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Optimal Multi-Criteria Selection of Energy Storage Systems for Grid Applications

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Currently, a wide variety of energy storage alternatives are available, each with a unique set of characteristics advantageous on selective applications. Current studies focus only on levelized costs on predicting the best-fit technology for specific applications. The study addresses this limitation by considering multiple factors on the selection process among technologies for specific applications. A systematic approach on the selection of energy storage technologies based on multiple and possible conflicting factors was proposed in this study for two specific applications: frequency regulation and load levelling. Fuzzy Analytic Hierarchy Process was utilized to generate the relative importance of each criterion. Monte Carlo simulations were performed to reflect the effect of battery characteristics and operating parameters uncertainties on the resulting scores of technologies. Grey Relational Analysis was used to aggregate the performance attributes of alternatives into a single score reflecting the desirability of alternatives. The levelized costs dominated all other criteria for both applications. Lithium ion battery dominated all technologies for both applications resulting from its well-rounded performance across all considered attributes. Results emphasized the importance of considering socio-economic indicators alongside techno-economic parameters on selecting the technology for future deployment. Thorough analysis on the results is important not only for decision-makers but for developers and innovators as well to direct future research.

1. Introduction

Energy storage is predicted to have a pivotal role in the pursuit of energy, and grid sustainability as it resolves several issues, such as but not limited to the volatility of renewable energy sources, inefficiency of energy generation technologies and processes, transmission congestion, environmental emissions, grid stability, islanding, and power quality (Delholm et al., 2013). Energy storage also provides a temporal dimension to the energy sector by time shifting energy supply during oversupply, and energy demand during energy shortage. This property satisfies the basic necessity of the electric grid to balance supply and demand for maximum efficiency and reliability (Moseley et al., 2015). According to the Energy Storage Association, these promising features of energy storage provide limitless opportunities for both energy and power applications. Despite its promising features, the vast number of available energy storage technologies with unique sets of characteristics, and the wide-range of applications requiring different operating parameters, raise issues on technological deployment. Several studies focus only on the levelized cost as the basis for choosing the best fit technology for specific applications. In reality, several other factors also play a role on the selection for technological deployment by several stakeholders. This knowledge gap on the effect of considering other factors on the selection of energy storage technologies for grid applications necessitates a systematic decision-making

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approach capable of scoring energy storage technologies based on the requirements and limitations set upon by specific applications to guide decision-makers.
A complex procedure is involved in selecting the most suitable technology for a specific application across multiple and possibly conflicting criteria based on the priorities of the qualified decision-makers. Additionally, the model requires that the preferences of decision-makers be balanced accordingly across an array of performance attributes. As a resolution, the Multi-Criteria Decision Making (MCDM) structure was developed. One of these is the Fuzzy Analytic Hierarchy Process (FAHP). FAHP is a modified version of the Analytic Hierarchy Process (AHP) originally proposed by Saaty (1977) to derive ratio-scale priorities from pairwise comparison judgments while taking into consideration the vagueness and ambiguity associated with the qualitative nature, and personal judgments of decision-makers (Promentilla et al., 2015). Additionally, Grey Relational Analysis (GRA) was used to determine the desirability of an alternative in comparison to an ideal reference sequence across different criteria (Eusebio et al., 2016). GRA was used to greatly reduce data requirements and tedious mathematical processes as this tool solves problems with complicated interrelationships among several factors (Kuo et al., 2008). A similar procedure utilizing these two models are presented in a study by Ocon et al. (2018) on the optimal selection of hybrid energy systems for microgrid applications.

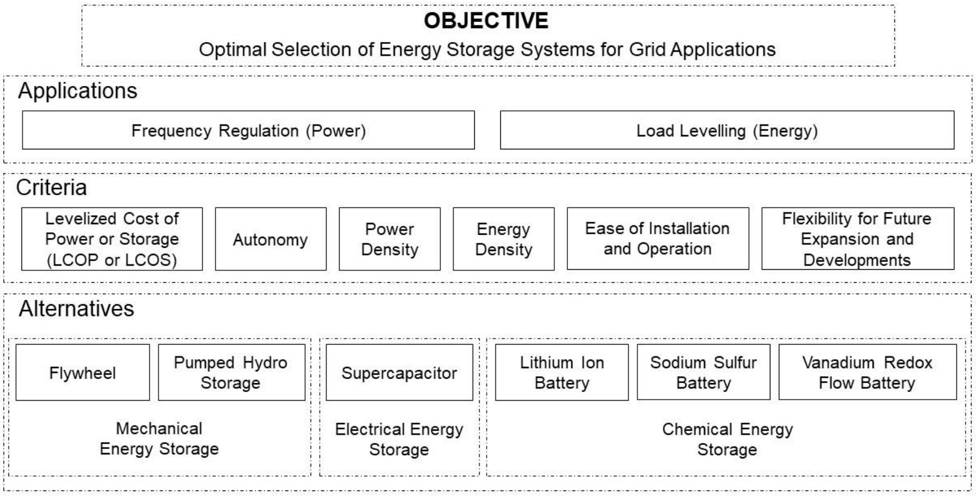

Figure 1. Overall decision structure of the study with a single objective of selecting the most appropriate energy storage system for two different applications with the same set of criteria and alternatives.

In this study, a systematic approach on the selection of energy storage technologies for selected grid applications considering multiple factors is proposed to address the issues associated with decision-making among qualified decision-makers. Simulations were performed to validate the proposed decision-making model. Due to a wide range of grid applications, the study considered only two grid functions that can benefit greatly from energy storage technologies. Frequency Regulation was chosen as the grid function requiring energy storage for power applications, while Load Levelling was chosen for energy applications. For both applications, the same set of alternatives namely: Flywheels; Pumped Hydro Storage; Supercapacitors; Lithium-ion Batteries; Sodium Sulfur Batteries; and Vanadium Redox Flow Batteries, were chosen and the same criteria (Levelized Cost of Electricity, Autonomy, Power Density, Energy Density, Ease of Operation and Installation, and Flexibility for Future Expansion and Developments) were considered for the selection of these alternatives. The study also aims to highlight the dependence of the ranking of alternatives on the operating conditions of each application, and the effects of each criterion on the overall score of alternatives. FAHP was used to derive the crisp local weights of each criterion through a pairwise comparison. And GRA was used to derive a single score and ranking for each alternative by aggregating the performance attributes of each alternative. Quantitative values for the performance attributes were generated through the use of mathematical simulations, an example is presented by Schmidt et al. (2018) in the calculations of the levelized cost of storage and power for energy storage systems for different grid applications, and through literature review. Qualitative parameters were quantified through scoring systems from surveys conducted on technical experts as presented in Ocon et al. (2018). Lastly, Monte Carlo simulations were performed to account for the uncertainties involved in the performance attributes of alternatives, and to generate a range of possible scores of alternatives based on these uncertainties as discussed in Promentilla et al. (2014).

2. Methodology

2.1 Structure of the decision-making model

Initially the decision-making structure was defined through the selection of the applications, objectives, scope and limitations, criteria, alternatives, and qualified decision-makers. The overall objective of the study was to optimally select the most appropriate energy storage system for Frequency Regulation, and Load Levelling. Six criteria were selected based on the opinions of several technical experts, and literature review. The alternatives selected were based on mature technologies and developing technologies with a wide range of applications, and has a promising future applicability for the selected applications based from surveys on technical experts and literature reviews. The decision-makers selected were limited to technical experts (energy storage, sustainability, and other related fields), policy-makers, electric cooperatives, grid companies, and investors.

2.2 Local priorities of criteria

A survey was conducted on qualified decision-makers to derive comparisons between all criteria in a pairwise fashion. The pairwise comparison used was based on a 9-point linguistic scale presented in Saaty (1980). FAHP was applied to the survey results to derive crisp local priorities of each criterion, and the consistency of the responses, represented by the consistency index (λ), using a fuzzy preference non-linear programming approach discussed further in Promentilla et al. (2015).

2.3 Performance attributes of alternatives

Performance scores of alternatives were generated from literature reviews, mathematical simulations, and surveys from experts. The Levelized Cost of Storage and Levelized Cost of Power were generated using the methodology discussed in Schmidt et al. (2018). To accommodate the uncertainty in the parameters used in generating the levelized costs, Monte Carlo simulations, assuming a uniform distribution for parameters with a range of values with equal probabilities of occurring, and a beta PERT distribution for range of values with a most probable value, involving 10,000 runs were performed. The simulations generated a range of possible levelized cost values for each alternative. Energy Densities, Power Densities, and Autonomies were obtained from different sources. Values for the Flexibility for Future Expansion and Development, and Ease of Operation and Installation were obtained from technical experts using a 5-point scoring system. A rubric was presented to guide technical experts. The survey generated range of values for both Flexibility for Future Expansion and Developments, and Ease of Operation and Installation with the average score treated as the most probable score for these criteria.

2.4 Overall score of alternatives

Monte Carlo simulations assuming a uniform distribution for a range of values with each value having equal probabilities of occurring, and a beta PERT distribution for range of values with a most probable value, were performed 10,000 times to generate randomized combinations of performance attributes for each alternative. From each of these runs, GRA was used to aggregate the performance attributes of alternatives across different criteria into a single score with a detailed procedure presented in Kuo et al. (2008). The results for each run were then normalized thus yielding the normalized overall score of all alternatives.

3. Results and discussion

3.1 Local priorities of criteria

Table 1. Local priorities of criteria in frequency regulation and load levelling

Ranking	Frequency Regulation		Load Levelling	
	Criteria	Local Priority	Criteria	Local Priority
1	Levelized Cost of Power	0.3438	Levelized Cost of Storage	0.3065
2	Energy Density	0.1720	Flexibility for Future Expansion and Developments	0.1728
3	Ease of Operation and Installation	0.1284	Autonomy	0.1462
4	Flexibility for Future Expansion and Developments	0.1234	Energy Density	0.1437
5	Power Density	0.1195	Power Density	0.1334
6	Autonomy	0.1130	Ease of Operation and Installation	0.0974

The results of the application of FAHP on the pairwise comparison matrix generated from the survey are listed in table 1. The results show consistent responses given by the closeness of the consistency indices (λ) to a value of 1 (0.7232 for Frequency Regulation, and 0.6129 for Load Levelling). It can be seen that the main drivers for the decision structure are Levelized Cost of Power for Frequency Regulation, and Levelized Cost of Storage for Load Levelling. Other criteria have significantly lower effects on the decision structure and the remaining criteria affect the overall decision structure to the same degree as represented by the closeness of their magnitudes. This reflects that factors reducing the cost of technologies, and increasing the total energy and power delivered by the technology over its entire lifespan greatly increase the overall desirability and ranking of energy storage systems.

3.2 Overall scores of alternatives

From the local priorities of the criteria, the performance attributes of the alternatives were then determined to generate the overall score of alternatives for both applications. The Energy Density, Power Density, and Autonomy were obtained from literature values and were utilized in this study as a range of possible values to accommodate variations brought about by the dependence of properties on specific system designs. The Levelized Cost of Storage and Levelized Cost of Power were obtained using the methodology discussed in Schmidt et al. (2018), with battery characteristics obtained from several literature reviews. The range of levelized cost values used in the study were generated by performing 10,000 simulations with unique sets of battery characteristics obtained by randomly selecting a value for a parameter within a specified range obtained from literature reviews. Flexibility for future expansion and developments and ease of operation and installation were obtained from a survey on technical experts. The survey involved a 5-point scoring system with each score having a corresponding description in the rubrics provided to the respondents. The range of score per alternative was defined by the minimum and maximum value, and the most probable value was represented by the average of the scores given by the technical experts.

Table 2. Overall score of alternatives for both frequency regulation and load levelling

Ranking	Frequency Regulation		Load Levelling	
	Alternative	Average Overall Score	Alternative	Average Overall Score
1	Lithium-ion Battery	0.2025	Lithium-ion Battery	0.2096
2	Supercapacitor	0.1756	Pumped Hydro Storage	0.1888
3	Sodium Sulfur Battery	0.1602	Sodium Sulfur Battery	0.1732
4	Vanadium Redox Flow Battery	0.1598	Vanadium Redox Flow Battery	0.1726
5	Flywheel	0.1534	Supercapacitor	0.1375
6	Pumped Hydro Storage	0.1117	Flywheel	0.1126

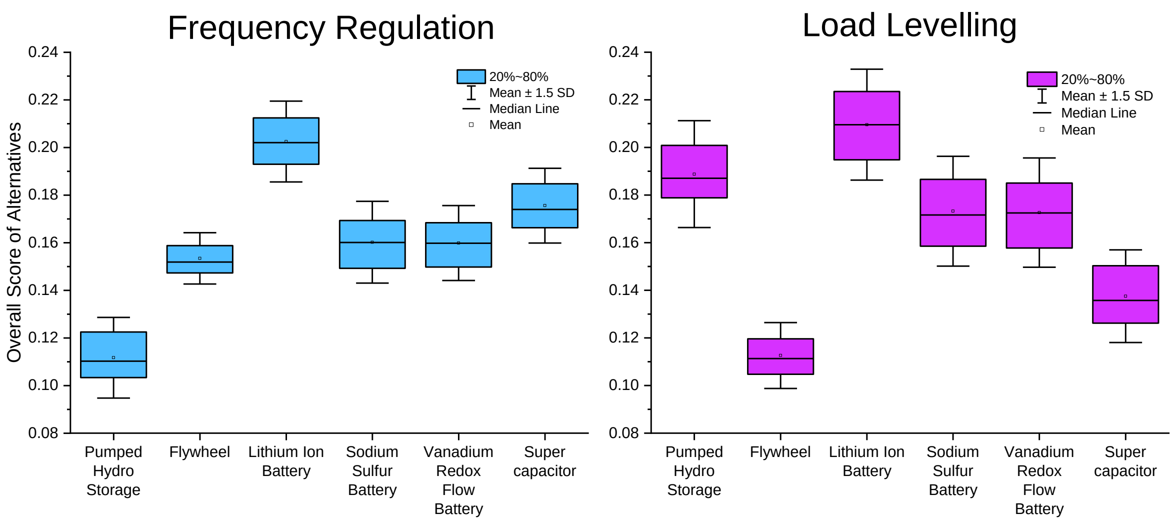

Figure 2: Box plots for the overall score of all alternatives in cases a) frequency regulation and, b) load levelling

From the results of section 3.1, and the simulation in section 3.2, GRA was applied to aggregate the scores of each alternative across all performance attributes resulting into a crisp single score per run in the simulation. The resulting range of scores per alternative for both Frequency Regulation and Load Levelling were given in figure 2, and the ranking of alternative per application based on the average scores were given in table 2.

Lithium-ion Batteries were observed to dominate both applications. Supercapacitors closely followed Lithium ion Batteries for Frequency Regulation, while Pumped Hydro Storage closely followed that for Load Levelling. Only Lithium-ion Batteries and Supercapacitors are projected to rank first for Frequency Regulation as shown in figure 3. All battery systems, and Pumped Hydro Storage are the storage systems capable of ranking first for Load Levelling. The low score of Pumped Hydro Storage for Frequency Regulation validated that it is ill-suited for power applications as stated in Schmidt et al. (2018). Results also reflect the ill-suitedness of Flywheels and Supercapacitors for long-term energy applications as shown in Load Levelling.

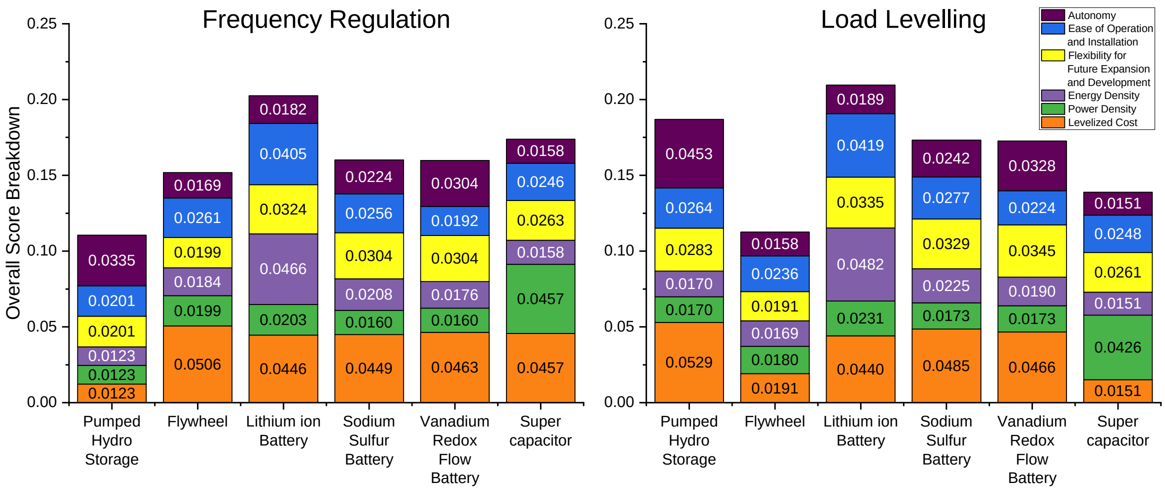

Figure 3: Percentage contribution of criteria on the overall score of alternatives for cases a) frequency regulation, and b) load levelling.

To further visualize the effect of each performance attribute on the score of alternatives, the breakdown of the scores for each alternative are given in figure 3. Lithium-ion battery dominated both Frequency Regulation and Load Levelling resulting from its good performance across all attributes. Pumped Hydro Storage has the poorest performance among all alternatives for Frequency Regulation from its low performance scores on the important attributes for Frequency Regulation. This validated the claim that Pumped Hydro Storage is not only unfit for Frequency Regulation due to its slow response but because of its Levelized Cost of Power, Power Density, and Energy Density. Flywheels and Supercapacitors have performed poorly for Load Levelling mainly because of their low Levelized Cost of Storage resulting from low energy capacities. Results verify that costs are not sufficient enough to select the best fit technology for specific applications as the least costly technologies for both scenarios failed to always score the highest among all alternatives. Consideration of other technical parameters for operation, and socio-economic parameters greatly affects the overall valuation of alternatives.
It is imperative in this study to consider all factors greatly affecting the decision-making structure involved in the deployment of a technology for a specific scenario, and definition of a specific application. The study emphasizes the importance of considering multiple factors in the decision-making process as a single factor, despite its obvious importance to the decision-making process, is insufficient to accurately predict the most suited technology for a specific application. It also emphasizes the importance of selecting and defining the application, and its scope and limitations, as varying the application and operating parameters greatly affected the priorities of decision-makers, and the overall ranking of alternatives. Lastly, it is important to accurately define the scope of the study, the involved decision-makers, the geography and political climate under consideration, and several dimensions necessary for system selection as this definition can greatly affect the resulting ranking of alternatives.

4. Conclusions and recommendations

In this study, a systematic approach for the selection of energy storage technologies for Frequency Regulation and Load Levelling was proposed to address the lack of knowledge on considering multiple factors on decision-making, and to resolve difficulties arising from the wide variety of technology options with unique characteristics. A survey on qualified decision-makers for the applications resulted to overall consistencies of 0.7232 for Frequency Regulation, and 0.6129 for Load Levelling. The Levelized Cost of Power dominated all other criteria for Frequency Regulation, and Levelized Cost of Storage for Load Levelling. Lithium-ion Battery dominated all alternatives for both Frequency Regulation, and Load Levelling resulting from its good performance scores across all performance attributes given its current state despite the presence of other technologies with better levelized costs. Results emphasized the importance of considering other factors on the decision-making structure, which most literature review fail to accommodate. Thorough analysis on the score breakdown is deemed useful to guide not only decision-makers, but developers and innovators as well for the future roadmap of various technologies. Further development and innovation on poorly performing attributes will enable future competitiveness of other technologies. Projections and predictions of parameter values over time are deemed crucial to determine how the ranking of technologies will be affected towards the future. Application of the tool on other applications, considering other factors, and considering other alternatives are also recommended. Lastly, sensitivity analysis is important to determine the relative impact of battery characteristics, operating parameters, and judgments of decision-makers on the overall scoring and ranking of alternatives.

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