Evaluation and Analysis of Battery Technologies Applied to Grid-Level Energy Storage Systems Based on Rough Set Theory

Zhiyuan Xie¹ · Liang Du¹ · Xiaojun Lv¹ · Qing Wang¹ · Jianglei Huang¹ · Tianyi Fu² · Shengyue Li²

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Abstract

Interest in the development of grid-level energy storage systems has increased over the years. As one of the most popular energy storage technologies currently available, batteries offer a number of high-value opportunities due to their rapid responses, flexible installation, and excellent performances. However, because of the complexity, multifunctionality, and wide deployment of power grids, trade-offs in battery performance exist, especially when considering economics, environmental effects, and safety. Therefore, establishing a comprehensive assessment of battery technologies is an urgent undertaking. In this work, we present an analysis of rough sets to evaluate the integration of battery systems (e.g., lead–acid batteries, lithium-ion batteries, nickel/metal–hydrogen batteries, zinc–air batteries, and Na–S batteries) into a power grid. Specifically, technological properties, economic significance, environmental effects, and safety of these battery systems are evaluated on the basis of rough set theory. In addition, some perspectives are provided to promote the development of battery technologies for grid-level energy storage.

Keywords Grid-level energy storage · Battery · Assessment · Rough set theory

Introduction

Electrical energy is highly essential in the twenty-first century to promote sustainable economic growth and social prosperity. Ways to generate and utilize electrical power are changing dramatically across the world, thus presenting enormous challenges for power networks to meet transmission and distribution demands with unpredictable daily and seasonal variations. Electrical storage systems, as a technology for storing and supplying electrical energy, could provide a stable, safe, and versatile power source for a large number of applications; thus, these systems play a fundamental role in daily life. In practical use, electrical power storage systems demonstrate multiple attractive functions for power network operations and load balancing, including: (1) storage of surplus power during peak generation periods and provision of vacant power during peak load periods; (2)

alleviation of the intermittence of renewable energy generation; and (3) assistance in efforts to manage distributed power generation and failure prediction. Considering the expansion and growing complexity of power applications, grid-level electrical energy storage systems are increasingly necessary to address load leveling, alleviate the intermittence of renewable energy supply, regulate frequency, and manage power [1–3].

Batteries are the most desirable electrochemical devices for grid-level electrical energy storage; these devices are characterized by easy modularization and rapid responses [4–6]. Moreover, battery systems demonstrate the important advantages of flexible installation and short construction cycles, thus providing great investment benefits when applied to grid-level energy storage systems [1, 7]. Recent years, various batteries technologies are successfully developed. The performance of batteries, including their efficiency, cycling life, power, and energy density, has been remarkably improved by emerging technical innovations [8–11]. However, due to the complexity, versatility, and large-scale deployment of electrical storage grids, great challenges are often encountered during the integration of existing battery systems into these grids when taking performance, cost, environmental impacts, and safety issues

✉ Zhiyuan Xie
540625141@qq.com

¹ State Grid Zhejiang Zhedien Tendering Consulting Co., Ltd., Hangzhou 310000, Zhejiang, China

² State Grid Zhejiang Procurement Company, Hangzhou 310000, Zhejiang, China

into consideration. As an ideal energy storage system, battery systems should be constructed on the basis of the requirements of grid energy storage applications, which may include high capacity, high energy efficiency, long lifetime, high power and energy densities, and low self-discharge ratio. Moreover, a robust and safe battery module is critical for building an efficient battery system. Assessment of the economic and environmental impacts of batteries in grid-scale applications should also be carried out [12]. However, to date, the existing electrochemical battery systems cannot fully meet all requirements because trade-offs often exist in different properties. Therefore, selecting the most appropriate electrochemical battery system to support the development of power grids has attracted wide research interest.

Due to multiple factors influencing the applicability of batteries in power storage systems, the evaluation process for different batteries involves great complexities. Many researchers have focused on assessing the performance of battery units, such as their discharge–charge cycling performance, specific energy, and power density. For example, Xu et al. [13] presented a semi-empirical lithium-ion batteries (LIB) degradation model that assesses the loss of battery lifetime from operating profiles. Deng et al. [14] developed a cycling life and environmental effect assessment technique for Li–S batteries for electric vehicles. Assunção et al. [15] analyzed the cost, remaining lifetime, and capacity of reused batteries from electric vehicles in their second application as an energy storage system by assessing their technical and economic properties on the basis of the technical performance of different energy storage technologies. Moreover, Fares and Webber [16] assessed the lifetime of batteries in a micro-grid operating in islanded mode by using experimental data. However, although some evaluation methods have been established, most of the proposed indicators focus only on technical aspects. Very few assessments describe the comprehensive assessment of battery storage systems used for power grids. More importantly, a comprehensive and systematic evaluation index system has yet to be formed. Therefore, developing an objective, comprehensive, and quantitative analytical method to assess the operating characteristics (e.g., technological properties, economic significance, environmental impact, and safety) of different energy storage types in the practical use of grid systems is an urgent matter. The complexity of these characteristics introduces many uncertain factors to such an assessment, thus leading to incomprehensive evaluation results. Interestingly, rough set theory, a mathematical tool used to deal with vague and imprecise issues, is considered to be a reasonable, and effective approach to such evaluations [17, 18].

In this work, we present the quantitative analytical method of rough sets to evaluate the integration of electrical energy storage systems (e.g., lead–acid batteries [LABs], LIBs, nickel/metal–hydrogen batteries [Ni–MHs], zinc–air

batteries [ZABs], and Na–S batteries [Na–SBs]) into a power grid to establish a comprehensive assessment for different battery technologies. Using rough set theory, we assess some key characteristics of battery technologies for energy storage, including their technological properties (e.g., energy efficiency, operating voltage, cycling performance, and energy density), economic significance, environmental impact, and safety, to identify their advantages, and challenges. In addition, perspectives on future directions are presented to provide insights into the development of novel energy storage systems for grid-level energy storage.

Rough Set Theory

Definition of Rough Set Theory

Rough set theory, an effective tool used to solve vague and uncertain issues, is a mathematical approach first introduced by Zdzislaw Pawlak, a known mathematician, in the early 1980s [18]. Rough set and fuzzy set theories are similar methods used to treat imprecise data. However, in contrast to the concept of partial membership in fuzzy set theory, rough set theory expresses uncertainty, and imprecision by a boundary region of a set [19, 20]. The rough set refers to the process of topological operations, also known as approximations [21], and is generally built on the assumption that an information system of the elements of the universe has been established. It comprises a framework that can be used to induce minimal decision rules and further classify objects. Specifically, rough set analysis mainly attempts to direct a reasonable assessment for multiple factors by searching for large databases. The main principles of rough set theory are indiscernibility, approximation, reduction, and decision rules [22]. During rough set analysis, the role of the reduction process is to eliminate redundant attributes, and the obtained reduction set is considered a minimal attributes set, which preserves the partition of the finite objects set and, therefore, serves as the original class [23, 24]. Decision rules are established by combining the reduction attributes set values. Due to the unique advantages of rough set theory in dealing with inaccurate data, research in this area has boomed since the 1990s. Today, rough set theory is recognized as an effective technique for classifying objects [25–27].

Rough set theory is defined as follows [18, 28]:

Definition 1 Set U to be a non-empty set and R to be an equivalence relation on U . Knowledge information representation system S is defined as follows: $S = (U, R, V, f)$, where U , defined as $U = \{X_1, X_2, X_3, \dots, X_n\}$, is considered the universe of discourse and the set of all samples; R , defined as $R = C \cup D$, is the attribute set, in which subset C is a condition attribute set reflecting the feature of objects and D

represents the decision-making attribute set reflecting the variety of objects; V is an attribute value set defined as $V = \bigcup_{r \in R} V_r$, where V_r denotes the range of r values; and $f: U \times R \rightarrow V$ is an information function used to determine the attribute value of every object x in U , which means if any $x_i \in U$, $r \in R$, then $f(x_i, r) = V_r$.

Definition 2 Set B , which is defined as $B \subseteq R$, as the attribute subset. If the object $x_i, x_j \in U$, $\forall r \in B$, when if and only if $f(x_i, r) = f(x_j, r)$, then x_i and x_j are indiscernibility, that can be written as $\text{IND}(B)$ in short.

Definition 3 The basic set includes a finite set (U) and the equivalence relation variety of $U(R)$. Then, $K=(U, R)$ denotes the knowledge base. In the knowledge base, if $B \subseteq R$, then $\cap B$ refers to the inter-sets of all equivalence relations in B . It is also called the indiscernibility relation of B , which can be written as $\text{IND}(B)$. Every set of $\text{IND}(B)$ is called a basic set.

Definition 4 For an information system $S=(U, R, V, f)$, in which x represents any sample subset $x \subseteq U$ and R has an equivalence relation with U , lower and upper approximations are calculated as follows: $R_-(X) = \{x \in U, [x]_R \subseteq X\}$; $R^-(x) = \{x \in U, [x]_R \cap X \neq \emptyset\}$.

Definition 5 Suppose $r \in R$. If $\text{IND}(R) \neq \text{IND}(R - \{r\})$, then r in R is considered as necessary; otherwise, r is regarded as a redundancy.

Definition 6 In the decision system $S=(U, R, D, V, f)$, assuming that $U/D = \{D_1, D_2, \dots, D_k\}$ denotes the division of the domain U by the decision attribute set D , $U/P = \{P_1, P_2, \dots, P_m\}$ denotes the condition attribute set $P(P \subseteq R)$ for the division of the domain U . $\text{pos}_P(D) = \frac{\bigcup_{D_i \in U/D} P(D_i)}{|U|}$ is considered the positive region of P for D .

Definition 7 In the information system $S=(U, R, V, f)$, $\forall p \subseteq C$, assuming $U/\{p\} = \{P_1, P_2, \dots, P_m\}$, the importance of attribute p is defined as

$$\text{sign}(\{p\}) = \sum_{i=1}^m \frac{|P_i| |U - P_i|}{|U|(|U| - 1)}. \quad (1)$$

Definition 8 In the information system $S=(U, R, V, f)$, $\forall c_i \in R$, and the weight of the attribute c_i in the information system is defined as

$$\omega(\{c_i\}) = \frac{\text{sign}(\{c_i\})}{\sum_{j=1}^{|c|} \text{sign}(\{c_j\})}. \quad (2)$$

Processes of Evaluating Batteries Based on Rough Set Theory

The specific steps of the grid application energy storage technology evaluation method based on rough set theory are as follows:

1. Establish the initial information system $S=(U, R, V, f)$. The attribute set of the information system in the comprehensive assessment includes technical properties, cost, environmental effect, and safety issues. The battery technologies to be evaluated are used as the object set in the information system. The data of each attribute obtained from each object are discretized to build an information system S .
2. Reduce information system attributes. The information system can be reduced by the discretization method on the basis of rough set theory to calculate uncertain relationships. Reduction of information system attributes refers to the deletion of irrelevant or unimportant attributes while maintaining classification properties. The information system can be simplified through information reduction and removal of unnecessary attributes without losing the basic information of concern. This step can effectively improve the clarity of the information system and help obtain concise decision rules from complex decision systems.
3. Evaluate the calculation of indicator weights. The importance and weight of the attribute (evaluation index) can be calculated based on the reduced information system by using Eq. (1)–(2).
4. Establish a comprehensive evaluation model.

Evaluation of Batteries Based on Rough Set Theory

Determination of Evaluation Indicators

Several factors should be considered when choosing and developing a suitable battery technology for a particular application. Evaluating different battery systems to select the most suitable technology is necessary to adapt to complex and multifunctional applications in a grid-level energy storage system. Setting scientific and reasonable evaluation indicators is the first step of comprehensive evaluation. In the present work, a comprehensive and systematic evaluation index system is set up based on technological features, economic significance, environmental impacts, and safety. The characteristics of battery systems that are mainly considered in the assessment process are as follows [16, 29–32]:

(1) Round-trip efficiency

Round-trip efficiency, also known as the energy efficiency, refers to the ratio of released energy (W_r) to stored energy (W_s) and is defined as $\eta = W_r/W_s$; this characteristic represents the amount of stored electricity that can ultimately be extracted from the battery. Good overall efficiency is necessary for a competitive storage system. Good efficiency means the power transfer chain experiences limited loss to realize optimum operations during energy transfer and self-discharge. Therefore, selecting criteria to measure energy conservation goals for daily network load leveling applications is an essential task.

(2) Specific energy

Specific energy represents the maximum amount of energy accumulated per unit of mass or volume of the battery; this characteristic is especially important for certain applications, in which mass and volume are limited.

(3) Specific capacity

Specific capacity is defined as the amount of electricity that can be discharged per unit of mass.

(4) Operating voltage

Operating voltage refers to the voltage of the battery during operation, that is, the potential between the anode and cathode of the battery when the battery is under normal working conditions.

(5) Cycling life

Cycling life represents the number of times a battery can perform stable discharge–charge cycles and is expressed as the maximum number of cycles N ; here, one cycle corresponds to the time of one discharge, and one charge means the battery can release the originally designed energy level after each recharge. This characteristic depends on many variables, such as storage technology type and operating conditions.

(6) Self-discharge

Self-discharge refers to the portion of initially stored energy dissipated over a period of non-use in the form of electrochemical losses in the battery, which is subject to material electrochemistry, battery manufacturing processes, and storage environments.

(7) Cost

Cost is an important economical parameter that affects the total expenditure of energy production. In the present work, the cost is divided by the energy production to obtain the cost per unit of useful energy.

(8) Environmental impact

Environmental impacts involve all potential pollutions generated during the entire life cycle of battery use. For example, harmful substances discharged into the surrounding environment during a battery's use could pollute water and air during its lifetime. The environmental impact of the residual material after the battery is discarded could also cause pollution; this impact is a dimension that must not be overlooked in the energy storage system.

(9) Safety

Safety represents the maintenance of good condition and absence of threats to human health under normal use conditions and incident events.

Establishment of an Information System

Based on the characteristics of various energy storage systems and the requirements of a grid-level energy storage system, we choose five battery systems to analyze promising batteries for application in grid energy storage. These five energy storage technologies (e.g., LABs, LIBs, Ni–MHs, ZABs, and Na–SBs) are taken as examples, recorded as $U = \{X_1, X_2, X_3, X_4, X_5\}$, and evaluated using the rough set method. These five battery technologies are used for case analysis based on the above performance index system. The relevant values are shown in Table 1.

Reduction of Information System Attributes

The performance index of a battery is discretized by using SPSS 16.0 to assess the performance of different battery technologies on the basis of rough set theory. The discretized data results are shown in Table 2.

Since the attribute values of the evaluation objects corresponding to C_4 and C_8 are identical, that is, they have the same resolving power, only the attributes of one of these objects need to be retained. Therefore, Table 2 can be further reduced to Table 3.

Table 1 Evaluation indices and corresponding parameters of battery technologies [30, 33–37]

Battery	Round-trip efficiency (%)	Specific energy (Wh/kg)	Specific capacity (W/kg)	Operating voltage (V)	Cycling life	Self-discharge (% per day)	Cost (\$/kwh)	Environmental pollution	Safety
LABs	80	40	180	2	2000	0.2	400	8	5
LIBs	95	250	285	3.6	6000	1	1000	6	2
Ni–MHs	70	70	728	1.2	2000	0.8	700	4	6
ZABs	60	600	600	1.2	400	4	800	2	6
Na–SBs	85	150	160	1.8	4000	20	600	5	2

Table 2 Information system for evaluating battery technologies

U	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
X_1	2	1	1	2	1	1	1	2	2
X_2	2	2	1	2	2	1	2	2	1
X_3	1	1	2	1	1	1	2	1	2
X_4	1	2	2	1	1	2	2	1	2
X_5	2	2	1	2	2	2	2	2	1

Table 3 Reduced information system for evaluating battery technologies

U	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_9
X_1	2	1	1	2	1	1	1	2
X_2	2	2	1	2	2	1	2	1
X_3	1	1	2	1	1	1	2	2
X_4	1	2	2	1	1	2	2	2
X_5	2	2	1	2	2	2	2	1

Table 4 Importance and weight of each performance parameter

U	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
Importance	1	1	1	1	1	0.4	1	1	1
Weight	0.119	0.119	0.119	0.119	0.119	0.047	0.119	0.119	0.119

Calculation of Indicator Weights

According to the definitions described above, the set of all samples U is written as $U = \{X_1, X_2, X_3, X_4, X_5\}$, and the attribute set R is defined as $R = \{C_1, C_2, C_3, C_4, C_5, C_6, C_7, C_9\}$. Then, the importance and weights of the attributes are calculated as follows: $U/\text{IND}(R) = \{X_1, X_2, X_3, X_4, X_5\}$, $U/\text{IND}(R-C_1) = \{X_1, X_2, X_3, X_4, X_5\}$; $U/\text{IND}(R-C_2) = \{X_1, X_2, X_3, X_4, X_5\}$; $U/\text{IND}(R-C_3) = \{X_1, X_2, X_3, X_4, X_5\}$; $U/\text{IND}(R-C_4) = \{X_1, X_2, X_3, X_4, X_5\}$; $U/\text{IND}(R-C_5) = \{X_1, X_2, X_3, X_4, X_5\}$; $U/\text{IND}(R-C_6) = \{X_1, \{X_2, X_5\}, X_3, X_4\}$; $U/\text{IND}(R-C_7) = \{X_1, X_2, X_3, X_4, X_5\}$, $U/\text{IND}(R-C_9) = \{X_1, X_2, X_3, X_4, X_5\}$; $\text{IND}(P) = \text{IND}(Q) = U/\text{IND}(R)$, $\text{pos}_P(Q) = \{X_1, X_2, X_3, X_4, X_5\}$, $\text{pos}_{R-C_1}(Q) = \{X_1, X_2, X_3, X_4, X_5\} = 5$;

$$\begin{aligned} \text{pos}_{R-C_2}(Q) &= \{X_1, X_2, X_3, X_4, X_5\} = 5; \text{pos}_{R-C_3}(Q) = \{X_1, X_2, X_3, X_4, X_5\} = 5; \\ \text{pos}_{R-C_4}(Q) &= \{X_1, X_2, X_3, X_4, X_5\} = 5; \text{pos}_{R-C_5}(Q) = \{X_1, X_2, X_3, X_4, X_5\} = 5; \\ \text{pos}_{R-C_6}(Q) &= \{X_1, X_2, X_3, X_4, X_5\} = 3; \text{pos}_{R-C_7}(Q) = \{X_1, X_2, X_3, X_4, X_5\} = 5; \\ \text{pos}_{R-C_9}(Q) &= \{X_1, X_2, X_3, X_4, X_5\} = 5 \end{aligned}$$

The importance and weights of C_1 – C_9 are calculated according to Definitions 7–8 of rough set theory as shown in Table 4. Technological properties, economic significance, environmental impact, and safety should be of great concern when using battery technologies in energy storage systems, in which self-discharge is not the major limiting factor when selecting and developing the battery system.

Fig. 1 Evaluation results of the five battery technologies assessed in this work

Comprehensive Evaluation of Battery Technologies

Assuming the final score of the battery system to be S , F_{ij} represents the score of the C_j measure of the X_i criterion, and the corresponding weight is W_{ij} .

$$S = \sum_{i=1}^5 \sum_j F_{ij} \cdot W_{ij} \quad (3)$$

The final scores of the five battery technologies determined through pre-research are shown in Fig. 1. Different battery technologies demonstrate unique advantages and disadvantages (Fig. 2). ZABs clearly demonstrate great promise in grid energy storage applications on account of their relatively high specific energy and capacity. Moreover, ZABs are based on zinc electrodes and free-oxygen fuel from the atmosphere and, thus, characterized by low cost, environment friendliness, and safety. Several primary ZABs have been commercialized. However, some challenges to the wide-scale application of ZABs have been noted on account

of issues related to their electrodes and electrolytes. For example, air cathodes suffer from sluggish reaction kinetics due to four-electron oxygen reactions, which leads to low discharge voltages, high charge voltages, and low energy efficiency [38, 39]. Besides, in a typical alkaline electrolyte, zinc electrodes interact with the electrolyte, resulting in passivation, and dendrite growth issues, both of which are detrimental to battery life [40]. In addition, owing to the unique half-open structure of ZABs, electrolytes may suffer from issues, such as carbonation in the atmosphere and water loss, during discharge–charge cycling [41, 42]. LABs, which exhibit high specific capacity, high energy efficiency, good cycling durability, and low self-discharge, have long been recognized as reliable energy storage systems. However, the lead content of LABs could pollute the environment and threaten human health, thus limiting their long-term applications. LIBs have been successfully commercialized in portable electronics as power sources due to their attractive features, which include remarkably high round-trip efficiency, high operating voltage, and long cycling life. However, the high price of lithium resources and safety issues result in the limited applications of LIBs in stationary energy storage, so the optimal management and recycling of LIBs are required [43]. Ni–MHs demonstrate great promise in power grid applications due to their relatively high energy density, high specific capacity, long cycling life, and environmental friendliness. However, compared with LABs, Ni–MHs exhibit lower energy efficiency and require much higher cost. In addition, when operated at low temperatures, they suffer from significantly decreased performance. Na–SBs, which show a relatively high efficiency, high operating voltage, and long cycling life, have been used in small-scale energy storage applications. However, safety issues brought about by their high-temperature operating conditions impede their further application.

Fig. 2 Radar plots of the five battery technologies assessed in this work

Conclusions and Outlooks

Electrical energy grids serving as energy storage and regulatory systems have attracted increasing attention for their ability to address load leveling, alleviate the intermittence of renewable energy supply, and regulate frequency. The success of an electrical energy grid critically depends on progress in the development of efficient power supply systems. Due to their desirable properties, electrochemical batteries are considered promising energy storage devices with many useful applications. In this work, the characteristics of LABs, LIBs, Ni–MHs, ZABs, and Na–SBs are investigated in a grid-level energy storage system. Comprehensive assessment considering key technical properties (e.g., round-trip efficiency, specific energy and capacity, operating voltage, cycling life, self-discharge), economic significance, environmental impacts, and safety issues are conducted on these batteries to establish a perspective on battery technology evaluation. Ultimately, we aim to set up a roadmap to guide future studies and improve grid-level energy storage systems. The most favorable battery technologies in the future will be characterized with high specific energy and capacity, long cycling lifetime, low self-discharge, low cost, environment friendliness, and safety.

Despite considerable progress in battery development, however, many other challenges must be addressed to realize the practical applications of this energy storage system in a grid. Some directions for future work include:

1. Although a large number of battery technologies have been reported, the fabrication of low-cost high-performance batteries with excellent power and energy densities, operating safety, and cycling stability remains a great challenge. In-depth investigations of high-performance and novel battery systems are necessary. Many efforts, for example, to investigate high-performance potassium-ion batteries with relatively high energy density but lower cost compared with LIBs, are ongoing [44].
2. Since standard methods to evaluate battery performance and battery data are lacking, comparison of literature results is difficult. Thus, developing consistent and clear rules to evaluate and compare the performance of different battery technologies is important. For example, the reported current, energy, and power densities of batteries should be calculated based on uniform standards (e.g., test area, mass of consumed active material, and assembled battery volume).
3. Developing high efficiency and low-cost battery manufacturing technologies is highly necessary to meet the large-scale requirements of energy storage grids.

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Zhiyuan Xie graduated from Gezhouba Hydropower Engineering College in July 1996. After that, he was engaged in relay protection commissioning in the commissioning company of Zhejiang Transmission and Transformation Engineering Company from August 1996 to June 2004. He worked as a substation engineer and engaged in project management in the project management department of Zhejiang Power Transmission and Transformation Engineering Company from July 2004 to June

2007. From July 2007 to present, he engaged in the bidding practice and management in State Grid Zhedien Tendering and Consulting Co. Ltd.