Pumped Hydropower versus Battery Storage Systems in Neom Mountains: A TOPSIS Analysis Approach

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Abstract: - This study presents a comparative analysis between hydropower storage systems (HPSS) and lithium-ion batteries (LIBs) for large-scale energy storage in NEOM Mountain. The study is significant for engineering practices by bridging a literature gap in comparing two energy storage systems, HPSS, and LIBs, by evaluating their strengths and weaknesses through key metrics. The study employs TOPSIS to evaluate economic, environmental, social, and system sustainability impacts. The study was conducted by inviting 208 professionals working on the project to weigh the criteria and impacts through a survey. Data was calculated and analyzed in TOPSIS. Data showed that HPSS is the preferred choice. Despite the constraints faced, such as financial limitations and cultural considerations, this study provides valuable insights for sustainable energy decisions in NEOM.

Key-Words: - Decision-making, HPSS, LIB, MCDM, NEOM, renewable energy, sustainability, TOPSIS.

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1 Introduction

Reliance on conventional fuel sources, including oil and coal, has greatly affected the environment, causing irreversible damage, necessitating the shift to renewable energy, [1]. The industry witnessed significant growth over the past few years, supplying over 40% of the global energy worldwide, with an expected market size increase in the coming years, [2]. The focus now shifts to efficiently storing this energy, considering environmental, economic, and social sustainability, especially for large-scale projects like NEOM. NEOM, a futuristic city under construction in Tabuk Province, Saudi Arabia, is advertised as a model for smart technologies and sustainable living with a mountain area destined to be a tourist attraction year-round. This renewable energy expectation challenges engineers in selecting the most suitable energy source and storage system. The intermittent nature of renewable energy and variable sustainability characteristics requires a robust energy storage system.

There is an evident gap in the literature comparing these two categories' financial and technical aspects, [3]. A comparison between two entities in these categories, Hydropower storage systems (HPSS) and Lithium-ion batteries (LIB) will be demonstrated throughout this paper. LIBs have been commercialized and used in numerous applications, nevertheless, facing economic limitations in larger-scale applications [4], while HPSS systems present a cost advantage for larger-scale projects. Multi-criteria decision-making (MCDM) using TOPSIS as an analysis tool is employed.

2 Literature Review

2.1 Lithium-ion Batteries (LIBs)

Their lightweight, compact design and specific energy ranging from 100Wh kg^{-1} to 150Wh kg^{-1} have made them the preferred storage devices, [4]. LIBs follow a conventional structure with a graphite mesocarbon microbeads (MCMB) anode, a lithium metal oxide cathode, and a lithium salt electrolyte solution, [5]. LIBs have notable environmental impacts throughout their life cycle. A life cycle assessment reveals LIB production is estimated to contribute about 60% to most impact production categories, [6]. The overall global warming potential (GWP) per kWh of battery production is approximately 71 kg-CO_2-eq/kWh, which can be reduced through recycling, lowering greenhouse gas emissions by 11%, [7]. The unit cost of energy storage systems, especially LIBs, depends on factors such as energy storage capacity and the power they can deliver. Sustainability problems span the entire lifecycle, and having a lot of raw materials in one place can lead to resource shortages and price changes. For LIBs to be successful in the long run, they need to have a wide range of suppliers from different parts of the world and be able to make new resources by recycling, [8]. Over time, the battery's capacity goes down because of factors that cannot be changed, which means it can store less energy, and the rate of wasted electricity goes up, [6].

2.2 Hydropower Storage Systems (HPSS)

Hydropower is a long-lasting source of renewable energy that is used worldwide. For example, Bhutan, Paraguay, and Norway get most of their commercial electricity from it [9]. Hydropower plants use the kinetic motion of water to convert it into energy. This is done by using the differences in height that dams or diversion structures create. HPSS is a way to store hydroelectric energy and uses two reservoirs at different heights to balance the load. It operates like a big battery, storing extra energy and releasing it when needed, [10].

Limitations on water availability, problems with topography, and high costs pose challenges despite the eco-consciousness of hydropower systems. Such systems impact the environment and have an effect on marine life and habitats. Negative effects include the spread of species, changes in littoral zones, less clear water, and higher death rates for higher species, [11], [12], [13]. Hydropower systems, with their large-scale infrastructure, can have a socio-economic effect on people's lives. Building dams can force people to relocate, boomtowns to form, and cultural heritage to be lost. However, there are cases like the Yibin–Chongqing and Brazil that show how regional economies can benefit by increasing consumption, investment, GDP, jobs, and income, [14], [15]. The sustainability of hydropower storage systems depends on economic, environmental, and social factors, [16]. Planning, coordinating, and reducing risks are all important for the long-term success and sustainability of hydropower projects, [16].

2.3 Comparison

When deciding between Hydropower Storage Systems (HPSS) and Lithium-ion Batteries (LIBs), one has to consider a number of factors, such as fundamental attributes (Table 1, Appendix), cost, and the environment, [4]. A comparison of HPSS and LIB systems shows that they differ in terms of maximum power rating, discharge time, maximum cycles or lifetime, energy density, and efficiency. There are big differences between HPSS and LIB systems in these basic characteristics, [4].

Economic comparison of different systems reveals that the location, market conditions, and project requirements all affect the amount of raw materials and operating costs each system needs. LIBs need diverse materials, and their price depends on weight, power, and storage capacity. On the other hand, HPSS mostly uses concrete, steel, and copper for building and mechanical parts, [17]. Costs for LIB systems have been approximately 18 times higher than HPSS due to frequent battery replacements and higher raw material expense. Environmental considerations show LIBs exhibit discernible impacts during the end-of-life and production stages, primarily due to battery unit replacements every 20 years. Operational impacts, related to energy losses during use, outweigh production-stage effects. HPSS, with barely noticeable impacts in the end-of-life stage, shows a slightly higher impact than LIBs only in natural land transformation, [17].

In summary, the decision-making process involves weighing these factors to determine the most suitable energy storage system based on specific needs and priorities.

3 Research Methodology

Choosing the right system for the right project can be a tiresome process, especially in the presence of different criteria and alternatives. Thus, Multi-criteria decision-making (MCDM) simplifies this process, aiding in strategic decisions. It encompasses methods for decision-making under multiple criteria, with different methods suited to various disciplines. This process involves criteria identification, alternative selection, and their comparison, with criteria weights influencing outcomes. Different weighting methods (subjective, objective, and combinative) impact the decision-making process.

TOPSIS an MCDM widely used method for its simplicity, calculates distances from Positive Ideal Solution (PIS) and Negative Ideal Solution (NIS) to rank alternatives and separate options-based PIS and NIS. TOPSIS is effective in handling uncertainties and has proven efficient in decision-making related to energy storage, particularly in cost-effectiveness and scalability. Its adaptability to subjective or objective scenarios makes it a robust MCDM method.

TOPSIS involves normalizing the decision matrix, computing a weighted normalized decision matrix, determining PIS and NIS, calculating distances from PIS and NIS, and determining a preference value. Weights in TOPSIS are critical and categorized as subjective, objective, or integrated.

3.1 Procedure

In decision-making for the power storage system in the Neom Mountains, economic, environmental, social, and system sustainability criteria play a crucial role. These criteria will be evaluated using the TOPSIS, comparing pumped hydropower storage systems and battery storage systems.

A council of 208 professionals in construction, environmental, sustainability, and community well-being contributed to refining the survey for criterion assessment. Surveyors (professionals in NEOM) weighted the main and sub-criteria on a scale of 1 to 5. The total score for each criterion was then divided by the overall score of all four criteria, resulting in weights between 0 and 1, with a cumulative value of 1 for the four criteria. Criteria evaluation involves quantitative analysis for economic impact and qualitative approaches for other criteria.

3.2 Expansion of the Methodology

To expand the methodology for selecting the most suitable energy storage system in the Neom Mountains, this study utilizes the MCDM) approach, specifically TOPSIS. This method simplifies complicated strategic decisions that involve many alternatives and competing standards. TOPSIS is mathematically founded on its capability to rank alternatives based on their geometric distance from a hypothetical best and worst case.

3.2.1 The TOPSIS Mathematical Framework

The TOPSIS method comprises several rigorous stages to map qualitative and quantitative data into a final preference ranking:

1. Construction and normalization of the decision matrix: The procedure starts with a decision matrix $\underline{\underline{D}}$, where alternatives (Hydropower vs. Lithium-ion Batteries) are assessed against various criteria (economic, environmental, social, and sustainability). The normalization of the matrix is a mathematical requirement because the criteria used may have different units — for example, kg-CO2-eq for emissions versus USD for cost.
   - Normalization equation: Each entry r_{ij} of the normalized matrix $\underline{\underline{R}}$ is normally calculated to eliminate dimensional units. This enables direct comparison across various metrics.
2. Calculation of the weighted normalized decision matrix: Criteria weights w_j are determined via professional surveys. Professionals in NEOM weighted these criteria on a scale of 1 to 5, which were then converted into weights between 0 and 1, ensuring the sum of all weights equals 1 $\left(\sum_j w_i = 1\right)$.
   - Weighted matrix $\underline{\underline{V}}$: The weighted normalized value v_{ij} is calculated as:

$$v_{ij} = w_j \times r_{ij}, \tag{1}$$

where w_j represents the importance assigned to the j^{th} criterion.

3. Determination of ideal solutions: TOPSIS identifies two anchor points based on the "criteria objectives" (minimizing costs/impacts vs. maximizing benefits):
   - Positive Ideal Solution (PIS or $\underline{\underline{V}}^+$): The best performance values across all criteria.
   - Negative Ideal Solution (NIS or $\underline{\underline{V}}^-$): The worst performance values across all criteria.
4. Distance calculation and preference value: The method calculates the n-dimensional Euclidean distance of each alternative from these ideal points:
   - Distance to PIS (S_i^+): Represents how far an alternative is from the "perfect" solution.
   - Distance to NIS (S_i^-): Represents how far it is from the "worst" solution.

   The final relative closeness or preference value (C_i^*) is determined by:

$$C_i^* = \frac{S_i^-}{S_i^+ + S_i^-}. \tag{2}$$

An alternative is considered the "ideal" choice as C_i^* approaches 1.

3.2.2 Sensitivity Analysis

To ensure the robustness of the TOPSIS results, the study incorporates sensitivity checks where data is re-evaluated across specific professional cohorts (construction, environmental, and sustainability specialists) to confirm if the preference for HPSS holds regardless of which group's priorities are emphasized.

4 Results and Discussion

The results of the survey conducted permitted the calculation of weights per each criterion under study (Figure 1):

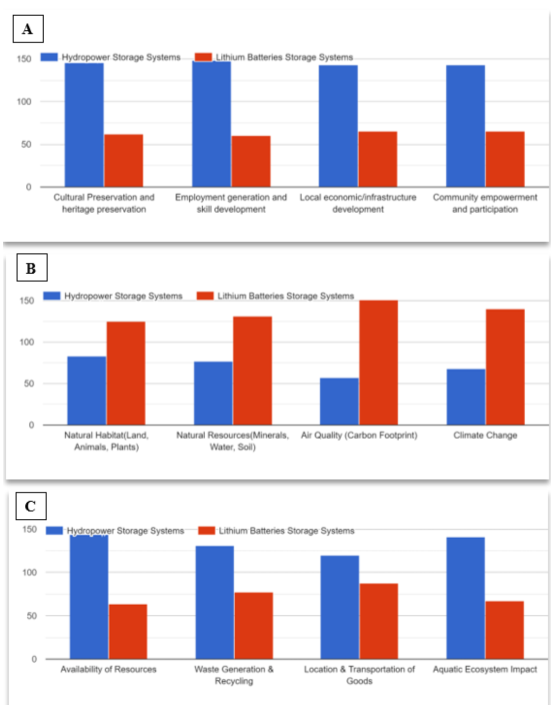

Fig. 1: Extracted from the performed survey, the following results show the storage system impact per criteria. A. Storage Systems Environmental Negative Impact. B. Storage Systems Social Positive Impact. C. Storage Systems Sustainable Impact.
Source: created by the authors.

4.1 Cost Analysis

The study covers initial costs, including design, procurement, installation, and commissioning, along with operating, maintenance, and salvaging costs for lithium battery and pumped hydropower storage systems. Cost comparison at various power capacities and operational periods for large-scale energy production and reliability over time shows lithium battery and pumped hydropower storage systems at 1000 MW power with a 100-hour cycle duration, costs of $311/kWh and $69/kWh for lithium battery and pumped hydropower storage systems, respectively (Figure 2, Appendix).

4.2 Sensitivity Checks

The results indicate that pumped hydropower storage is the preferred choice over lithium battery storage systems across economic, environmental, social, and system sustainability impacts. Sensitivity checks were conducted on three professional groups: Construction Specialists, Environmental Specialists, and Sustainability Specialists. Construction specialists, representing 63% of surveyors, favor HPSS over LIBs. Environmental Specialists, accounting for over 51% of the criteria weights, also reaffirm the original results, with HPSS as the ideal solution. However, environmental specialists express a preference for lithium batteries concerning negative impacts on natural resources, potentially due to the resource consumption of hydro-plant construction. Sustainability Specialists support the original results, favoring pumped hydropower storage systems. Notably, sustainability specialists lean towards lithium batteries when considering negative impacts on natural habitats, possibly due to the disturbance caused by hydro-plant construction in virgin lands.

4.3 Constraints and Limitations

The study encountered several limitations that may have affected the results: The economic comparison used data from the U.S. Department of Energy because there was no regional data available. To do a specific economic analysis, it is necessary to hire a professional firm and incur a large cost. Also, a more in-depth quantitative and qualitative study of environmental, social, and sustainability issues are needed. Neom's unique environment, which includes a preserved setting and a mix of people living traditional lives, complicates the study.

The survey, targeting professionals, missed key stakeholders such as farmers and shepherds, whose perspectives are integral to energy storage decisions. The survey aimed to establish weights for criteria and sub-criteria and assess preferences between two alternatives. However, the scale used (1 to 5) in weighing criteria resulted in 76% of respondents choosing 4 or 5. Adopting a larger scale, such as 1 to 10 or Saaty's scale, could have addressed this limitation.

4.4 Practical Implications for Neom and Large-Scale Energy Projects

4.4.1 Choosing the Right Infrastructure for Strategy

The study establishes a comprehensive framework for the selection of energy storage systems, illustrating that HPSS consistently surpass Lithium-ion Batteries (LIBs) in large-scale applications such as NEOM:

- Economic scalability: HPSS costs about $69 per kWh for a 1000 MW project with a 100-hour cycle, while LIBs cost about $311 per kWh.
- Operational longevity: HPSS has a much longer operational life of 30 to 60 years, while LIBs usually need to be replaced every 20 years.
- Efficient use of resources: HPSS uses stable building materials like concrete, steel, and copper, which avoids the risks of price changes and shortages that come with the raw materials needed for LIBs.

4.4.2 Social and Environmental Impact

For cities of the future like NEOM, the choice of HPSS fits with long-term sustainability goals, even though there are some environmental problems in certain areas:

- Social advancement: HPSS has a bigger positive effect on creating jobs, improving local infrastructure, and giving communities more power than battery systems do.
- Environmental trade-offs: HPSS has a lower potential for global warming over its entire life cycle. This is attributed to the fact that it does not require frequent replacement and does not pollute as much during production as LIBs do.
- Mitigation requirements: To use HPSS, careful planning is needed to monitor how it will affect natural habitats and aquatic ecosystems.

4.4.3 Improvements to the Way Decision-Makers Work

The study suggests several practical improvements to the TOPSIS and MCDM methodologies to facilitate making better decisions for similar large-scale projects in the future:

- Involving more stakeholders: Future surveys should include more than just professional groups. They should also include stakeholders in the area who are affected by big infrastructure projects, such as farmers and shepherds.
- Granular measurement scales: Switching from a 1–5 scale to Saaty's scale (1–10) would provide clearer information and help understand how strong preferences are.

5 Conclusion

In conclusion, the study shows how important the decision-making process is for NEOM's energy storage systems. Even with challenges and restrictions, the results consistently show that HPSS is better than LIBs on a number of different criteria. The results not only show that HPSS is good for the economy, but they also show that it is good for the environment, society, and long-term sustainable effects. The study gives stakeholders strategic insights so they can make informed decisions that are in line with the project's vision and goals, like NEOM.

This study suggests that subsequent research should examine the expansion of the scale from 1 to 10 or the adoption of Saaty's measurement scale to yield a more extensive array of responses and enhance the robustness of the collected data, thereby facilitating a clearer comprehension of surveyors' preferences regarding various criteria and sub-criteria. Furthermore, incorporating comprehensive economic analyses and quantitative/qualitative studies would yield a precise evaluation of environmental, social, and sustainability dimensions.

Future research will involve enhancing the MCDM and TOPSIS models to yield more accurate results.

Multiple-Input-Multiple-Output (MIMO) techniques [18], [19], [20], [21], [22], [23], commonly utilized in telecommunication systems for enhancing communication efficiency, can be effectively adapted for MCDM in business research. MIMO's ability to handle several inputs and outputs simultaneously provides a robust framework for evaluating various business decision-making criteria, leading to more informed and optimized outcomes. Integration of MIMO spatial cycling models with MCDM can be accomplished using approaches such as AHP, TOPSIS, and others. This integration will allow for the simultaneous consideration of multiple criteria, enabling the weighting of criteria based on their importance, and providing a comprehensive decision-making framework.

Future work will also use a more flexible and adaptable approach to AHP. AHP is a common way to make choices that ranks options based on a number of factors using pairwise comparison matrices. But these matrices could be affected by human judgment that is not always correct or consistent. One possible source of uncertainty could be modeled as speckle noise, which is common in wireless communication fading systems and coherent imaging systems. It can also be used as a metaphor for how decisions are made at random times. This proposal suggests adding stochastic models of speckle noise to AHP matrices to make it easier to deal with uncertainties. This could lead to decision-making frameworks that are more flexible and resilient.

The aim of this proposed future study is to create and utilize a stochastic model that replicates the effects of speckle noise [24], [25], [26], [27] on pairwise comparison matrices within the AHP framework. The goal is to make prioritizations more realistic and reliable by using noise models to account for randomness and uncertainty in the decision-making process.

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APPENDIX

Table 1. Fundamental characteristics between HPSS and LIB systems

EES	Max power rating (MW)	Discharge time	Max cycle or lifetime	Energy density (Wth/L)	Efficiency
HPSS	3000	4-16h	30-60 years	0.2-2	70-85%
LIB	100	1 min- 8h	1000-10000 years	200-400	85-95%

Source: [4]

Calculation

Criteria weights:	***0.25***	***0.06***	***0.07***	***0.06***	***0.06***	***0.05***	***0.06***	***0.06***	***0.06***	***0.06***	***0.07***	***0.06***	***0.06***
Criteria Objectives:	***Min***	***Min***	***Min***	***Min***	***Min***	***Max***	***Max***	***Max***	***Max***	***Max***	***Max***	***Max***	***Max***
V=W.R = Batteries	0.246	0.054	0.056	0.119	0.056	0.025	0.024	0.026	0.026	0.026	0.031	0.035	0.027
PHS	0.055	0.036	0.033	0.045	0.027	0.059	0.059	0.057	0.057	0.058	0.053	0.048	0.057

Positive Ideal Solution V^+ =	**0.055**	**0.036**	**0.033**	**0.045**	**0.027**	**0.059**	**0.059**	**0.057**	**0.057**	**0.058**	**0.053**	**0.048**	**0.057**
Negative Ideal Solution V^- =	**0.246**	**0.054**	**0.056**	**0.119**	**0.056**	**0.025**	**0.024**	**0.026**	**0.026**	**0.026**	**0.031**	**0.035**	**0.027**

Criteria:	Cost	Natural Habitat	Natural Resources	Air Quality	Climate Change	Cultural Preservation	Employment Generation	Local Development	Community Empowerment	Availability of Resources	Waste Generation	Location & Transportation	Aquatic Ecosystem	
S_i^+ = Batteries	-0.191	-0.018	-0.023	-0.074	-0.029	0.034	0.035	0.031	0.031	0.032	0.022	0.013	0.030	**0.225**
PHS	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	**0.000**

Criteria:	Cost	Natural Habitat	Natural Resources	Air Quality	Climate Change	Cultural Preservation	Employment Generation	Local Development	Community Empowerment	Availability of Resources	Waste Generation	Location & Transportation	Aquatic Ecosystem	
S_i^- = Batteries	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	**0.000**
PHS	0.191	0.018	0.023	0.074	0.029	-0.034	-0.035	-0.031	-0.031	-0.032	-0.022	-0.013	-0.030	**0.225**

Output

C_i^* = **Batteries**	**0.000**	
PHS	**1.000**	Max = **1.000**

Fig. 2: TOPSIS Calculation and Results

Source: created by the authors.

Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

The authors equally contributed in the present research, at all stages from the formulation of the problem to the final findings and solution.

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