–8].

Energy storage systems (ESSs) play a vital role in enhancing grid stability, facilitating renewable energy integration, and boosting overall energy efficiency. Several studies have explored different ESS technologies and their diverse applications. An extensive review of ESS technologies and their significance in modern energy systems is provided in [9]. The work in [10] focuses on large-scale photovoltaic power plants, underscoring the importance of ESS in balancing supply and demand within solar energy systems. Similarly, ref. [11,12] explore the challenges and opportunities of ESS in microgrid applications, addressing key issues such as scalability and economic viability. In [13], insights into the latest advancements in ESS types and applications are discussed, while [14] offers a numerical and graphical comparison of various storage technologies. Both [10] and [15] present comparative analyses of electrical energy storage systems, highlighting their potential to enhance sustainability in power systems.

Although energy storage systems (ESSs) significantly enhance power system stability, efficiency, and renewable energy integration, their deployment is constrained by several factors, including technological limitations, economic challenges, environmental concerns, and social considerations. The results in [16] indicate that the profit-maximizing size of ESSs is influenced more by technological factors, such as charge/discharge efficiency and self-discharge rates, rather than market price volatility. In [17] a study examines the use of grid-scale battery storage to offset variable generation from combined cycle gas turbines (CCGT) in the UK. The batteries are charged using renewable energy and discharged during periods of high demand. The research compares the life cycle environmental impacts of CCGTs and batteries, revealing that batteries have a much lower global warming potential. If batteries supply 29.1% of the power provided by CCGTs, up to 1.98 million tonnes of CO_2 equivalent emissions could be save.

With aims to contribute towards global climate and sustainability ambitions, the Sultanate of Oman has announced the "Oman 2040 Vision", which outlines the transition plan for the country to invest in clean and sustainable energy resources. Specific national targets established in this strategic plan include reaching 20% renewable energy contribution within the nation's overall energy mix by 2030 and even more ambitiously achieving between 35 and 39% by the year 2040 [18]. This proposed ramp-up in renewable energy integration will help alleviate pressing budgetary pressures on state finances while also promoting environmental sustainability as a national priority. As a reference point, renewable energy resources like solar and wind presently only account for around 6% of the total contracted power generation capacity within Oman's Main Interconnected System (MIS) electricity grid. However, based on the planned renewable projects already in the pipeline, this share is set to exceed 25% rapidly by the year 2027 based on the current progress [19], underscoring the Sultanate's commitment to realizing its vision of sustainability. Also, achieving Oman's decarbonization targets requires expanding renewable energy generation. However, the integration of more solar and wind power poses stability and reliability challenges due to their intermittent availability. Simultaneously, spilling excess renewable power generation over during off-peak electricity demand periods can lead to the detrimental wastage of clean energy resources if robust storage solutions are not implemented in parallel. Consequently, the deployment of cutting-edge and adequately sized ESSs emerges as one of the highest-impact solutions available currently to manage renewable intermittency problems for upgrading the Sultanate of Oman's Main Interconnected System grid infrastructure.

The selection of energy storage systems (ESSs) for sustainable energy development involves complex decision-making due to the wide range of technological options and the need to balance multiple factors. Multi-criteria decision-making (MCDM) approaches have been widely used to address such challenges. For example, MCDM has been applied in diverse fields such as the evaluation of alternative fuel vehicles [20], industrial applications [21], renewable energy site selection [22–24], and the evaluation and selection of energy storage alternatives [25–30]. These approaches help decision-makers assess trade-offs between technical, economic, and environmental criteria, leading to more informed and sustainable choices. Selecting the most suitable energy storage for renewable resource development becomes complex due to varying requirements and implications in different systems, geographical areas, and contexts. To enhance decision-making effectiveness by considering technical, economic, environmental, and social factors, a multiple-criteria decision-making (MCDM) AHP-VIKOR method has been employed in this study. The research aims to study the energy storage requirements in Oman, aligning with the government's vision for renewable resources and the future needs of the MIS. Energy storage alternatives and criteria are determined through literature analysis and expert input, paving the way for a comprehensive evaluation using the AHP-VIKOR method.

To the best of the author's knowledge, this is the first article that addresses the selection of energy storage systems (ESSs) using a multi-criteria decision-making (MCDM) approach, specifically tailored to Oman's context. There is a notable gap in research focused on Oman's unique geographical, technical, and policy landscape. This study fills that gap by providing a comprehensive analysis of ESS options optimized for these factors. The key contributions of this research include:

1. A tailored MCDM approach that incorporates Oman-specific criteria and expert evaluations.
2. An in-depth assessment of ESS technologies in the context of Oman's renewable energy goals and grid infrastructure.
3. A framework for ESS selection that can guide policymakers and energy planners in similar developing economies transitioning to renewable energy.

By focusing on Oman's specific needs and future energy landscape, this study aims to provide actionable insights for implementing effective energy storage solutions to support the country's ambitious renewable energy targets.

2. An Overview of Energy Storage Technologies (Classifications and Characteristics)

In the field of electrical energy storage systems (ESSs), a comprehensive categorization reveals various types, each characterized by distinct attributes. The primary classifications encompass thermal energy storage, mechanical energy storage, chemical energy storage, and electrochemical energy storage. Figure 1 summarizes the article's classification of numerous energy storage topics [12,13].

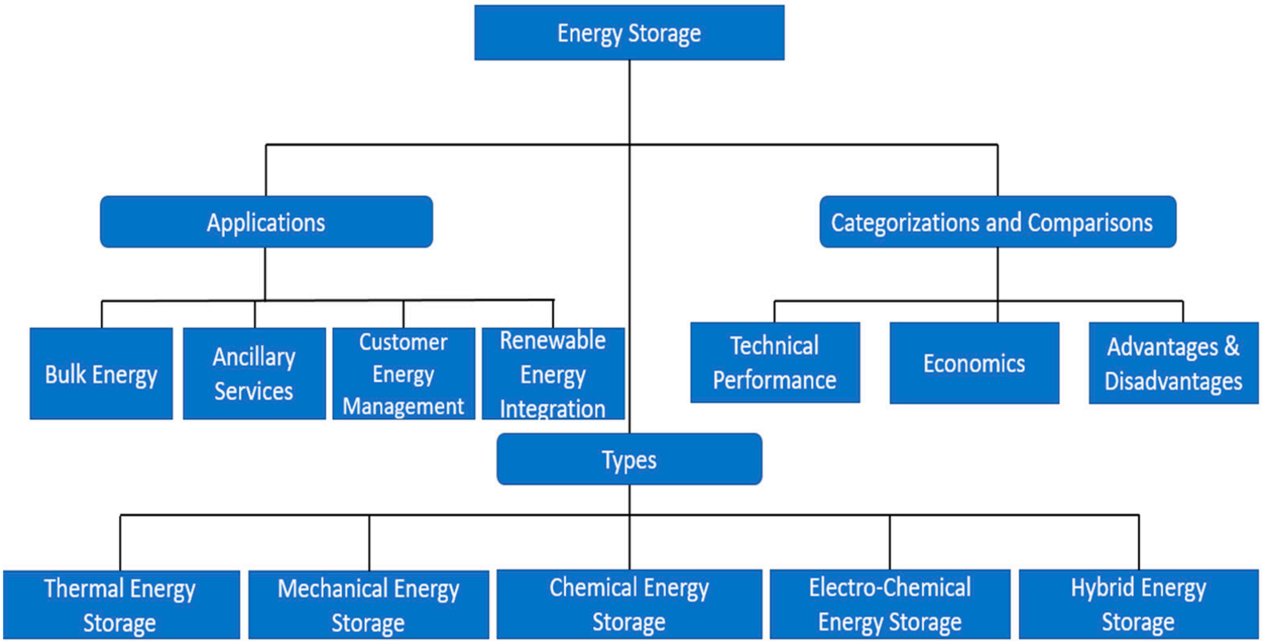

Figure 1. Classifications of numerous energy storage systems.

The diversity of ESSs is elaborated in Figure 2, with each type possessing unique characteristics. Subsequent sections delve into the specifics of each ESS type, elucidating their distinct properties.

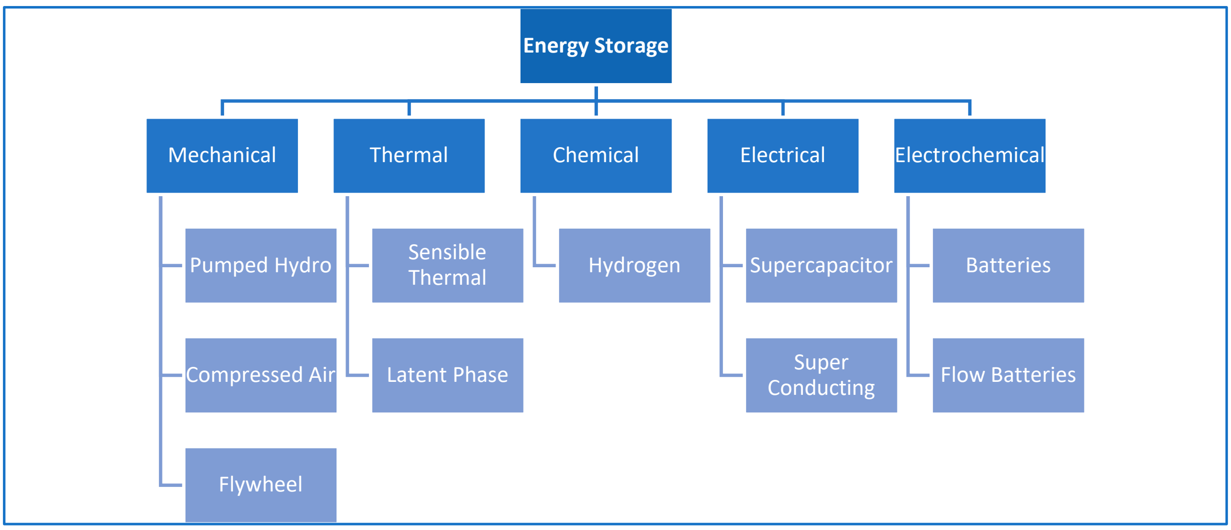

Figure 2. Types of energy storage systems.

3. Oman's Current Power System Overview and Future Electricity Demand

3.1. Electricity Demand

To address the escalating demand for power and water in the Sultanate of Oman, the Oman Power and Water Procurement Company (OPWP), a key entity within the Nama Group, plays a pivotal role in ensuring ample electricity and water capacities at the most economical rates [18]. As the exclusive purchaser of water and electricity for all

Independent Power Producer (IPP) and Independent Water and Power Producer (IWPP) projects, OPWP continuously evaluates electricity demand at the system level, accounting for network losses and consumer-level loads. Analyzing historical demand data from 2013 to 2020 reveals an annual 4% increase in the Main Interconnected System (MIS) peak electricity demand, rising from 4634 MW in 2013 to 6237 MW in 2020. For future planning, OPWP outlines three demand scenarios (expected, low, and high) in its 7-year statement (2021–2027) [19]. Figure 3 illustrates these scenarios, projecting an average annual demand growth of 2%, with peak demand expected to reach 8370 MW by 2027, reflecting an annual average growth of 4%. The low and high case scenarios anticipate peak demand growth rates of 2% and 6%, respectively. To ensure adequate power generation resources, Oman has contracts with power generators, a topic explored in the following section.

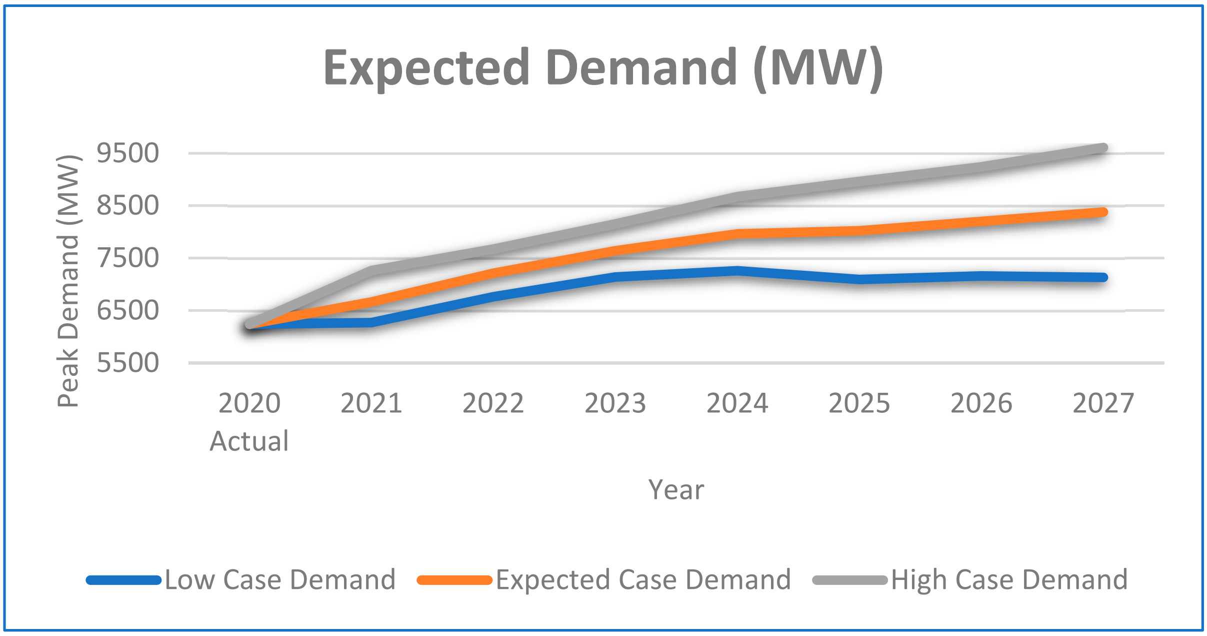

Figure 3. Expected peak demand for the different case scenarios.

Actual power capacity demand data, collected from the Oman Load Dispatch Centre (LDC) for the period from October 2021 to October 2022. The peak demand observed on 26 June 2022, at 15:00 h reached 6775 MW, while off-peak demand occurred on 8 January 2022, at 4:00 h, registering 1891 MW. After excluding the load demand on 5 September 2022, due to a grid blackout (1570 MW), a comparison with the projected peak values reveals a close match with the low case demand of 6760 MW [19]. This aligns with the low-demand curve depicted in Figure 3.

3.2. Power Generation Resources

To meet the burgeoning power demand, OPWP engages in floating, awarding, and executing Power Purchase Agreements (PPAs) with power plant owners in Oman for long-term contracts. Figure 4 and Table 1 showcase the contracted capacity from fossil fuel power plants until 2027, revealing a 28% decrease [18]. Notably, by 2024, several fossil fuel power plants are set to retire, leaving a total contracted capacity of 6823 MW, while the peak demand projection for the same year is 7260 MW, signaling a shortage of 437 MW. Considering OPWP's 7-year statement, which lacks plans for new fossil fuel power plants, the government contemplates addressing this shortfall through renewable energy, a topic explored in the subsequent section.

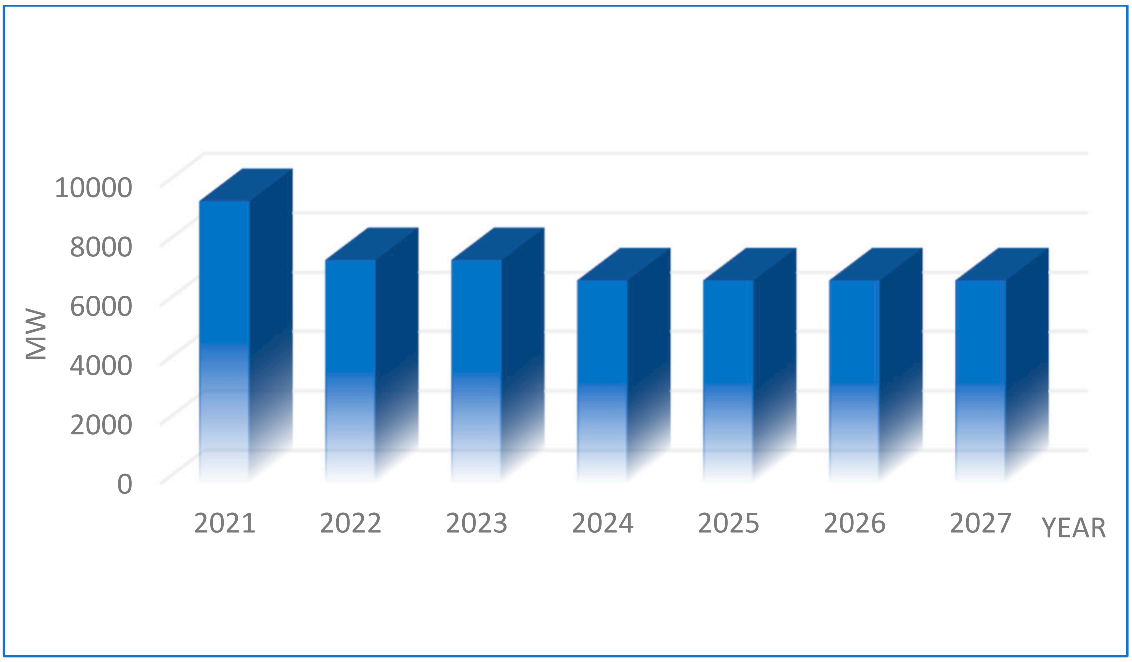

Figure 4. Contracted capacity using fossil fuel power plants.

Table 1. Contracted capacity from 2021 to 2027 [19].

	2021	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**
				Net MW			
Al Kamil IPP	291	-	-	-	-	-	-
Barka IWPP	397	-	-	-	-	-	-
Rusail IPP	694	-	-	-	-	-	-
Sohar IWPP	597	-	-	-	-	-	-
Barka II IPP	688	688	688	-	-	-	-
Sohar II IPP	766	766	766	766	766	766	766
Barka III IPP	766	766	766	766	766	766	766
Sur IPP	2018	2018	2018	2018	2018	2018	2018
Ibri IPP	1537	1535	1535	1535	1535	1535	1535
Sohar III IPP	1741	1738	1738	1738	1738	1738	1738
Total	**9495**	**7511**	**7511**	**6823**	**6823**	**6823**	**6823**

3.3. Renewable Energy Future in Oman

Oman’s commitment to clean and sustainable energy, as outlined in the “Oman 2040 Vision”, targets a 20% renewable energy contribution by 2030 and 35–39% by 2040 [18]. OPWP aligns its plans for the Main Interconnected System (MIS) with this vision, introducing contracted capacity from renewable energy resources. Figure 5 illustrates the expected renewable energy contribution from 2021 to 2027, peaking at 27% in 2027 [19].

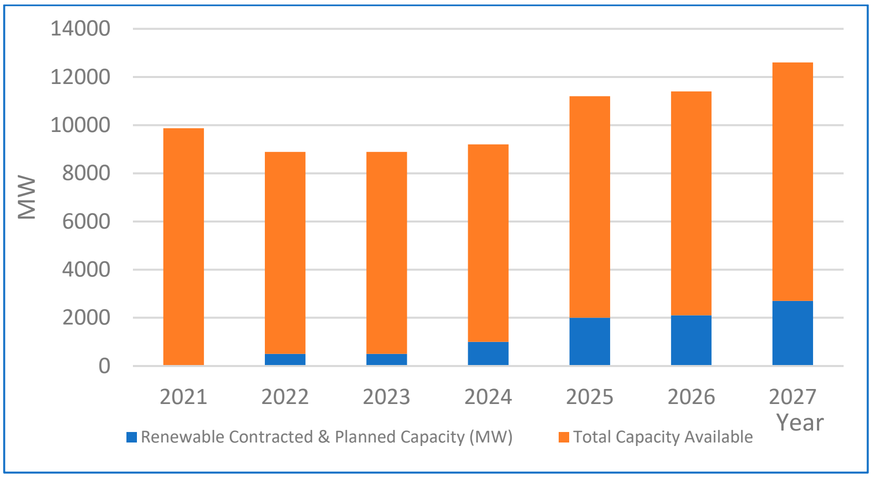

Figure 5. Renewable resources contribution from the total capacity.

As of 2022, renewable energy contributes approximately 6% of the total contracted capacity, with a 500 MW PV solar power plant coming into service. According to OPWP's 7-year statement and Oman's 2040 vision, this percentage is anticipated to exceed 25% by 2027, driven by plans for 2100 MW from PV solar plants and a 100 MW wind power plant in Jalan Bani Bu Ali. The contribution percentages, including energy storage, are detailed in Table 2.

Table 2. Renewable energy percentage contribution on MIS [18].

Year	2021	2022	2023	2024	2025	2026	2027
Non-Renewable Contracted Capacity (MW)	9495	7511	7511	6823	6823	6823	6823
Non-Firm Contracted Capacity (MW)	380	380	380	380	380	380	380
Total Non-Renewable Contracted Capacity (MW)	9875	7891	7891	7203	7203	7203	7203
Renewable Contracted and Planned Capacity (MW)	0	500	500	1000	2000	2100	2700
Total Renewable Capacity Contributions (Contracted and Planned) During Demand Requirement	0	180	180	225	280	330	330
Total Capacity Available	9875	8391	8391	8203	9203	9303	9903
% Renewable Capacity from Total Capacity	0%	5%	5%	12%	21%	22%	27%

Data analysis reveals that Oman's power shortage will predominantly be addressed by solar PV power plants. Figures 6 and 7 illustrate low- and high-demand scenarios, as well as power generation and demand in June, emphasizing the importance of addressing potential power shortages through renewable energy sources, highlighting a need for energy storage systems (ESSs) to secure grid stability.

Figure 8 illustrates the solar power generation at the Ibri Solar PV plant over several days in June 2022. It shows that the generation is not stable throughout the entire day, with some days experiencing significant drops in output power. In some instances, the drop exceeds 85% within minutes. Figure 9 underscores the vulnerability of grid security when relying solely on renewable resources without ESS, as outlined in the existing 7-year plan of the Oman Power and Water Procurement Company (OPWP). The figure shows that the projected load for 2027 exceeds, in certain period, the available generation capacity, highlighting the importance of energy storage systems in meeting the future demand.

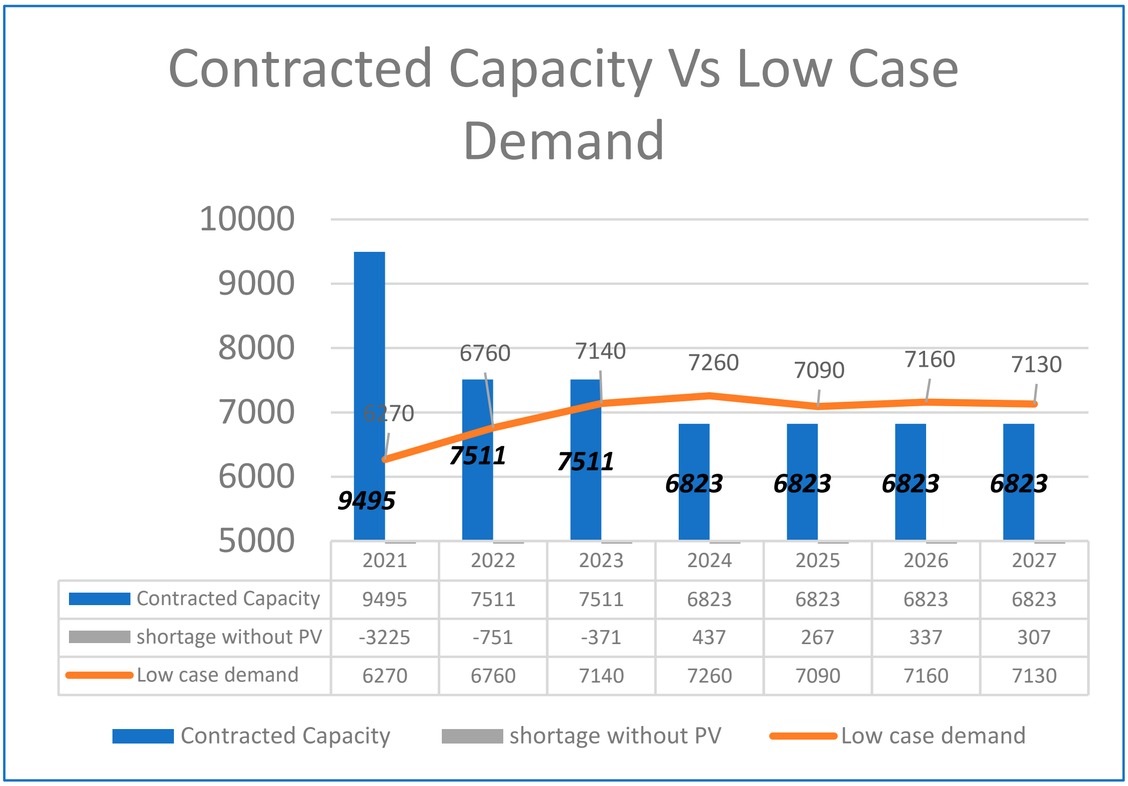

Figure 6. Low case demand and the contracted capacity.

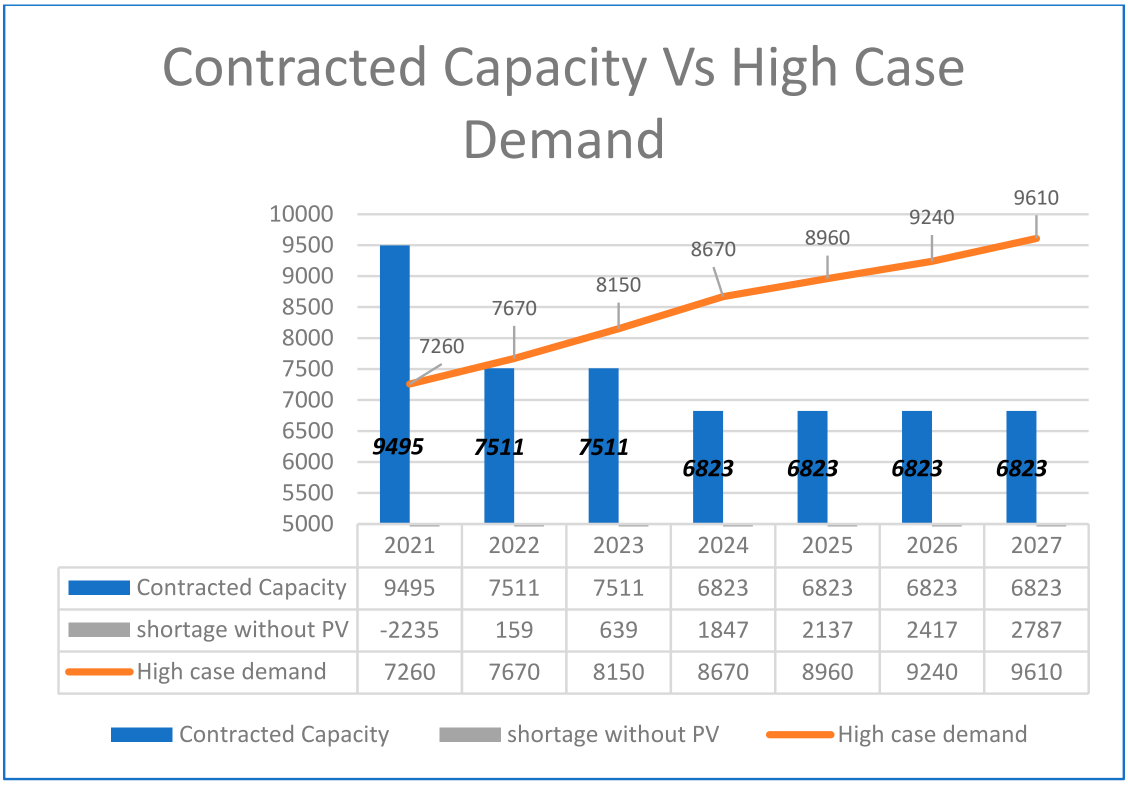

Figure 7. High-case-demand scenario and contracted capacity.

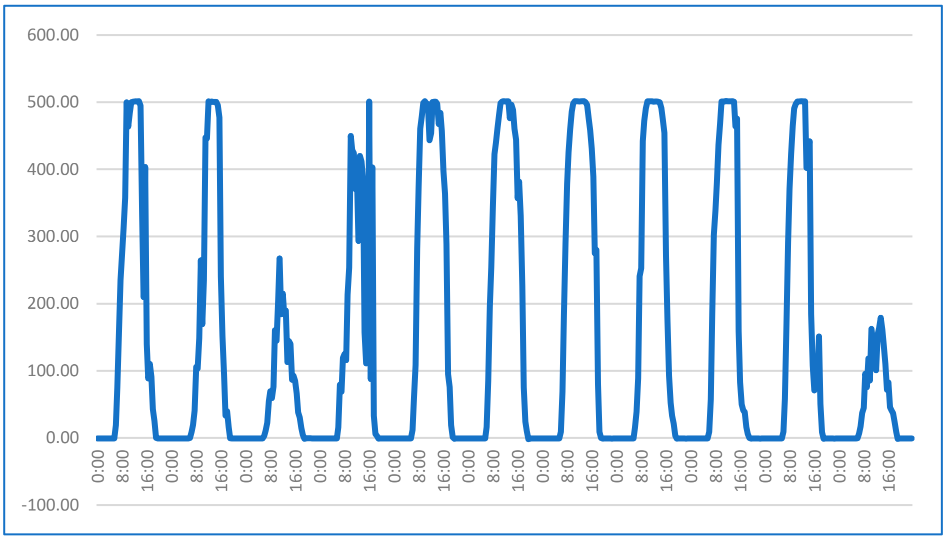

Figure 8. Ibri PV solar power plant generation over a few days in June 2022.

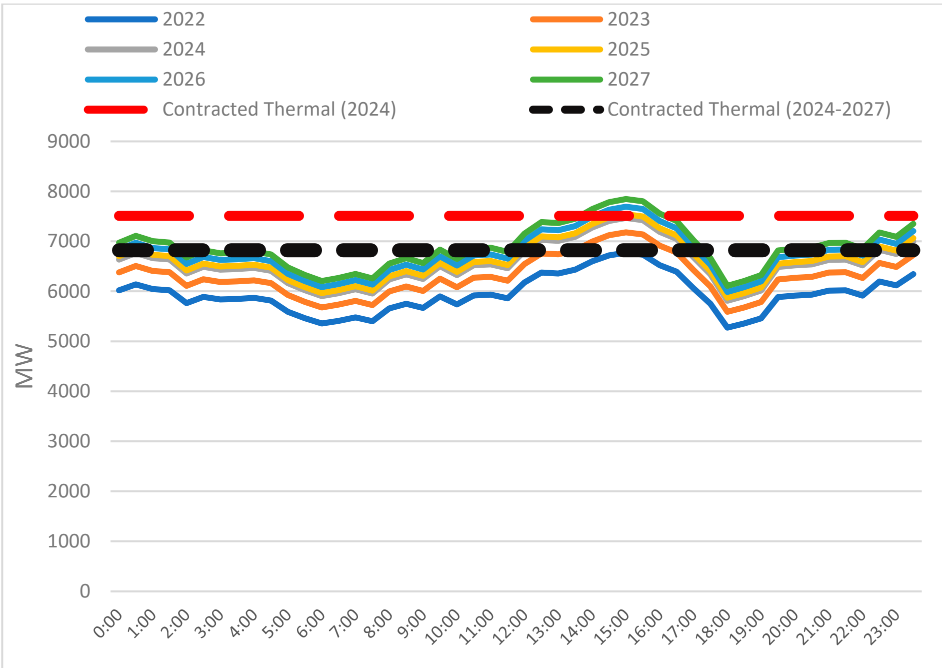

Figure 9. Demand in June for different years vs the contracted capacity.

4. The Need (Motivations) for Energy Storage in Electrical Systems

Energy consumption is rapidly increasing due to technological advancements, industrialization, and economic growth. This surge in electricity demand necessitates additional power generation resources to balance supply and demand. However, traditional fossil-fuel power plants face challenges in addressing this power shortage due to financial and environmental concerns. While renewable resources offer an alternative, they introduce their own challenges because of their dependence on intermittent and volatile natural resources. The unpredictable nature of these resources makes power generation control and adjustment difficult, jeopardizing the safety and stability of the power grid, which was originally designed for instantaneous electricity consumption. Regulatory standards require electricity providers to maintain a constant supply that matches customer demand, further complicating the use of renewable energy.

Large-scale energy storage systems (ESS) have emerged as effective tools for aligning grid electricity demand with supply on a second-by-second basis, offering solutions that extend beyond this primary purpose. ESS are used in various grid-level applications to enhance electricity infrastructure operation across key performance dimensions. These applications can be broadly categorized into two primary usage areas: high-power systems that provide power quality and grid stability, and high-energy systems that focus on supply–demand balancing. The discharge durations for these systems depict their specific applications:

Second-long discharges: assist with voltage and frequency regulation, smoothing power fluctuations, and supplying reactive power to support grid resilience.

Minute-long discharges: provide spinning reserves, uninterruptible power backup, and black-start restoration functionalities to quickly stabilize grids during disruptions.

Hour-long discharges: enable load leveling to shift peak demands, reduce peak power requirements, facilitate energy arbitrage trading, support stand-alone microgrid operations, and integrate intermittent renewable sources through stored energy buffers.

By deploying storage systems tailored to these critical grid functions, from transmission infrastructure to distribution feeder lines, utilities and operators have improved economic returns, technical capabilities, adaptability, and reliability.

4.1. Matching the Supply to the Demand

The electrical power system must address two key requirements: maintaining a near-real-time balance between load and generation and adjusting load (or generation) to manage power flows. Utilities have limited control over the load side, with diverse consumers, including large industrial and commercial enterprises and individual households, switching loads on and off unpredictably. Customers expect a constant power supply, creating mismatches between supply and load. This imbalance is managed by spinning reserves or energy storage systems until an alternative power supply, such as longer-term generators, takes over [17]. Mismatches result in frequency instability, with generators slowing down or speeding up, impacting grid frequency. Energy storage, as depicted in Figure 10, plays a crucial role in controlling demand and supply mismatches.

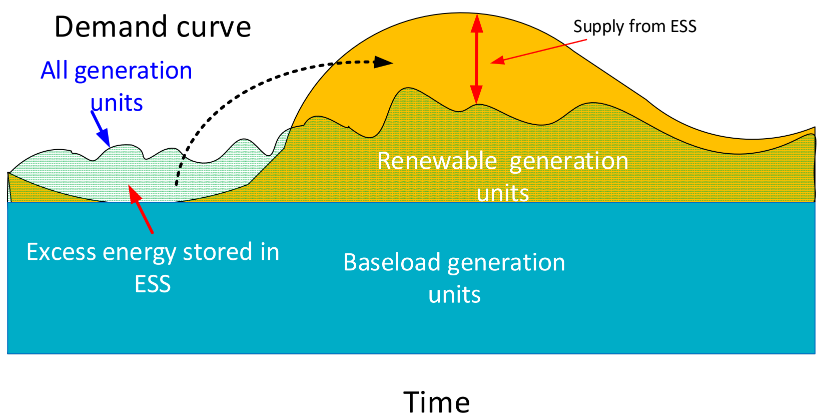

Figure 10. Electrical demand and supply management.

During off-peak periods, baseload plants, wind, solar, and hydro generators are operating and producing more electricity than the grid demand requires. The excess power generated is stored in ESS facilities. This charges the ESS by taking advantage of times when supply exceeds the load on the grid.

During periods of peak electricity demand, the stored energy in the ESS is then discharged to provide additional supply to the grid to meet higher load. This allows the ESS to supplement the other generating stations in matching and balancing overall electricity supply and demand between off-peak and peak times.

The flowchart in Figure 11 illustrates the process of utilizing energy storage systems to mitigate imbalances between power demand and generation availability on the grid. It depicts the logic for charging storage when excess supply exists and discharging storage when additional power is needed to meet demand. By continually assessing the real-time mismatch and directing excess electricity to/from the storage asset, the variability and intermittency of net load seen by other grid generators is smoothed. This enables a better integration of renewable resources and maintains balance, which ensures reliable delivery of electricity within the system. The coordinated charging and discharging of storage acts as a buffer that compensates for short-term fluctuations in supply and demand.

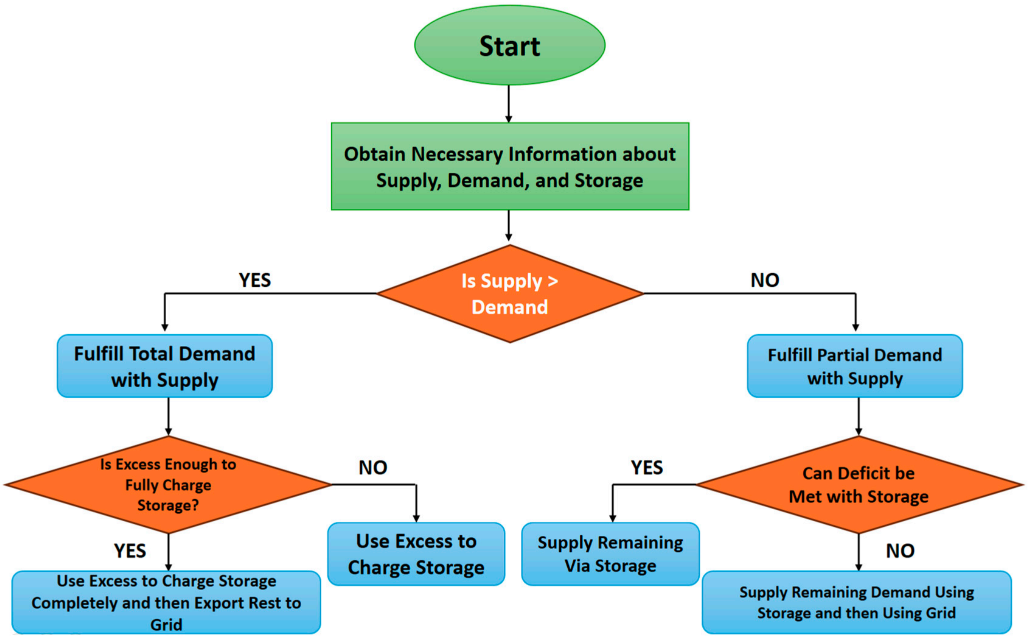

Figure 11. Energy storage controlling the demand and supply mismatch.

4.1.1. Economic Efficiency Improvement

Energy storage systems (ESSs) enable decoupling between electricity generation and demand, allowing for electricity to be generated during off-peak times and stored for use during peak periods—a concept known as "Load Shifting". This load-shifting strategy, encompassing load leveling and peak shaving, involves using fast-acting load generators during peak loads to supply power shortages. An ESS presents a more cost-effective solution to address power shortages during peak loads, enhancing economic efficiency. Figure 12 illustrates a load profile where an ESS is used to reduce peak demand [4].

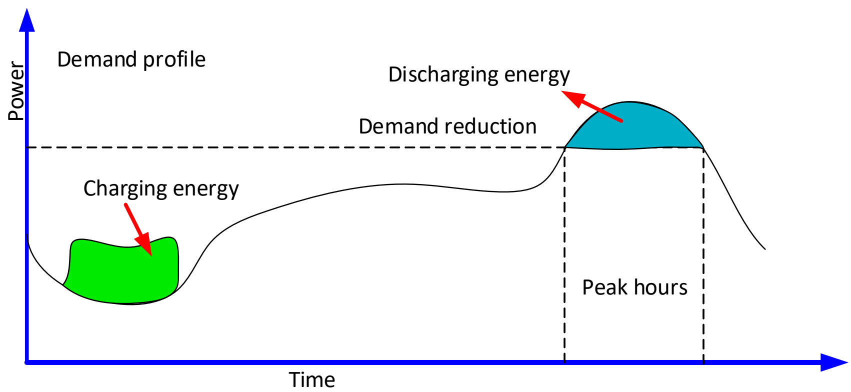

Figure 12. Load profile where the ESS is used to reduce the peak demand.

4.1.2. Maintaining Grid Stability

When electricity consumption suddenly exceeds current electrical power generation or decreases below the current power generated, grid frequency stability becomes threatened. Synchronous generators connected to the grid may slow down or speed up in response, causing frequency fluctuations if the imbalance is sustained. To mitigate this risk, a reserve power capacity with fast-acting characteristics must be maintained to stabilize grid frequency. Energy storage systems prove to be a suitable solution, capable of swiftly adapting output to offset load changes and correcting frequency deviations before they escalate or cascade [4,5].

4.2. Driving Factors for Energy Storage Systems in Oman's Renewable Energy Transition

Several key factors are driving the need for energy storage systems (ESSs) in Oman's transition to renewable energy [4,5,18,19]:

1. Intermittency of Renewable Sources: Oman's push towards solar and wind energy introduces variability in power generation due to the intermittent nature of these resources. ESSs can help smooth out this variability.
2. Supply–Demand Balance: As the share of renewable energy increases, maintaining a balance between supply and demand becomes more challenging. ESSs can store excess energy during high production periods and release it during peak demand time.
3. Grid Stability Concerns: The high penetration of renewable energy can lead to grid instability issues. ESSs can provide rapid response capabilities to maintain frequency and voltage stability.
4. Alignment with Oman Vision 2040: The country's long-term development plan emphasizes sustainable energy. ESSs are crucial for achieving the ambitious renewable energy targets set in this vision.
5. Reduction in Fossil Fuel Dependency: Oman aims to diversify its energy mix and reduce reliance on fossil fuels. ESSs enable a greater integration of renewables, supporting this transition.
6. Energy Security: By enabling greater renewable integration and providing backup power, ESSs enhance Oman's overall energy security.

5. Methodology

5.1. Evaluation Criteria for Selection of Energy Storage Technologies

The process of selecting the optimal energy storage system (ESS) involves the careful consideration of various factors. These factors are categorized into four main criteria: technical, environmental, economic, and social, with nineteen sub-criteria [25–30]. Technical criteria include parameters such as energy efficiency, energy density, storage capacity, charge time, risk, and response time. Economic criteria encompass indicators like capital cost, operation and maintenance cost, and technology lifetime. Environmental considerations involve CO_2 intensity, air and water pollution, land disruption, as well as social and political acceptance. Social factors include job creation, government incentives, and health and safety. Figure 13 illustrates the main and sub-criteria used for ESS selection.

Nine energy storage technologies have been identified as alternatives for the selection process. These include pumped hydro energy storage (PHES), compressed air energy storage (CAES), flywheel energy storage (FES), hydrogen energy storage fuel cells, lead-acid battery, Nickel-cadmium (NiCd), lithium-ion batteries (Li-Ion), superconducting, and supercapacitor. Each technology presents distinct characteristics that contribute to the selection process. The methodology involved establishing the characteristics of each storage technology, as shown in Appendix A. These characteristics, such as response time categorized as "short", "medium", or "long", were used to create the comparative framework in Appendix B. This classification aids the multi-criteria decision-making (MCDM) process by providing a qualitative basis for evaluating and selecting appropriate storage technologies based on performance metrics. Detailed information on the alternatives, main criteria, and sub-criteria is available in Appendix.

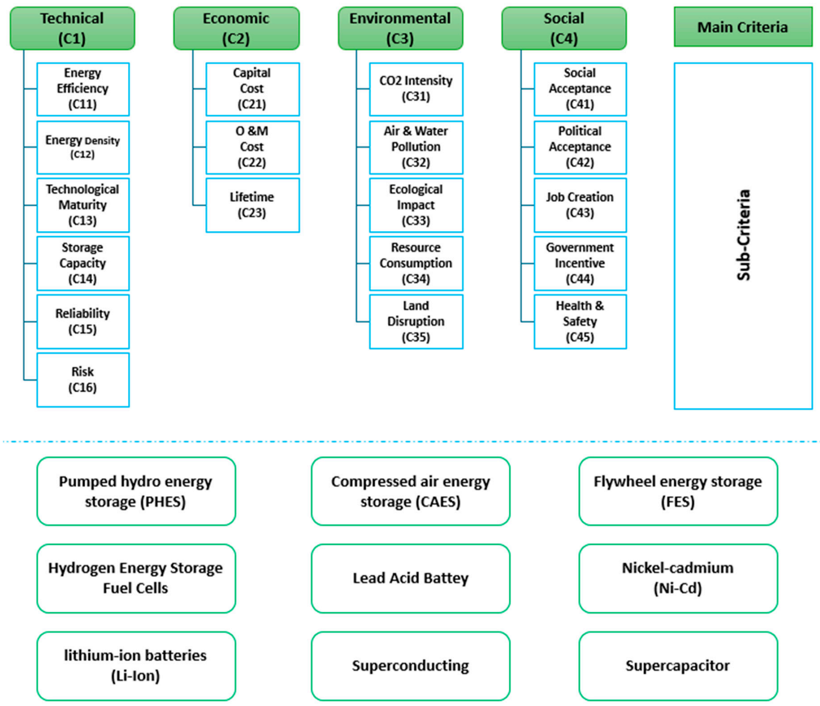

Figure 13. Main and sub-criteria; alternatives used for ESS selection.

5.2. Proposed Approach and Methodology

Considering the diverse objectives and conflicting characteristics of energy storage technologies, the selection process is framed as a multi-criteria decision-making (MCDM) problem. The formulation involves a systematic four-phase process:

1. Collection of Technology Types and Characteristics: we conducted through a comprehensive literature analysis to identify alternatives and criteria.
2. Weight Calculation: experts' evaluations are utilized to calculate the weights of the criteria.
3. Ranking of Alternatives: the VIKOR method is employed to rank the alternatives.
4. Sensitivity Analysis: a thorough sensitivity analysis is conducted to assess the robustness of the results.

The methodology incorporates the Hesitate Fuzzy Analytic Hierarchy Process (HF-AHP) method for weight calculation and the Hesitate Fuzzy VIKOR method for ranking alternatives. Table 3 summarizes research on MCDM methods, specifically the use of HF-AHP in similar decision-making contexts.

Table 3. MCDM methods used to select the suitable alternatives using the HF-AHP method.

Type of MCDM Problem	Method(s)
Project evaluation	VIKOR/TOPSIS
Service quality evaluation of domestic airlines	VIKOR
Project evaluation	VIKOR/TOPSIS
Energy policy selection	VIKOR
Numerical examples	VIKOR
Evaluation of people's livelihood projects	VIKOR
Evaluation of emergence response solutions	VIKOR/TOPSIS
Inpatient admission assessment	VIKOR
Personnel selection	VIKOR

Table 3. *Cont.*

Type of MCDM Problem	Method(s)
Electric vehicle design	DEMATEL/VIKOR
Intelligent transport system selection	VIKOR
Investment selection	VIKOR
Accessory supplier selection	VIKOR
Telecommunication service provider selection	VIKOR
Multi-criteria evaluation of energy storage technologies based on hesitant fuzzy information: A case study for Turkey	AHP-VIKOR
A Multi-Criteria Decision-Making Approach for Energy Storage Technology Selection Based on Demand	AHP-VIKOR

MCDM methods in similar contexts are used widely, and Table 3 shows some of the projects.

5.3. Hesitate Fuzzy Analytic Hierarchy Process (HF-AHP)

The HF-AHP method is employed to calculate the weights of evaluation criteria. The steps involved in this process are as follows [20]:

1. Definition of Linguistic Term Set: the syntax and semantics of the linguistic term set S are defined.

$$= \left\{ \begin{array}{c} no\ importance\ (ni),\ very\ low\ importance\ (vli), \\ low\ importance\ (li),\ meduim\ importance\ (mi),\ high\ importance\ (hi), \\ very\ high\ importance\ (vhi),\ absolute\ importance\ (ai) \end{array} \right\} \quad (1)$$

2. Preference Matrices: matrices for main criteria and sub-criteria preferences are built through linguistic assessments of experts $E = \{e1, e2, e3, \ldots, e_m\}$ in group decision-making.
3. Transformation to Hesitate Fuzzy Linguistic Term Sets (HFLTS): preference relations are transformed into HFLTS, and the envelope $\left[p_{ij}^{k-}, p_{ij}^{k+}\right]$ for each HFLTS is obtained.
4. Optimistic and Pessimistic Calculations: Collective preference relations (p_c^-, p_c^+) are obtained for each criterion by using 2-tuple set. The 2-tuple set associated with S is defined as $S = S \times [0.5, 0.5)$. The function $\mathrm{D} : [0, \mathrm{g}] \rightarrow \mathrm{S}$ is given by:

$$\Delta(\beta) = (s_i,\ \alpha)\ with \left\{ \begin{array}{l} i = round\ (\beta) \\ \alpha = \beta - i \end{array} \right. \quad (2)$$

   where round assigns to β the integer number $i \in \{0,1, 2, \ldots g\}$ closest to β and Δ^{-1}: $S \rightarrow 0, g$ is defined by $\Delta^{-1} si, \alpha = i + \alpha$.
5. Weight Calculation: by normalizing the calculated midpoints of the intervals, the criteria weights are determined.

5.4. Hesitate Fuzzy VIKOR Method

The Hesitate Fuzzy VIKOR method is employed for ranking alternatives based on calculated weights. The key steps involved are as follows [20]:

1. Decision Matrix Establishment: a decision matrix is established for the alternatives:

$$X = \begin{array}{c} \\ Alternative\ 1 \\ Alternative\ 2 \\ \\ \end{array} \begin{bmatrix} Attribute\ 1 & \cdots & Attribute\ N \\ I11 & & I1n \\ \vdots & \ddots & \vdots \\ Im1 & \cdots & Imn \end{bmatrix} \quad (3)$$

2. Normalization of Decision Matrix [21]: the normalized decision matrix is determined.

$$f_{ij} = \frac{I_i^j}{\sqrt{\sum_{i=1}^{m} \left(I_i^j\right)^2}} \qquad i = 1, 2, \ldots m\,; j = 1, 2, \ldots n \tag{4}$$

3. Utility and Regret Measures Calculation [30]: utility and regret measures are calculated for each alternative.

$$S_i = \sum_{i=1}^{n} wi \left[\frac{(f_{ij})_{max} - (f_{ij})}{(f_{ij})_{max} - (f_{ij})_{min}} \right] for\ benificia\ attributes \tag{5}$$

$$S_i = \sum_{i=1}^{n} wi \left[\frac{(f_{ij}) - (f_{ij})_{min}}{(f_{ij})_{max} - (f_{ij})_{min}} \right] for\ Non - benificia\ attributes \tag{6}$$

$$R_i = Maximum\ of \sum_{i=1}^{n} wi \left[\frac{(f_{ij})_{max} - (f_{ij})}{(f_{ij})_{max} - (f_{ij})_{min}} \right] for\ benificia\ attributes \tag{7}$$

$$R_i = Maximum\ of \sum_{i=1}^{n} wi \left[\frac{(f_{ij}) - (f_{ij})_{min}}{(f_{ij})_{max} - (f_{ij})_{min}} \right], \quad i = 1, 2, \ldots\ for\ Non - benificia\ attributes \tag{8}$$

4. Q-Value Calculation: the Q-value is computed to determine the ranking of alternatives.

$$Qi = v\left[\frac{Si - (Si)_{min}}{(Si)_{max} - (Si)_{min}}\right] + (1 - v)\left[\frac{Ri - (Ri)_{min}}{(Ri)_{max} - (Ri)_{min}}\right], \quad values\ taken\ as\ 0.5; However\ it\ can\ take\ any\ value\ from\ 0\ to\ 1 \tag{9}$$

The proposed methodology offers a systematic and comprehensive approach to the selection of energy storage technologies, incorporating multi-criteria decision-making techniques for enhanced decision support.

In this research, the selection of the ESS is formulated as an MCDM problem and solved using four phases. The methodology provides a robust framework for decision making, considering various criteria and employing advanced MCDM techniques. Figure 14 shows the flowchart for the proposed methodology.

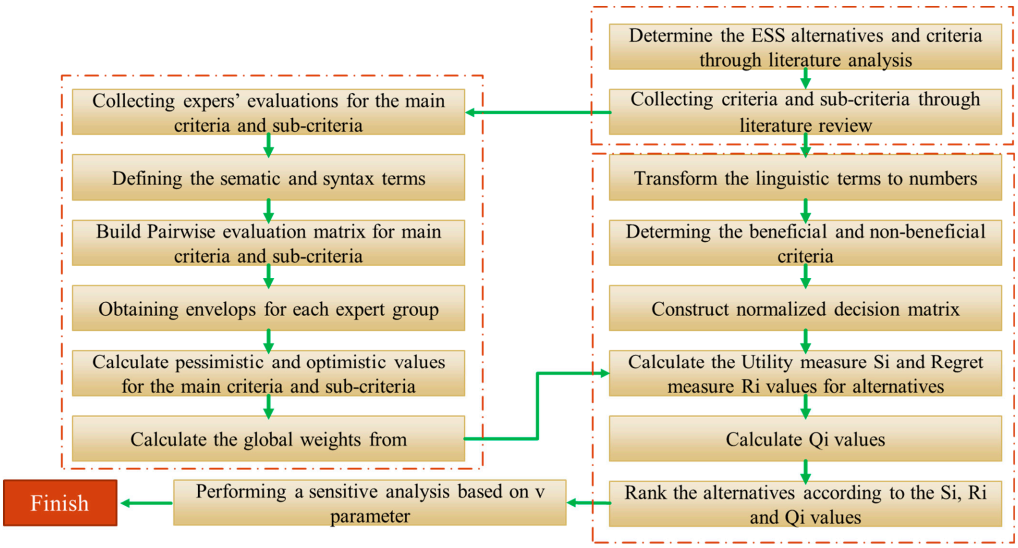

Figure 14. The proposed methodology flowchart.

6. An Application of the Proposed Approach in Oman

The methodology is applied to the Oman Main Interconnected System (MIS) grid, employing the criteria outlined in the selection process. The energy storage system (ESS) alternatives considered for evaluation are pumped hydro energy storage (PHES), compressed air energy storage (CAES), flywheel energy storage (FES), hydrogen energy storage fuel cells, lead-acid battery, Nickel-cadmium (NiCd), lithium-ion batteries (Li-Ion), superconducting, and supercapacitor. The decision-making process involves evaluating energy storage technologies using four main criteria: technical, environmental, economic, and social, with nineteen sub-criteria. Technical criteria include energy efficiency, energy density, storage capacity, charge time, risk, and response time. Economic criteria cover capital cost, operation and maintenance cost, and technology lifetime. Environmental considerations involve CO_2 intensity, air and water pollution, and land disruption. Social factors include job creation, government incentives, and health and safety. All parameters were assessed through a two-step process. First, the main criteria were evaluated, followed by the sub-criteria, using expert opinions. In this study, 14 experts with extensive experience and diverse backgrounds in the Omani electrical sector were selected. The group was composed of CEOs from power and energy sectors, senior engineers, department heads, and managers from the transmission company and distribution companies, as well as academics from the universities specializing in power and energy engineering. Additionally, managers from power plants in Oman were included. These experts, with an average of 13 years of experience, were chosen for their deep understanding of Oman's energy landscape, power systems, energy storage technologies, and the specific challenges and opportunities within the sector. This approach ensured a comprehensive and informed evaluation for the decision-making process. These alternatives are assessed based on characteristics provided in Appendix B.

Step 1: the identification of alternatives and criteria is conducted through an exhaustive literature analysis.

Step 2: A total of 14 experts, consisting of professionals from academic institutions and various companies in Oman within the electrical sector, participate in pairwise evaluations for the main criteria. The linguistic evaluations provided by the experts are organized. Envelopes reflecting the range of evaluations from the 14 mixed-expert panel, including both academic and industry professionals from the electrical sector, are compiled in Table 4.

Table 4. Experts' evaluation pairwise assessment for the main criteria.

		C1		***C2***		***C3***		***C4***	
Linguistic Evaluations of Expert 1	***C1***			mi	mi	hi	hi	vli	vli
	C2	ai	ai			hi	hi	mi	mi
	C3	hi	hi	mi	mi			vli	vli
	C4	vhi	vhi	mi	mi	mi	mi		
Linguistic Evaluations of Expert 2	***C1***			mi	mi	mi	mi	ni	ni
	C2	ni	ni			mi	mi	ni	ni
	C3	ni	ni	vli	vli			ni	li
	C4	vhi	vhi	mi	mi	mi	mi		
Linguistic Evaluations of Expert 3	***C1***			li	li	vli	vli	mi	vhi
	C2	mi	mi			hi	hi	ai	ai
	C3	vhi	vhi	vhi	vhi			li	li
	C4	li	li	li	li	mi	mi		

Table 4. *Cont.*

		C1		***C2***		***C3***		***C4***	
Linguistic Evaluations of Expert 4	***C1***			hi	hi	li	li	li	li
	C2	hi	hi			hi	hi	vli	vli
	C3	vhi	vhi	vhi	vhi			li	li
	C4	vhi	vhi	vhi	vhi	vhi	vhi		
Linguistic Evaluations of Expert 5	***C1***			hi	hi	hi	hi	mi	mi
	C2	hi	hi			hi	hi	li	li
	C3	hi	hi	hi	hi			mi	mi
	C4	vli	vli	li	li	hi	hi		
Linguistic Evaluations of Expert 6	***C1***			hi	hi	hi	hi	vli	vli
	C2	hi	hi			hi	hi	li	li
	C3	hi	hi	hi	hi			mi	mi
	C4	vli	vli	li	li	mi	mi		
Linguistic Evaluations of Expert 7	***C1***			mi	mi	hi	hi	mi	mi
	C2	vhi	vhi			hi	hi	li	li
	C3	hi	hi	vhi	vhi			mi	mi
	C4	vhi	vhi	hi	hi	vhi	vhi		
Linguistic Evaluations of Expert 8	***C1***			vhi	vhi	li	li	ni	ni
	C2	mi	mi			li	li	vhi	vhi
	C3	vhi	vhi	li	li			vhi	vhi
	C4	vli	vli	mi	mi	hi	hi		
Linguistic Evaluations of Expert 9	***C1***			mi	mi	vhi	vhi	hi	hi
	C2	hi	hi			li	li	mi	mi
	C3	li	li	hi	hi			hi	hi
	C4	mi	mi	vhi	vhi	hi	hi		
Linguistic Evaluations of Expert 10	***C1***			hi	hi	ni	ni	li	li
	C2	vli	vli			mi	mi	hi	hi
	C3	vhi	vhi	li	li			vhi	vhi
	C4	hi	hi	vli	vli	mi	mi		
Linguistic Evaluations of Expert 11	***C1***			hi	hi	mi	mi	li	li
	C2	vhi	vhi			hi	hi	mi	mi
	C3	hi	hi	mi	mi			li	li
	C4	hi	hi	mi	mi	vhi	vhi		
Linguistic Evaluations of Expert 12	***C1***			mi	mi	mi	mi	ni	ni
	C2	hi	hi			vhi	vhi	mi	mi
	C3	ni	ni	vli	vli			ni	li
	C4	vhi	vhi	hi	hi	mi	mi		
Linguistic Evaluations of Expert 13	***C1***			li	li	vli	vli	mi	vhi
	C2	vhi	vhi			mi	mi	ai	ai
	C3	ai	ai	hi	hi			hi	hi
	C4	mi	mi	hi	hi	vhi	vhi		

Table 4. *Cont.*

		C1		***C2***		***C3***		***C4***	
Linguistic Evaluations of Expert 14	***C1***			mi	mi	vhi	vhi	mi	mi
	C2	mi	mi			mi	vhi	hi	hi
	C3	hi	hi	mi	mi			hi	hi
	C4	vhi	vhi	hi	hi	hi	hi		

Step 3: the provided scale of linguistic terms were utilized, shown in Table 5, to convert linguistic terms into numerical values.

Table 5. Scale of the linguistic terms.

Linguistic Term		**Number**
No Importance (ni)	ni	0
Very Low Importance (vli)	vli	1
Low Importance (li)	li	2
Medium Importance (mi)	mi	3
High Importance (hi)	hi	4
Very High Importance (vhi)	vhi	5
Absolute Importance (ai)	ai	6

Step 4: pessimistic and optimistic preference values are derived based on the linguistic terms scale (Very Low Importance (vli), Low Importance (li), Medium Importance (mi), High Importance (hi), Very High Importance (vhi)), leading to the construction of Table 6.

Table 6. Pessimistic and optimistic values.

Pessimistic Collective Preference Values				
	Technical	**Economic**	**Environmental**	**Socio-Political**
Technical		3.07	2.93	1.93
Economic	3.64		3.50	3.14
Environmental	3.71	3.29		2.71
Socio-political	3.50	3.21	3.86	
Optimistic Collective Preference Values				
	Technical	Economic	Environmental	Socio-political
Technical		3.36	2.93	2.21
Economic	3.64		3.64	3.14
Environmental	3.71	3.29		3.00
Socio-political	3.50	3.21	3.86	

Step 5: the weights of the main criteria are determined using the calculated midpoints, as detailed in Table 7.

Table 7. Weights of the main criteria.

Main Criteria	**Linguistic Intervals**	**Interval Utilities**				**Midpoints**	**Weights**
C1: Technical	[li, 000, mi, −0.133]	[	2.643	2.833	]	2.738	0.211
C2: Economic	[mi, 4, hvi, −0.200]	[	3.429	3.476	]	3.452	0.266
C3: Environmental	[li, 000, mi, −0.267]	[	3.238	3.333	]	3.286	0.253
C4: Socio-political	[li, 0.467, mi, 0.400]	[	3.524	3.524	]	3.524	0.271

The graphical representation of the main criteria weights is shown in Figure 15.

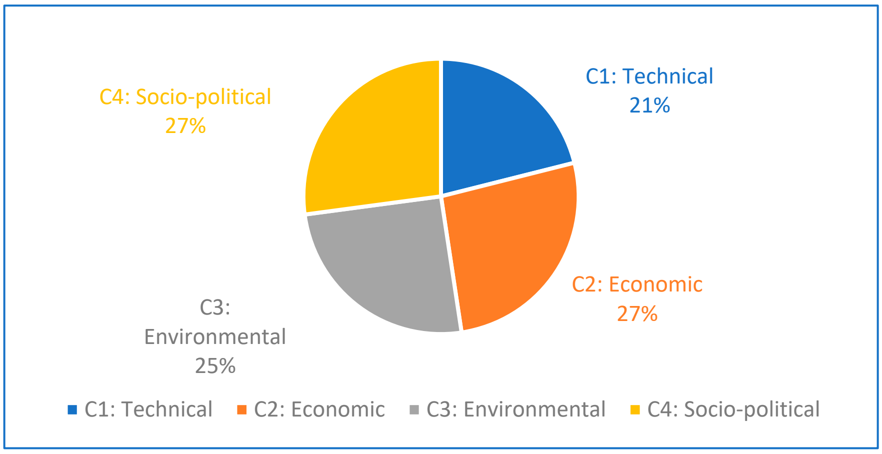

Figure 15. Main criteria weights.

Step 6: the weight calculation steps are iterated for sub-criteria, yielding global weights presented in Table 8.

Table 8. Global weights for the sub-criteria.

Criteria	Sub-Criteria	Weights	Local Weights	Global Weights
C1	C11	0.211	0.157	0.0331
	C12		0.210	0.0443
	C13		0.155	0.0326
	C14		0.156	0.0328
	C15		0.161	0.0338
	C16		0.192	0.0405
C2	C21	0.266	0.359	0.0952
	C22		0.290	0.0769
	C23		0.352	0.0934
C3	C31	0.253	0.187	0.0473
	C32		0.195	0.0492
	C33		0.204	0.0514
	C34		0.197	0.0498
	C35		0.218	0.0550
C4	C41	0.271	0.205	0.0555
	C42		0.185	0.0501
	C43		0.200	0.0542
	C44		0.187	0.0506
	C45		0.224	0.0607

Step 7: normalized decision matrix obtained; and the weights are assigned for the sub-criteria and the values of Si, Ri and Qi are calculated.

7. Results and Discussions

The proposed AHP-VIKOR methodology for selecting the optimal energy storage system (ESS) technology has been applied in the context of the Oman MIS. The key results are presented below.

7.1. Ranking of Alternatives

The final rankings of the nine ESS alternatives are shown in Table 9, detailing the Si, Ri, and Qi values alongside the ranks.

Table 9. Si, Ri, and Qi values with ESS ranks.

Technology	Alternatives	Si	Ri	Qi (v = 0.5)	Rank (v = 0.5)	Final Rank
Pumped hydro energy storage (PHES)	**A1**	0.260101	0.0497752	0.026	9	1
Compressed air energy storage (CAES)	**A2**	0.459393	0.0472864	0.207	8	2
Flywheel energy storage (FES)	**A3**	0.436801	0.0934405	0.665	7	3
Hydrogen energy storage fuel cells	**A4**	0.482315	0.0952288	0.730	5	4
Lead-acid battery	**A5**	0.742303	0.0849459	0.893	1	9
Nickel-cadmium (NiCd)	**A6**	0.662071	0.0849459	0.810	4	7
lithium-ion batteries (Li-Ion)	**A7**	0.667623	0.0849459	0.815	3	8
Superconducting	**A8**	0.56729	0.0952288	0.819	2	6
Supercapacitor	**A9**	0.48552	0.0934405	0.715	6	5

The multi-criteria decision analysis has revealed pumped hydro energy storage (PHES) and compressed air energy storage (CAES) as the optimal technologies for integration with Oman's power grid.

These findings align with other previous research which identified PHES and CAES as mature and cost-effective options for large-scale energy storage [27]. Their technical attributes like high efficiency, storage capacity and long lifetimes allow for effective load shifting to better match demand. Additionally, the abundant topography in Oman enables the setup of PHES plans leveraging water pumps and reservoirs. The man-made caverns required for CAES can also be constructed given the geological landscape [29]. The high scores of PHES and CAES across technical, economic, and environmental parameters reinforce their strengths over other alternatives like batteries, which have limitations in storage capacity, efficiency and lifespan. The strategic adoption of PHES and CAES will facilitate Oman's renewable energy goals under its 2040 vision. Solar and wind power output can be stabilized using the load-shifting capability of these storage technologies.

These analyses provides a reference to guide investments and policy decisions regarding energy storage. Specific opportunities exist for PHES plants by enhancing existing dam infrastructure while locating suitable sites for CAES cavern construction.

7.2. Sensitivity Analysis

The robustness of the ESS rankings was validated through sensitivity runs by varying the assigned weights of criteria. Figure 16 demonstrates sample outcomes where the top ranks of PHES and CAES were retained despite modified weight distributions.

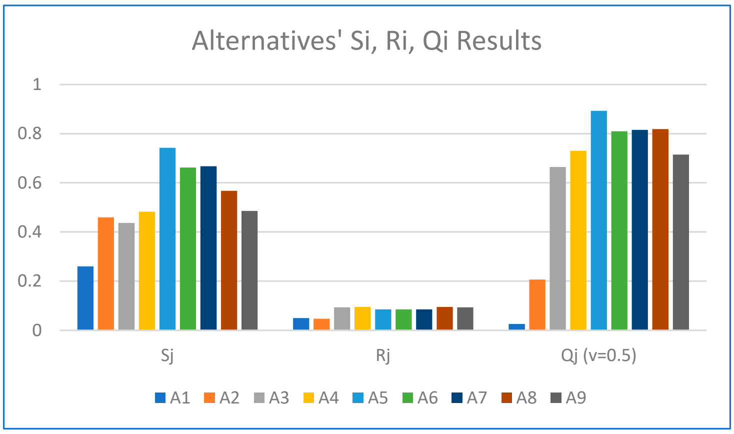

Figure 16. Graphical representation of Si, Ri, and Qi values for alternatives.

Multiple iterations assessing effects of weight changes on technology rankings confirmed PHES and CAES as consistently favorable selections suitable for integration in Oman's grid.

The application of a systematic selection process coupled with multi-criteria analysis has facilitated the identification of optimal energy storage solutions aligned to the requirements of the Oman power system. Figure 16 also provides a graphical illustration of the utility, regret, and overall measure values.

The analysis reveals pumped hydro energy storage (PHES) and compressed air energy storage (CAES) as the top choices with the first and second ranks. They exhibit strong performance across various parameters like technical maturity, economic viability, environmental friendliness and social/political acceptance.

8. Conclusions

In the study, a multi-criteria decision-making (MCDM) framework has been applied, incorporating the Hesitate Fuzzy Analytic Hierarchy Process (HF-AHP) and Hesitate Fuzzy VIKOR methods. These techniques were used to evaluate and rank various energy storage technologies for Oman national grid. The evaluation was based on four key criteria: technical, economic, environmental, and social, all tailored to Oman's specific context. This structured approach allowed for a systematic assessment of the most suitable technologies for integration into the national grid.

Through this analysis, the study identified pumped hydro energy storage (PHES) and compressed air energy storage (CAES) as the optimal energy storage systems for Oman's power grid. These technologies were selected based on their strong performance across multiple criteria, including technical maturity, economic feasibility, environmental benefits, and social acceptance. Their ability to enhance grid stability while supporting renewable energy integration made them the top choices. The study also incorporated an in-depth analysis of Oman's geographical and technical context. It took into account factors like topography and geological conditions, which are highly favorable for implementing both PHES and CAES. This country-specific analysis provided insights into the practical feasibility of deploying these energy storage solutions within Oman's energy infrastructure.

Expert input played a crucial role in this decision-making process. The study gathered evaluations from industry professionals and academics within Oman's energy sector. These experts contributed their knowledge and experience, ensuring that the assessment of energy storage systems was grounded in real-world conditions and aligned with the country's renewable energy goals. Additionally, the study developed a tailored decision-making framework to guide energy planners and policymakers in Oman. This framework serves as a tool for making informed decisions regarding large-scale energy storage investments. It aims to support the country's transition to renewable energy by identifying the most appropriate technologies for achieving Oman's ambitious 2040 vision for sustainable energy.

Author Contributions: Conceptualization, K.M.A.; Methodology, Z.M.A.-A., K.M.A., A.S.A.-H. and R.S.A.-A.; Software, Z.M.A.-A. and K.M.A.; Validation, K.M.A. and A.S.A.A.; Formal analysis, Z.M.A.-A. and K.M.A.; Investigation, K.M.A. and A.S.A.-H.; Resources, K.M.A. and R.S.A.-A.; Data curation, Z.M.A.-A.; Writing – original draft, Z.M.A.-A.; Writing – review & editing, K.M.A., R.S.A.-A., A.S.A.-H. and A.S.A.A.; Visualization, K.M.A. and A.S.A.-H.; Supervision, K.M.A., A.S.A.-H. and R.S.A.-A.; Project administration, K.M.A., R.S.A.-A. and A.S.A.-H.; Funding acquisition, K.M.A. and R.S.A.-A. All authors have read and agreed to the published version of the manuscript.

Funding: The APC was funded by Oman Liquefied Natural Gas LLC (Oman-LNG) through the consultancy research grant CR/DVC/SERC/23/02, organized by the Sustainable Energy Research Center (SERC) at Sultan Qaboos University (SQU).

Data Availability Statement: Data is contained within the article.

Acknowledgments: The authors gratefully acknowledge the generous support of Sultan Qaboos University (SQU), the Sustainable Energy Research Center (SERC), Oman Liquefied Natural Gas LLC (Oman-LNG), as well as academics and industry experts from Oman's power and energy sectors.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A. Characteristics of Energy Storage Technologies

Storage Type	Technology	Energy Density (kWh/m^3)	Power Density (kW/m^3)	Energy Efficiency (%)	Self–Discharge Losses (%/Day)	Suitable Storage Duration	Storage Capacity (MW)	Technical Maturity	Charge Time	Response Time
Mechanical Energy Storage (MSS)	Pumped hydro energy storage (PHES)	0.1–0.2 [1] 0.5–1.5 [10,13,14] 0.01–0.1 [11]	0.2–2 [1] 0.5–1.5 [10,13,14] 0.5–1.3 [11]	70–80 [12] 75–80 [13]	0.0001–0.0001 [13]	Hours–Months [10] Long Term [10]	10.00– 8,000.00 [13,14] 10–5,000 [15]	Very Mature/ Fully Commercialized [13,14]	hrs–Months [15]	12 min [12] sec–min [15], sec–min [15], 1–2 min [15]
	Compressed air energy storage (CAES)	0.2–0.6 [1] 0.5–2.0 [10,13,14] 0.04–10 [11]	2–6 [1] 3–6 [10,13,14] 0.4–20 [11]	90 [12]	0.0001–0.0001 [13]	Hours–Months [10] Long Term [10]	0.01–3,000.00 [13,14] 3–300 [15]	Proven/Commercializing [13,14]	hrs–Months [15]	12 min [12] ≤15 min [15], 1–2 min [15]
	Flywheel energy storage (FES)	5000 [1] 1000–2000 [10,13,14] 40–2000 [11]	20–80 [10,13,14] 0.3–400 [11]	80–95 [12]	100 [10], >=20% per hour [10]	Seconds–Minuts [10] Short Term [10]	0.001–10.00 [13,14] 0.1–20 [15]	Proven/Commercializing [13,14]	Seconds– Minuts [15]	≤10 millisec [15] <4 ms–sec [15]
Chemical Energy Storage (CES)	Hydrogen Energy Storage Fuel Cells	>500 [10,13,14]	500–3000 [10,13,14]	20–50 [10,13,14] 25–58 [15]	0.5–2 [13]	Hours–Months [10]	0–58.8 [15] 0.1–50 [15]		hrs–Months [15]	<1 s
Electrochemical Energy Storage (EcES)	Lead–acid	90–700 [1] 10–400 [10,13,14]	50–80 [10,13,14] 25–90 [11]	65–80 [5] 75–90 [1] 63–90 [10]	01–0.3 [13]	Minutes–days [10], short–to–med. Term	0.00–50.00 [13,14] 0 –20 [15]	Very Mature/Fully Commercialized [13,14]	Min–Days [15]	milliseconds [8] 5–10 milli sec [15]
	Nickel–cadmium (NiCd)	15–150 [13,14]	37.66–141.05 [13,14]	59–90 [13,14]	0.07–0.71	Minutes–days [10], short–to–med. Term	0.00–50.00 [13,14] 0–40 [15]	Very Mature/Fully Commercialized [13,14]	Min–Days [15]	20 ms–sec [15]
	lithium–ion batteries (Li–Ion)	1300–10,000 [1] 1500– 10,000 [10,13,14] 60–800 [11]	200–400 [1] 200–500 [10,13,14] 90–500 [11]	85–98 [1] 90–97 [10,13,14]	01–0.3 [13]	Minutes–days [10], short–to–med. Term	0.00–3.00 [13,14] 0–0.1 [15]	Mature/ Commercialized [13,14]	Min–Days [15]	Seconds [15]
Electrical Energy Storage (ESS)	Superconducting	0.20–13.80 [11]	300–4000 [11]	80–99 [11]	10–15 [13–15]	Minutes–hours [10] short–term (<1 h)	0.01–200.00 [13,14] 1–10 [15]	Proven/Commercializing [13,14]	Minuts– Hours [15]	milliseconds [13] ≤10 millisec [15], <100 ms [15]
	Supercapacitor	1–35 [11]	15–4500 [11]	65 –99 [11] 84–97 [10]	20–40 [13]	Seconds–hours [10] short–term (<1 h)	0.00–5.00 [13,14] 0–0.3 [15]	Proven/Commercializing [13,14]	seconds– Hours [15]	milliseconds [13]
Thermal Energy Storage (TES)	Sensible Heat	25–120 [11]		7–90 [11]	0.5 [15], 0.05–1 [15]	Minutes–days minutes– months [10]	0.001–10.00 [13,14]	Mature/Commercialized [13,14]		Not for Rapid
	Latent Heat	100 –370 [11]		75–90 [11]	0.5–1	Minutes–days minutes– months [10]	0.001–300.00 [13,14]	Proven/Commercializing [13,14]		days–months [16], Short to long term [16] Not for Rapid
	Reaction Heat	300 [11]		75–100 [11]		Minutes–days minutes– months [10]	0.01–1.00 [13,14]	Proven/Commercializing [13,14]		Not for Rapid

Appendix B. Comparative Framework for Multi-Criteria Decision-Making (MCDM) in Energy Storage Technology Selection

		C1: Technical						C2: Economical			C3: Environmental					C4: Social		
	Alternatives	**Energy Efficiency (%)**	**Energy Density (kWh/m3)**	**Response Time**	**Storage Capacity (MW)**	**Charge Time (Days)**	**Risk**	**Capital Cost (Power Based) ($/kW)**	**O&M Cost ($/kW/year)**	**Lifetime**	**CO_2 intensity**	**Air & Water Pollution**	**Land Dis-ruption**	**Social Ac-ceptance**	**Political Accep-tance**	**Job Creation**	**Government Incentive**	**Health & Safety**
		C11	**C12**	**C13**	**C14**	**C15**	**C16**	**C21**	**C22**	**C23**	**C31**	**C32**	**C33**	**C34**	**C35**	**C41**	**C42**	**C45**
A1	Pumped hydro energy storage (PHES)	80	1.5	Long	8000	Long	Very Low	4300	3	40	Low	Low	Medium	Very High	Very High	Very High	High	Very High
A2	Compressed air energy storage (CAES)	90	10	Long	3000	Long	Low	1628	25	30	High	Low	Medium	Very High	Very High	High	Medium	Low
A3	Flywheel energy storage (FES)	95	5000	Medium	20	Very Short	Very Low	350	20	18	Low	High	High	Very High	Very High	Low	Low	High
A4	Hydrogen Energy Storage Fuel Cells	58	500	Medium	58	long	Very Low	10000	0.0135	20	Very Low	Medium	High	High	Very High	Very High	Very High	Very High
A5	Lead Acid Battey	90	700	Very Short	50	Short	Medium	900	50	20	Very Low	Very High	Low	Medium	Low	Low	Low	Very Low
A6	Nickel-cadmium (NiCd)	90	150	Short	50	Short	Medium	1500	20	20	Very Low	High	Low	Medium	Low	Low	Low	Low
A7	lithium-ion batteries (Li-Ion)	98	10000	Very Short	3	Short	Medium	4000	25	20	Very Low	High	Medium	Medium	Low	Low	Low	Medium
A8	Superconducting	99	13.8	Very Short	200	Very Short	Low	10000	10	25	Low	Medium	Low	Medium	Medium	Very Low	Medium	High
A9	Supercapacitor	99	35	Short	5	Very Short	Low	300	6	18	Low	Medium	Low	Medium	Medium	Very Low	Medium	High

References

1. Kebede, A.A.; Kalogiannis, T.; Van Mierlo, J.; Berecibar, M. A comprehensive review of stationary energy storage devices for large scale re-newable energy sources grid integration. *Renew. Sustain. Energy Rev.* **2022**, *159*, 112213. [CrossRef]
2. International Energy Agency (IEA). World Energy Outlook 2022. Revised Version. November 2022. Available online: https://www.iea.org/reports/world-energy-outlook-2022 (accessed on 10 December 2022).
3. *Remap 2030. A Renewable Energy Roadmap*; Summary of Findings; International Renewable Energy Agency (IRENA): Masdar City, United Arab Emirates, 2014.
4. Giannelos, S.; Djapic, P.; Pudjianto, D.; Strbac, G. Quantification of the Energy Storage Contribution to Security of Supply through the F-Factor Methodology. *Energies* **2020**, *13*, 826. [CrossRef]
5. Darma, I.D.; Indra, Y.S.; Purwadi, A. Energy storage systems for renewable energy power sector integration and mitigation of intermittency. *Appl. Energy* **2019**, *236*, 1140–1158.
6. International Energy Agency (IEA), Grid-Scale Storage. Available online: https://www.iea.org/energy-system/electricity/grid-scale-storage (accessed on 20 December 2023).
7. International Renewable Energy Agency, Electricity Storage and Renewables: Costs and Markets to 2030. Available online: https://www.irena.org/publications/2017/Oct/Electricity-storage-and-renewables-costs-and-markets (accessed on 20 December 2023).
8. European Association for Storage of Energy (EASE). *Energy Storage Targets 2030 and 2050 Ensuring Europe's Energy Security in a Renewable Energy System*; European Association for Storage of Energy: Brussels, Belgium, 2022.
9. Mitali, J.; Dhinakaran, S.; Mohamad, A.A. Energy storage systems: A review. *Energy Storage Sav.* **2022**, *1*, 166–216. [CrossRef]
10. Bullich-Massagué, E.; Cifuentes-García, F.-J.; Glenny-Crende, I.; Cheah-Mañé, M.; Aragüés-Peñalba, M.; Díaz-González, F.; Gomis-Bellmunt, O. A review of energy storage technologies for large scale photovoltaic power plants. *Appl. Energy* **2020**, *274*, 115213. [CrossRef]
11. Faisal, M.; Hannan, M.A.; Ker, P.J.; Hussain, A.; Mansor, M.B.; Blaabjerg, F. Review of Energy Storage System Technologies in Microgrid Applications: Issues and Challenges. *IEEE Access* **2018**, *6*, 35143–35164. [CrossRef]
12. Hossain, E.; Faruque, H.M.R.; Sunny, M.S.H.; Mohammad, N.; Nawar, N. A Comprehensive Review of Energy Storage Systems: Types, Comparison, Current Scenario, Applications, Barriers, and Potential Solutions, Policies, and Future Prospects. *Energies* **2020**, *13*, 3651. [CrossRef]
13. Koohi-Fayegh, S.; Rosen, M.A. A review of energy storage types, applications and recent developments. *J. Energy Storage* **2020**, *27*, 101047. [CrossRef]
14. Sabihuddin, S.; Kiprakis, A.E.; Mueller, M. A Numerical and Graphical Review of Energy Storage Technologies. *Energies* **2015**, *8*, 172–216. [CrossRef]
15. Nikolaidis, P.; Poullikkas, A. A comparative review of electrical energy storage systems for better sustainability. *J. Power Technol.* **2017**, *97*, 220–245.
16. Bradbury, K.; Pratson, L.; Patino-Echeverri, D. Economic viability of energy storage systems based on price arbitrage potential in real-time U.S. electricity markets. *Appl. Energy* **2014**, *114*, 512–519. [CrossRef]
17. Chowdhury, J.I.; Balta-Ozkan, N.; Goglio, P.; Hu, Y.; Varga, L.; McCabe, L. Techno-environmental analysis of battery storage for grid level energy services. *Renew. Sustain. Energy Rev.* **2020**, *131*, 110018. [CrossRef]
18. 2040 Oman Vision. Available online: https://www.national-day-of-oman.info/wp-content/uploads/2020/11/OmanVision2040-Preliminary-Vision-Document.pdf (accessed on 10 December 2022).
19. The Oman Power and Water Procurement Company (OPWP), 7 Year Statement 2021–2027. Issue 15. Available online: https://omanpwp.om/PDF/7%20Year%20Statement%20Issue%2015%202021%20-%202027.pdf (accessed on 13 October 2022).
20. Yavuz, M.; Oztaysib, B.; Onarb, S.C.; Kahraman, C. Multi-criteria evaluation of alternative fuel vehicles via a hierarchical hesitant fuzzy linguistic model. *Expert Syst. Appl.* **2015**, *42*, 2835–2848. [CrossRef]
21. Yıldıza, N.; Tüysüzb, F. A hybrid multi-criteria decision-making approach for strategic retail location investment: Application to Turkish food retailing. *Socio-Econ. Plan. Sci.* **2019**, *68*, 100619. [CrossRef]
22. Cristóbal, J.R.S. Multi-criteria decision-making in the selection of a renewable energy project in Spain: The Vikor method. *Renew. Energy* **2011**, *36*, 498–502. [CrossRef]
23. Estévez, R.A.; Espinoza, V.; Ponce Oliva, R.D.; Vásquez-Lavín, F.; Gelcich, S. Multi-Criteria Decision Analysis for Renewable Energies: Research Trends, Gaps and the Challenge of Improving Participation. *Sustainability* **2021**, *13*, 3515. [CrossRef]
24. Shao, M.; Han, Z.; Sun, J.; Xiao, C.; Zhang, S.; Zhao, Y. A review of multi-criteria decision making applications for renewable energy site selection. *Renew. Energy* **2020**, *157*, 377–403. [CrossRef]
25. Balezentis, T.; Streimikiene, D.; Siksnelyte-Butkiene, I. Energy storage selection for sustainable energy development: The multi-criteria utility analysis based on the ideal solutions and integer geometric programming for coordination degree. *Environ. Impact Assess. Rev.* **2021**, *91*, 106675. [CrossRef]
26. Qie, X.; Zhang, R.; Hu, Y.; Sun, X.; Chen, X. A Multi-Criteria Decision-Making Approach for Energy Storage Technology Selection Based on Demand. *Energies* **2021**, *14*, 6592. [CrossRef]
27. Barin, A.; Canha, L.N.; Abaide, A.R.; Magnago, K.F.; Wottrich, B.; Machado, R.Q. Multiple Criteria Analysis for Energy Storage Selection. *Energy Power Eng.* **2011**, *3*, 557–564. [CrossRef]
28. Zubir Zubiria, A.; Menéndez, Á.; Grande, H.-J.; Fernández Aznar, G.; Sañudo, R. Multi-Criteria Decision-Making Problem for Energy Storage Technology Selection for Different Grid Applications. *Energies* **2022**, *15*, 7612. [CrossRef]

29. Colak, M.; Kaya, I. Multi-criteria evaluation of energy storage technologies based on hesitant fuzzy information: A case study for Turkey. *J. Energy Storage* **2020**, *28*, 101211. [CrossRef]
30. Ghadikolaei, A.S.; Madhoushi, M.; Divsalar, M. Extension of the VIKOR method for group decision making with extended hesitant fuzzy linguistic information. *Neural Comput. Appl.* **2018**, *30*, 3589–3602. [CrossRef]