Energywith Technical Report

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Energywith Co., Ltd.

CONTENTS

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Energywith Technical Report

The business operations of Energywith Co., Ltd. (EW) cover the manufacture and sale of storage batteries as well as the provision of system services involving storage batteries. Building on more than a century of experience manufacturing lead-acid batteries, the company was relaunched in 2021 under the new name Energywith to express the idea of the contribution to the advancement of energy technology. This move marked a shift in our business model from one focused on the provision of physical products (the manufacture and sale of lead-acid batteries) to one emphasizing the provision of total solutions extending from the initial building of systems to their maintenance and inspection over the long term. By actively proposing optimal solutions to the challenges facing our customers, while continuing to pursue the highest level of quality, we aim to evolve from a specialized manufacturer of storage batteries into a provider of proposal-based energy storage solution and contribute to the realization of a sustainable society in the process.

Lead-acid batteries are nearly 100% recyclable. When these products reach the end of their service life, they can be collected and turned onto new batteries, achiving smaller carbon dioxide emissions comparing to use ore based lead. What’s more, they simplify the building of safe storage battery systems in comparison with lithium-ion batteries, and their adoption in renewable energy applications is expected to grow moving forward. EW believes lead-acid batteries will continue to occupy a key role in our proposal-based energy storage solution from the viewpoint of achieving a closed-loop supply chain incorporating reuse and recycling. As we work to boost performance moving forward, we will continue to pursue essential product development and build out the total supply chain necessary to fulfilling the role of a provider of system services based on storage batteries. EW is also developing nickel-zinc battery products employing an aqueous solution as the electrolyte, enabling easy recyclability and the ability to withstand environments too harsh for lithium-ion batteries.

In this volume we feature two papers by outside contributors, and we are grateful to the authors for making them available for publication in Energywith Technical Report. The first, from Professor Toshihiro Inoue of the Headquarters for Innovative Society-Academia Cooperation at the University of Fukui, is entitled “Lead Acid Batteries, Past and Future.” It reviews the history and characteristics of lead-acid batteries and suggests the potential this technology holds moving forward. With a history going back more than 160 years, during which countless technical breakthroughs and advances have occurred, lead-acid batteries continue to hold profound because of its electrochemical complexity and the potential for new advances in materials, processes, and uses. Professor Inoue urges EW to continue to pursue new advances, while giving due care to the relevant regulations. The second, entitled "Frontiers in Lithium-Ion Battery Degradation Modeling and Application to Lead-Acid Batteries," was contributed by the Computational Science Center of Kobelco Research Institute, Inc. Degradation prediction technology plays an extremely important role in the advancement of the storage solutions business. The charge-discharge mechanism of lead-acid batteries is more complex than that of lithium-ion batteries due to the dissolution and precipitation that accompanies the electrochemical reaction. Prediction in real-world environments is difficult because many of the factors causing degradation and its variability are unknown. The theme of degradation prediction is a challenging one that brings together a deep knowledge of battery systems, machine learning, and statistical analysis. At EW we are collaborating with outside specialists such as Professor Inoue and the staff of Kobelco Research Institute in our efforts to improve the quality and performance of storage batteries and to develop core technologies for use in system solutions.

Of the three technical reports, two deal with content related to proposal-based energy storage solution. The report entitled "Proposal-Based Energy Storage Solution" provides an overview of EW's proposal-based energy storage solution from the viewpoint of a provider of system services based on storage batteries. It summarizes advances thus far in the technology of detecting the state of storage batteries, which is essential to realizing the full functionality of storage batteries and to providing storage systems that are safe and reliable, and charts the direction of technical development moving forward. The second report, "Development of Core Technologies for Providing One-Stop Solutions in Renewable Energy Storage Systems," focuses on renewable energy storage systems, which form the third pillar of EW's business alongside lead-acid batteries for automotive and industrial use and power supply units. It describes the components of a complete renewable energy storage system incorporating long cycle life storage batteries for renewable energy (the LL1500 series), power conditioning systems (PCS), and energy management systems (EMS), and also provides an overview of the storage battery systems, control systems, and monitoring systems covered by EW's one-stop solutions spanning design, installation, maintenance, and disposal. The final report, "Decomposition and Evaluation of Battery Performance Variation Based on Statistical Interpretation," describes technology employing digital transformation (DX). As was noted in the preceding volume, EW's use of DX started with improving quality as the theme, then statistical analysis tools were incorporated and concrete results were achieved. DX is indispensable to our efforts to move from a business model consisting simply of selling storage batteries to one based on providing value arising from our knowledge of storage batteries, and its applications will continue to expand moving forward.

It is our hope that the Energywith Technical Report will enable readers to gain an understanding of the goals EW aspires toward. We look forward to your continued encouragement and guidance.

Lead Acid Batteries, Past and Future

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1 Abstract

The lead acid battery has over 160-year improvement for various applications. It is generally used for SLI car battery with combustion engine and for energy storage devices in the back-up system around the world, because of its low cost, valuable reliability and technology improvements.

The storage energy with renewable wind power and/or solar power can supply local grid and grid systems. It can also supply as an emergency power source in the event of a disaster. In addition, the production of lead as a material is not the specific region. It has advantages in resource security, easy handling and recycling. The lead acid battery is excellent storage devices that can be realized to develop materials, processes, and system control methods for further progress.

2 Introduction

The types of secondary batteries (rechargeable batteries) in widespread use today are lead-acid batteries, nickel/metal hydride (Ni/MH) batteries, and lithium-ion batteries. Of these types of rechargeable storage batteries, Ni/MH batteries and lithium-ion batteries are relatively new, having come into practical use around 1990.

In contrast, lead-acid batteries have over 160-year history since the invention by Gaston Planté[1)] in 1859. The lead-acid batteries are still remained in worldwide widely used today. Lead-acid batteries have even been referenced in problems appearing in "The Common Test for University Admissions" (entrance examinations) in Japan (previously known as "The National Center Test for University Admissions") [2)].

Lead-acid batteries have been used in a wide range of applications over the years, including mobile uses such as SLI (Starting, Lighting and Ignition) car batteries with combustion engine and stationary uses such as backup power supplies. They also have excellent characteristics in terms of the environment and as resources because the lead used in them can be recycled. In this paper, it looks back on the long history of lead-acid batteries and provide ideas for their future development.

3 History and features of lead-acid batteries

Lead-acid batteries have a long history same as dry cells. The active research and development seem to be started around 1950 that led to the analysis of their basic electrochemical reaction and its mechanisms. There can be seen numerous examples of key publications from this period, including review article by Tagawa, et al.[3)], paper on the lead dioxide electrode by N. A. Hampson, et al.[4)], and review articles by J. Perkins[5)] and P. Ruetschi[6)]. The papers by researchers such as J. Burbank[7)], P. Ruetchi, et al.[8), 9)], and K. Bullock[10)] provide detailed examples such as Potential-pH diagram and the mechanisms of lead oxidation reactions. A book of "Lead-Acid Batteries" by H. Bode[11)] is considered an excellent work on this field, and in recent years D. A. J. Rand, et al.[12)] and D. Pavlov[13)] have provided important books on the cell chemistry and engineering. There is also detailed review article by D. A. J. Rand[14)].

In a lead-acid battery, the positive electrode is made of lead oxide (lead dioxide or lead (IV) oxide), sponge like porous lead is used as the negative electrode, and dilute sulfuric acid is used as the electrolyte. As the lead-acid batteries, during discharge, lead sulfate is formed in both the positive and the negative electrodes. This causes the concentration of sulfuric acid in the electrolyte becomes low. The basic electrochemical reactions that occur in a lead-acid battery are shown below[5)], and approximately 2 V of electromotive force (EMF) is obtained per cell. A typical SLI car battery shows 12 V of battery voltage which consists of six cells connected in series.

$$\text{Negative Electrode: } Pb + SO_4^{2-} \underset{CHG}{\overset{DISCHG}{\rightleftarrows}} PbSO_4 + 2e^- \quad (1)$$

$$\text{Positive Electrode: } PbO_2 + 4H^+ + SO_4^{2-} + 2e^- \underset{CHG}{\overset{DISCHG}{\rightleftarrows}} PbSO_4 + 2H_2O \quad (2)$$

$$\text{Cell Reaction: } Pb + PbO_2 + 2H_2SO_4 \underset{CHG}{\overset{DISCHG}{\rightleftarrows}} 2PbSO_4 + 2H_2O \quad (3)$$

$$\text{EMF: } E = 2.041 - 0.1182pH \quad (4)$$

The electrochemical reactions that occur in lead-acid batteries are reversible, so it can be repeated charge-discharge cycles. Although it is commonly known that water undergoes electrolysis at 1.23 V, charging and discharging of a lead-acid battery shows at a voltage about 2 V. It is higher voltage than the water electrolysis. This is explained several reasons because the solubility of lead sulfate in the dilute sulfuric acid used as the electrolyte extremely low, the pH of the electrolyte is low, and the concentration of lead ions in the electrolyte is low, among other reasons. It can be calculated the positive and the negative potential by using the Nernst equations, then it shows the operation as a storage battery that can be obtained at a volage of approximately 2 V[4)–11)]. Though the actual value depends on factors such as the application and temperature, the cell operating voltage during charge-discharge is usually take place in a range from 1.6 V to 2.4 V per cell.

In today's marketplace, flooded electrolyte lead-acid batteries are used as automobile SLI batteries, including on vehicles with start-stop (idling stop) systems, and either flooded electrolyte lead-acid batteries or valve regulated lead-acid (VRLA) batteries are used for industrial applications. In the industrial field, they are also used in backup systems for telecommunications facilities, in stationary applications such as power storage, and in cyclic applications such as forklifts and automated guided vehicles (AGVs). VRLA is used oxygen recombination reactions which work oxygen generated on the positive electrode during charging is absorbed on the negative electrode and it reacts preventing the water loss in the electrolyte. Prototypes were developed in the 1960s. Initially, dilute sulfuric acid was added to a colloidal solution of silicon dioxide and allowed to partially solidify into gel state, which was used as the electrolyte. In the 1970s the gel electrolyte was replaced by a separator called an absorbent glass mat (AGM), made of a fibrous material with an average filament diameter of 0.8 to 20 μm, which was impregnated with dilute sulfuric acid. This is the VRLA configuration still used today. Details of the structure can be found in a patent from that period filed by Gates Rubber Co.[15)].

Whereas in the case of dry cells and lithium-ion batteries, the active materials are derived from powder material suppliers that are used for starting materials as manufacturing processes. In case of lead-acid batteries, there are just about the only type of batteries that are produced directly from raw materials into powder form at the beginning of production. As shown in **Figure 1**, the important point of the manufacturing process for lead-acid batteries is that the positive electrode, the negative electrode, and the both grids for the current collector are made of either pure lead or lead alloy. The lead oxide powder that is the active material is made from lead ingots. This now famous process was invented by Genzo Shimazu and is known as the lead oxide powder milling method[16)]. Extensive descriptions of battery manufacturing processes are provided in sources such as H. Bode[11)], T. L. Blair[17)], and L. Prout[18)–21)].

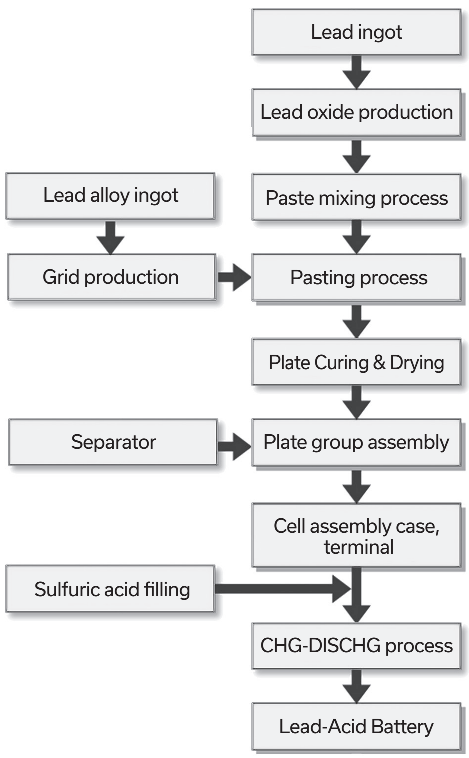

Figure 1. Example lead-acid battery (VRLA) manufacturing process

For details on the basic resource, battery materials, can be seen the report of the Japan Organization for Metals and Energy Security[22)]. Total reserves of lead are said to amount to about 90,000 kton. Of these reserves, 41% are said to be located in Australia, 20% in China, and 7% in Peru. The breakdown by country of the total raw lead production output of 12,832 kton is given as China 41%, U.S.A. 8%, India 7%, and South Korea 6%. In other words, lead is a resource that is not unevenly distributed by region or country. For comparison, total reserves of nickel, which is used in Ni/MH batteries and lithium-ion batteries, are said to amount of about 95,000 kton, with 22% located in Indonesia, 22% in Australia, and 17% in Brazil. The breakdown by country of the total production output of raw nickel of 2,632 kton is said to be Indonesia 33%, China 26%, Europe 13%, and Central and South America 10%. Finally, total reserves of lithium are said to amount to 22,000 kton, with 42% in Chile, 26% in Australia, and 10% in Argentina. The breakdown by country of the total raw lithium production output of 104.8 kton is given as Australia 52%, Chile 25%, and China 13%. When devising an “elements strategy” for battery materials, it is important to consider not only the regional locations of mineral reserves and extraction, but also the countries producing the raw materials and the sources of their capital.

Of the materials used in secondary batteries, lead is a metal with a relatively problem-free supply chain and an easily obtainable resource. It is also fortunate that the main application of lead metal is for lead-acid batteries, additionally, with some 73% of the lead consumed in Japan in 2020 being recycled[22]. This is a key feature of lead-acid batteries. However, the compliance of EU battery regulations[23), 24] may be emerge as a major issue.

4 Lead-acid batteries of the future

Although lead-acid batteries have a low energy density, their usable temperature range is wide, allowing them to be employed anywhere on Earth. In particular, their output characteristics at low temperatures are excellent, and this makes this type of battery indispensable in applications such as automobile SLI and start-stop (idling stop) systems.

To observe technical trends related to lead-acid batteries, data on intellectual property application filings in Japan was obtained by searching not only patent claims but also patents and utility models containing the term “lead-acid battery” or “lead battery” on the Japan Platform for Patent Information (J-PlatPat), and the results are shown in **Figure 2**. An increase in the number of hits can be observed from around 2012, and what is more the number of applications from outside Japan also increases. Some of the hits are for applications not directly related to lead-acid batteries, but many deal with various topics such as lead-acid battery manufacturing, additives, separators, lead-acid battery modules, system control methods or management methods, measuring technology, recycling, and vehicles. The number of applications filed from outside Japan and foreign applications filed by Japanese companies are both increasing. It shows that there is a need to look closely at lead-acid batteries both from the standpoint of possible future advances and in terms of intellectual property.

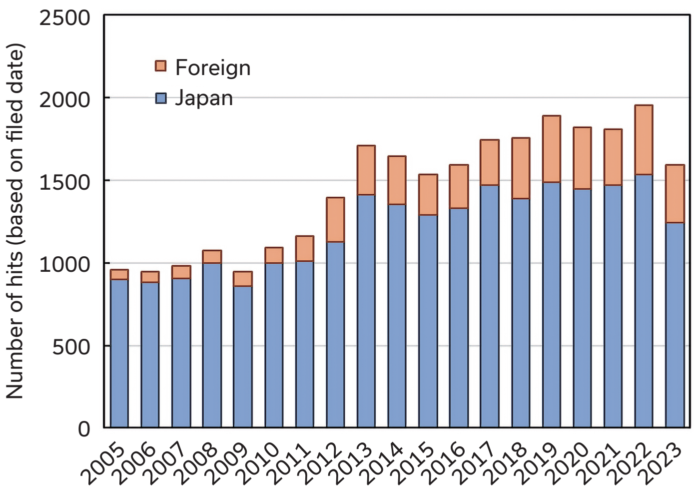

Figure 2. Number of patents and utility models in which the word “lead-acid battery” or “lead battery” appears in the text of the patent (applications filed in Japan)

Another notable feature of lead-acid batteries is the wide variation in possible per-cell capacities. Batteries are being manufactured with capacities ranging from around 1 Ah to over 3,000 Ah. Flooded lead-acid batteries or VRLA batteries for industrial use can be combined either in series or in parallel to create power supplies with capacities in excess of 10 MWh and provide support for social infrastructure in the form of backup power supplies for telecommunications facilities or data centers, cellphone base stations, and power generating stations.

In recent years, due to changes in the supply-demand structure for power, efforts have been made to achieve greater diversity in the environment surrounding distributed energy. For example, renewable energy systems such as storage systems combined with solar or wind power generation have been introduced, and this has increased the importance of storage systems. Effective ways of utilizing renewable energy include the installation of storage systems at power generating stations; the building of distributed systems at the region unit, building unit, or public facility (government office or school) unit level; and installation of storage systems in system networks. In particular, since schools are often designated as emergency evacuation sites in case of natural disasters, constructing a microgrid system combining solar power generation and lead-acid batteries as a hub can provide a system that can be made use of when disasters such as typhoons or earthquakes occur. Lead-acid batteries make it possible to build low-cost systems that combine high capacity and high voltage. Such systems are very safe, posing little danger of fire or explosion, and this together with their ease of maintenance and recycling makes them a superior option when building systems that will also need to be used in case of natural disasters. Such systems typically have a service life of around 20 years. With the collaboration of a system integrator, lead-acid batteries are excellent candidates for the configuration of network systems aimed at achieving green transformation (GX).

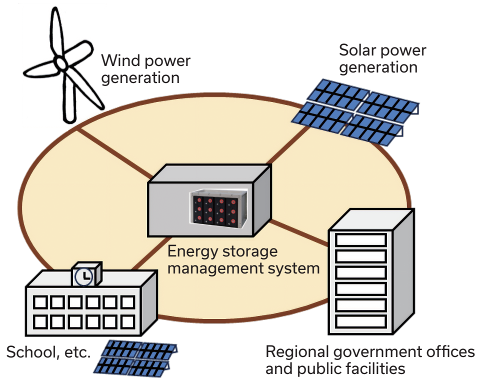

Figure 3. Example of energy management system in local area

At the same time, further performance advances for lead-acid batteries, in the factors causing their failure mode should be improved. The major failure mode is grid corrosion of positive current collector during charging and the softening of positive active material, which means becoming small particle of positive active material and damage of its structure. To preventing positive grid corrosion and keeping its structure led to improve cell operating life. It is also thought that modifications to the manufacturing process such as curing the active material or the use of additives may be effective for positive active material and its structure. Additionally, it is necessary to control balancing with positive and negative active materials such as boosting the charge acceptance at the negative active material, improving the separator, and preventing electrolyte loss. It is very important approach to raise the level of analysis of the interfaces inside lead-acid batteries, such as the interface between the grid and the active material in positive electrode, the interface between the electrode and the separator surface, and the interface between the active material and the electrolyte reaction area. Furthermore, applying digital technology of the sort employed in digital transformation (DX) efforts are effective in applications such as material and process design as well as simulation of chemical reactions. Improving the accuracy of these new control technologies, service life diagnostic systems, and system simulation, as well as efforts to improve low-temperature characteristics, are also expected to enable the building of systems that are easier to manage.

When it comes to storage battery development, a lot of R&D attention is focused nowadays on high-end chemistry such as lithium-ion batteries or the next generation new battery types, but also with regard to R&D and business considerations for lead-acid batteries, with their long history, it is necessary to consider as a whole industrial system. Additionally, it is indispensable to pay attention to trends in areas such as lithium-ion batteries for stationary applications and international standards[23), 24)] adopted by bodies such as the EU and IEC. For lead-acid batteries, the tendency of the supply chain to become more of a closed system (including storage batteries and system recycling) is key issue. The application of innovative advanced analysis technology from research and development work on lithium-ion batteries as well as the utilization of AI are expected to lead to the realization of superior lead-acid batteries and processes. It may be possible that dry cells and lead-acid batteries will continue in use far into the future. It seems to be interesting research to consider reference electrode suitable for lead-acid batteries, that can operate at temperatures below freezing point. A theme for development of new reference electrode may be helpful as future advances occur in lead-acid batteries.

5 Conclusion

Lead-acid batteries have built up their present standing as storage batteries over a long history. Although as storage batteries they are certainly not going to disappear anytime soon, it is necessary to be aware of the relevant regulations[23), 24)] and to be in corporates with the progress of society. On the other hand, in academic terms lead-acid is a complex battery chemistry due to its use of an acidic aqueous solution as the electrolyte and 2 V cell voltage, meaning that one must constantly consider the effects of electrochemical reactions including with oxygen and hydrogen. It is very complex battery in electrochemistry when one considers how phenomena such as changes in electrochemical potential or overvoltage are based on the Nernst equations, Potential-pH diagrams, or the Tafel equations. It is believed that through the efforts of engineers having a deep interest in the theory and practice of electrochemistry, it moves that lead-acid batteries will continue to advance in association with society and continue to make an important contribution.

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Frontiers in Lithium-Ion Battery Degradation Modeling and Application to Lead-Acid Batteries

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Secondary batteries, including lead-acid, nickel-metal hydride, and lithium-ion batteries, are being increasingly adopted in various fields such as information devices, electric vehicles, and spacecraft. As a result, battery degradation prediction has gained significant attention as a crucial technology for preventive maintenance. This paper provides an overview of the numerous lithium-ion battery degradation prediction techniques proposed thus far, and presents case studies of degradation prediction for individual cells and modules/packs. In particular, we focus on the construction of techniques using "physics-based model" that describe degradation phenomena as equations over time. Furthermore, we discuss the applicability and challenges of applying these models to lead-acid batteries, for which relatively few reports exist.

1 Introduction

In recent years, the use of both mounted and stationary lithium-ion batteries (LIBs) in mobile devices such as smartphones, electric vehicles, homes, and more has grown rapidly, and this has led to an increase in interest in technology for predicting aspects of performance such as heat generation, safety, degradation, and remaining service life.[1), 2)] In particular, since battery degradation is directly related to product service life, prediction technologies have been developed using a variety of methods, including empirical functions, simulations based on electrochemical reactions (physics-based models), and machine learning employing large volumes of data.[3)–11)] In contrast, there are few reports on the use of degradation prediction technology for lead-acid batteries,[17)–20)] in spite of their long history of use as secondary batteries, leaving a large amount of room for future development.

This paper begins with an outline of the current state of LIB degradation prediction technology, presenting examples of developments in simulation pf heat generation and degradation in battery cells or packs. This is followed by a discussion of the degradation mechanisms of lead-acid batteries and the possibility of applying LIB models to them.

2 Types of secondary battery degradation prediction models

Factors causing LIB degradation during charging and discharging or during storage can vary greatly depending on the electrode material or conditions, but side reactions accompanying lithium intercalation are the main ones, with known examples including the growth of a solid electrolyte interface (SEI) on the surface of the anode active material, structural transition or elution of the cathode active material, electrolyte degradation or exhaustion, deposition of lithium metal, and an increase in contact resistance between the active materials or with the collector foil.[2)] **Figure 1** shows a map classifying representative degradation prediction models.[10)] The horizontal axis represents the classification of models as black box (user's viewpoint) versus white box (developer's viewpoint), and the vertical axis the classification of models as hypothesis driven versus data driven. Here, hypothesis driven refers to methods of deriving models that are based on various assumptions or simplifications, and data driven to methods of building models that match the measurement data using machine learning. The second quadrant at upper left is represented by empirical equations such as the square root of time (t) rule.[3)] Such models are simple and widely used, but their validity and extrapolability are up for debate.

Physics-based models[4)–7)] (first quadrant) are represented by a method of representing the amount of degradation by a differential equation related to time. Such models are more exact than empirical equations, but they are difficult to apply to cases involving complex phenomena or a large number of unclear factors. However, data driven approaches[8)-11)] employing machine learning have recently come into use. Data driven black box methods (third quadrant),[8), 9)] which do not concern themselves with the mechanism of degradation, deliver superior performance in regression and prediction, but are difficult to use to provide feedback for design. In contrast, data driven white box methods (fourth quadrant)[10, 11)] involve the active application of machine learning and deep learning to analysis images and are expected to help elucidate aspects such as the electrode microstructure, although the computational load will be large.

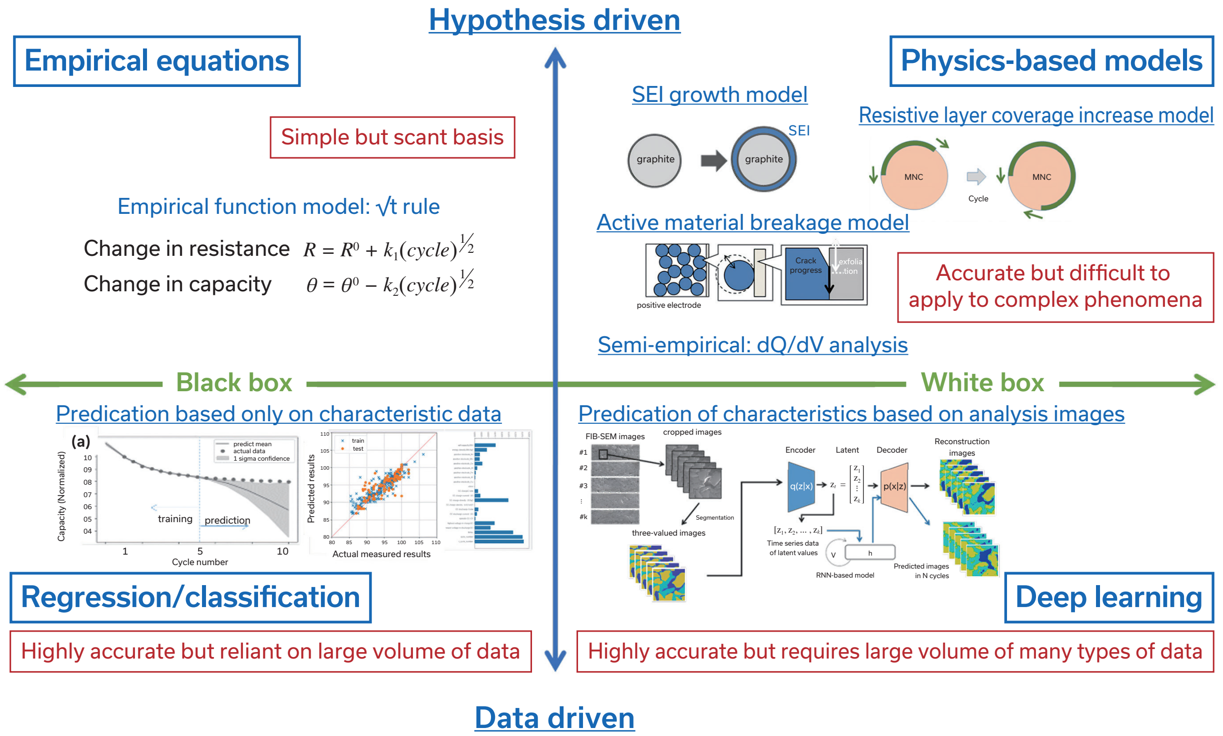

Figure 1. Map of representative lithium-ion battery degradation prediction methods

3 Lithium-ion battery degradation prediction using physics-based models

At explained in the preceding section, a variety of LIB degradation models are possible, but due to questions of space we will limit ourselves here to an example of using a physics-based model of the sort shown in the second quadrant of **Figure 1** for single-cell degradation modelling and its extension to the entire pack.

The basis for accurately predicting battery degradation status is the building of an internal resistance model to reproduce precisely the voltage resistance, amount of heat generation volume, and temperature during charging and discharging of a single LIB cell. Dynamic equivalent circuit[12)] models in which the internal resistance is represented by the state of charge (SOC) or current and temperature functions and electrochemical models based on reaction, chemical species transport, or the Poisson equation (so-called Newman models,[13)] single-particle models,[14)] etc.) are widely used. Physics-based models that simulate a variety of degradation mechanisms are added based on the above. **Figure 2** (a) shows a representative calculation flowchart for a single cell. The cathode-anode potential during charging and discharging is calculated using an internal resistance model, degradation model equations are used to obtain the amount of side reactions such as SEI growth (electrolyte decomposition) and cathode structural transition, and the increase in internal resistance and amount of capacity reduction are estimated. The results are then used as feedback to the internal resistance model.

Figure 2 (b) compares measured change in the capacity maintenance rate with values predicted using the physics-based model.[15)] It can be seen that by considering multiple degradation factors it is possible to track complex degradation behavior.

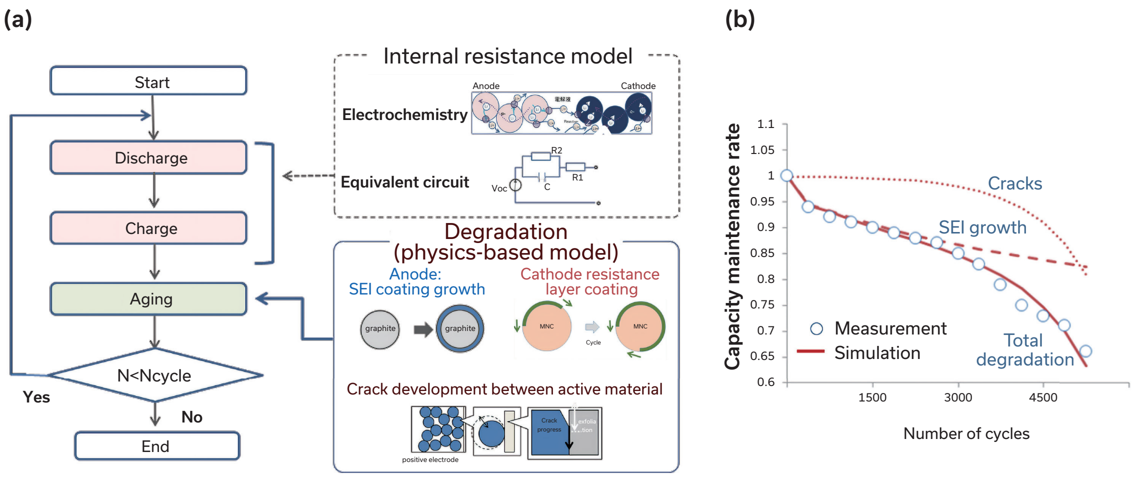

Figure 2. (a) An example calculation flowchart for single-cell degradation simulation based on a physics-based model. Degradation models assuming various degradation phenomena are added to the basic internal resistance model. (b) Comparison of measured change in capacity maintenance rate and values predicted by the physics-based model.

It is possible to extend a single-cell model to predict the charge-discharge characteristics and degradation characteristics of a battery module or pack while a vehicle is operating. In this case, since variability in the cell temperature affects degradation progress and resistance variability, it is necessary to accurately model aspects affecting each cell connected to the circuit (in which the cells are linked with series and parallel connections), such as the current conditions, cell holder or heat insulating material, busbar, and cooling mechanism, and to simulate the paths of heat diffusion and transfer. Here we present an example in which an electrochemical model and thermal circuit model are coupled to build a model to predict the temperature and degradation status of each cell of a battery pack used in an electric vehicle.[16] **Figure 3**(a) shows an outline of the vehicle-mounted battery pack subject to modelling. It consists of 16 modules (connected in series), and each module is composed of 18 laminated cells. The load current is calculated from the applied power time history of the battery pack when operating in WLTC class 3b mode. **Figure 3**(b) shows the capacity reduction of each cell at a variety of environmental temperatures. It can be seen that the higher the environmental temperature, the larger the temperature rise and the reduction in capacity. At an environmental temperature of 40°C, at the 300th cycle the cruising range is reduced from the initial value by 17%, and this reduction is roughly equivalent to that at the 1,000th cycle at an environmental temperature of 20°C (see **Figure 3**(c)). In other words, degradation is 3.5 times faster at an environmental temperature of 40°C.

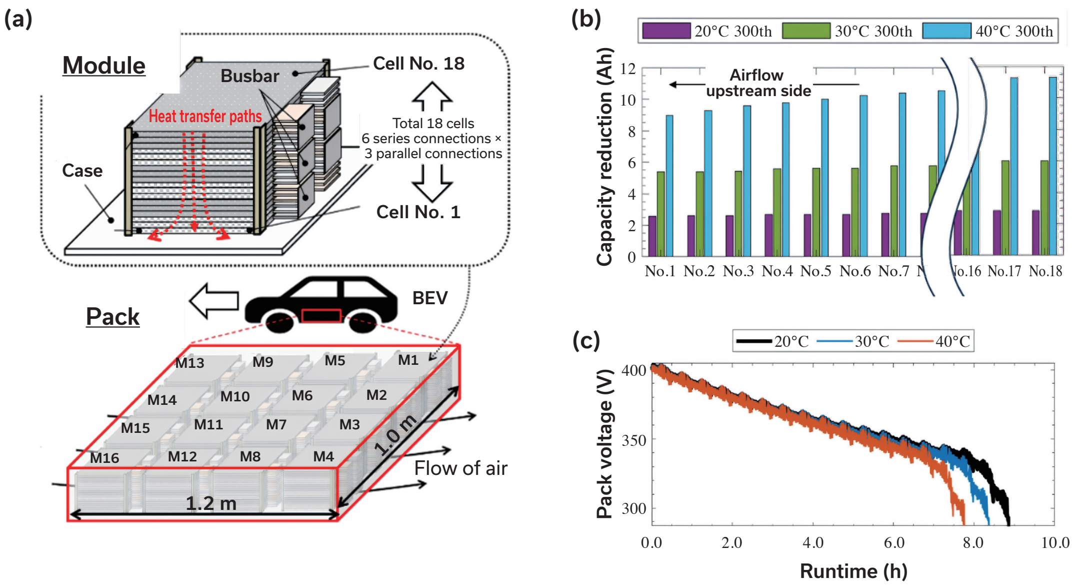

Figure 3. (a) Outline of vehicle-mounted battery pack subject to modelling.
(b) Capacity reduction of each cell at a variety of environmental temperatures.
(c) Change in battery pack voltage at each environmental temperature.

4 Potential for application to lead-acid batteries

Although the charge-discharge mechanism of lead-acid batteries, involving the deposition and dissolution of lead(II) sulfate ($PbSO_4$), etc., may be more complex than that of LIBs, similar internal resistance models, such as equivalent circuit models[17] and electrochemical models,[18] are used. (However, aspects such as the circuit configuration and electrochemical reactions differ.) Sulfation, electrolyte stratification, gas generation, lattice corrosion, etc., may be considered as suitable internal resistance models for lead-acid battery simulations based on physics-based models.[19), 20] **Table 1** lists representative degradation mechanisms and examples of methods for modelling them. As with LIBs, multiple degradation phenomena interact with each other in actuality, and many of the parameters (such as reaction speed constants and reaction activation energy) that contribute to the progression of degradation are unknown. Therefore, the process of minutely determining parameters based on cyclical characteristic data obtained under a variety of conditions, such as the measured temperature, charge-discharge rate, and cumulative discharge, is key. Methods such as monitoring changes in the size of the active material through SEM observation, identifying the crystalline structure through XRD, and quantitative analysis of the electrolyte are likely to be effective in specifying the dominant degradation mechanisms.

As with LIBs, it will likely be possible to predict degradation and its variability per module or pack, or per unit or container. In this case, we expect that temperature variability will make a large contribution in addition to per cell capacity or internal resistance factors, so it is important to consider the effect of the enveloping materials or cooling mechanisms on heat transfer. Furthermore, machine learning or statistical analysis are likely to be effective when predicting performance in the real world because many factors affecting degradation and its variability are unclear. Recently, Hasegawa, et al,[21] undertook an exploratory data analysis of storage systems for wind power generation plants and found that specific current and voltage behaviors during charging had a high correlation with the progression of degradation. This shows the future possibility of predicting service life based on realtime operation data and developing technology for preventive maintenance and optimizing operation to match storage requirements.

The above shows that the establishment of lead-acid battery degradation prediction technology will have a large practical impact, and that it is essential to create models alongside efforts to elucidate phenomena. This is a very challenging theme for battery engineers and researchers because, in addition to knowledge of numeric computation, deep domain knowledge related to batteries is key.

Table1. Representative lead-acid battery degradation mechanisms and examples of methods for modelling them

Degradation mechanism	Example modelling methods
Cathode grid corrosion	Considering speed of coating growth as a function of electrode potential
Sulfation	Expressing capacity decrease as a function of discharge rate or temperature
Electrolyte stratification	Considering as a function of actual capacity decrease
Active material degradation	Expressing capacity decrease as a function of SOC, etc.
Electrolyte leakage	Expressing as a function of charge-discharge rate, temperature, time, etc.
Gas generation	Considering as a function of electrode potential or temperature

5 Conclusion

This paper presented an overview of LIB single-cell internal resistance models, described the thinking behind degradation models, and provided examples of their extension to degradation simulation for battery modules and packs. Representative methods of modelling lead-acid battery degradation mechanisms were summarized and issues related to their application to actual batteries noted. Future plans include trial efforts to further improve the accuracy of models through combination with in-situ SEM observation during charging-discharging and sophisticated analytic technologies such as operando XAFS.

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Proposal-Based Energy Storage Solution

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1 Introduction

Energy storage devices play an extremely important role in our lives, with uses extending from mobile devices to vehicles, while also including stationary apparatus. There are many types of energy storage devices, such as dry cells, nickel-cadmium batteries, lead-acid batteries, nickel-metal hydride batteries, and lithium-ion batteries. As the importance of such energy storage devices grows, the need for battery management systems (BMS) increases. Furthermore, reducing emissions of greenhouse gases (GHG) over the life cycle of the materials used, from procurement through disposal and recycling, is becoming ever more important from the standpoint of achieving a carbon-free, recycling-oriented society. Against this background, our first priority as a company is to contribute to the realization of a carbon-free, recycling-oriented society, driving our business operations based on our corporate philosophy: "Energywith adds new wisdom to energy storage and focuses on quality to provide people with reliability and safety as a 'trusted energy storage solution company.'"

This report presents an overview of proposal-based energy storage solution offered by EW as a provider of energy storage devices and related system services and backed by the technology, experience, and expertise accumulated over our 109-year history.

2 Roles and benefits of energy storage devices

Products equipped with energy storage devices include "ubiquitous devices" exemplified by mobile devices, automatic guided vehicles (AGV), transport vehicles such as automobiles, and stationary apparatus such as uninterruptible power supplies (UPS) and storage systems for renewable energy. Among these products, as shown in **Table 1**, energy storage devices serve functions such as energy supply, power assistance, regeneration, and buffering. They contribute to enhancing the functionality, performance, and efficiency of the products, as well as stabilizing power quality. Moving forward we can look forward to the emergence of energy storage devices with even better performance as well as new varieties of energy storage devices. In addition, we can expect further expansion in products and services utilizing energy storage devices as part of the trend toward digital transformation (DX).

Table1. Roles and benefits of energy storage devices

Roles	Benefits	Applications and benefits (examples)
Energy supply	Increased portability and usability	As suggested by the term "ubiquitous devices," mounting energy storage devices in mobile devices eliminates the need for power cables and allows such devices to be used anywhere.
	Backup	When a power outage occurs, a UPS supplies power from a storage device, allowing the equipment to which is connected to continue to operate. Energy storage devices can also be used in conjunction with solar power generation systems to enable supply of power to continue when no power is being generated, such as at night.
	Autonomous operation	In electric vehicles, etc., energy storage devices provide energy that enables the vehicle to operate.
Assist, regeneration, buffering	Improved performance Improved fuel efficiency Energy conservation	In hybrid and electric vehicles, an electric motor can assist the engine during acceleration or uphill driving, resulting in a more powerful driving experience. Regenerative brakes convert kinetic energy to electrical energy that is used to charge the storage device, and the use of stored electricity during powered operation boosts fuel efficiency, contributing to energy conservation.
	Improved system efficiency	In solar power generation systems and regenerated power utilization systems,[1), 2)] generated and regenerated power is accumulated in a storage device for later use, thereby boosting generation and energy efficiency. Also, in HEVs or PHEVs, by operating using the engine and motor within the ranges where their drive efficiency is highest, better overall efficiency can be achieved while reducing maintenance costs and manpower through reduced wear on gears, and production of noise, NOx and SOx can be reduced as well.[3)]
	More stable power quality	In environments subject to severe power fluctuations, energy storage devices can be used to supply and absorb power as necessary, contributing to more stable power quality.[4)]

3 Proposing storage solutions

Figure 1 shows the energy capacity and output of products equipped with energy storage devices. **Figure 2** compares the characteristics of different types of energy storage devices. The evaluation scores reflect present-day levels relative to a score of 5 for excellent devices.

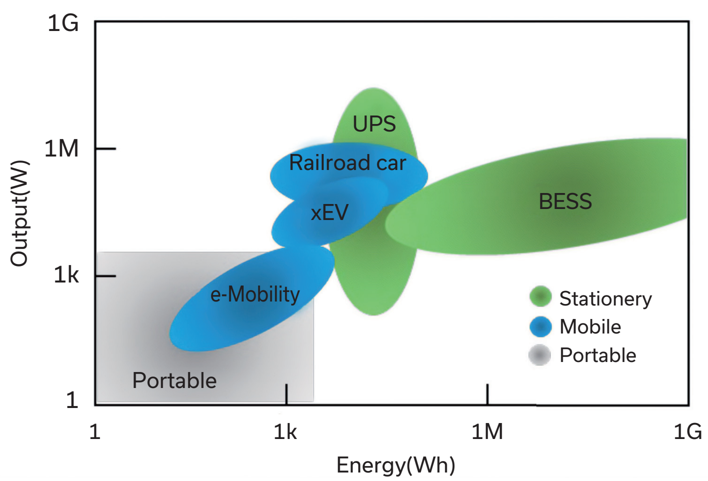

Figure 1. Energy capacity and output of products equipped with energy storage devices

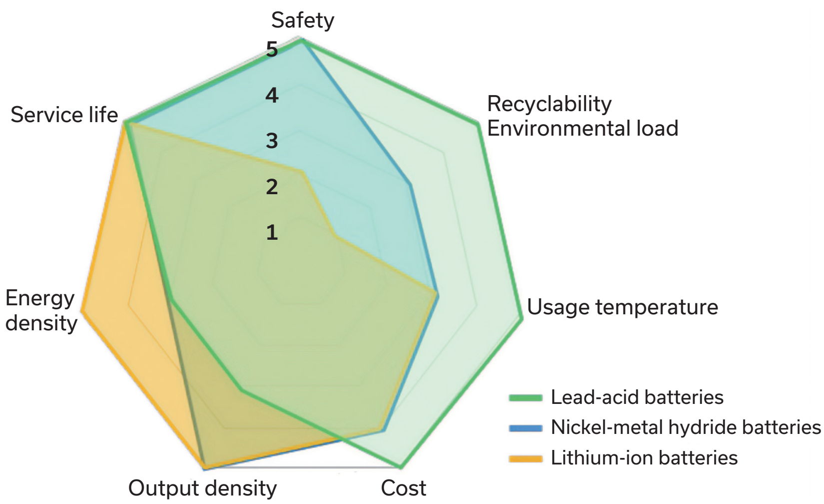

Figure 2. Comparison of characteristics of energy storage devices types

Products and services utilizing energy storage devices now cover a broad range, and the specifications of the energy storage devices they employ also varies greatly. When selecting energy storage devices, it is important to take into account aspects such as the usage temperature, service life, price, and safety in addition to the power and energy needed to realize the designed product functionality. In recent years it has also become necessary to consider factors such as the supply chain and carbon footprint of product (CFP) over the entire life cycle. To maximize the roles and benefits of the various types of energy storage devices mentioned above, EW proposes optimized energy storage solutions tailored to specific requirements, including hybrid systems[5] incorporating diverse energy storage devices. We are also teaming up with other companies to build optimal energy systems that include energy devices other than energy storage devices, such as sodium-sulfur (NaS) batteries, heat pump water heaters, and power generators.[6), 7)]

4 Safe and secure storage systems

According to the Japan Automobile Federation (JAF), the number one reason for JAF's service calls is a dead battery.[8] What's more, government agencies and the like seem to constantly be releasing warnings regarding the danger of accidents involving energy storage devices, especially lithium-ion batteries.[9] There is a growing demand for storage device status detection and battery management systems (BMS) to ensure safe and secure use of energy storage devices and equipment incorporating energy storage devices and to extract optimum performance from them.

Against this background, EW is prioritizing efforts to make energy storage devices more reliable and as well as BMS development.

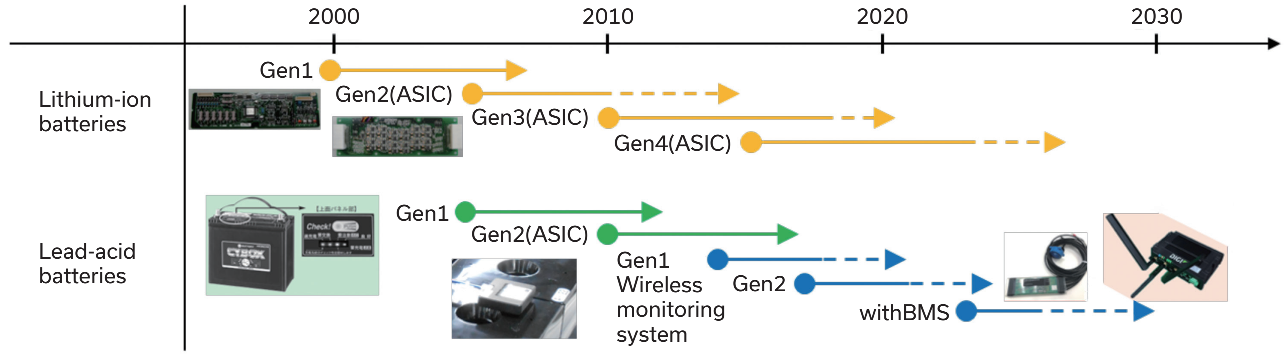

Figure 3. Progress in battery monitoring

Figure 3 shows progress in battery monitoring at EW. In our previous corporate incarnation as Shin-Kobe Electric Machinery Co., Ltd., we developed lithium-ion batteries and cell controllers for use in HEVs, and these were utilized in HEV models that went on the market in 2000. We went on to develop and commercialize[11] a dedicated battery monitoring IC[10] designed for compactness, low cost, and high precision, and a BMS for battery status calculation that incorporated Kalman filtering and machine learning. Both of these were adopted in products of various types. In the area of lead-acid batteries, we extended the above technologies to development work on status detection technology,[11] and this resulted in 2004 in the development and marketing of an automotive AI battery (CYBOX). This product consists of a battery with a status determination device embedded in its upper portion, allowing constant monitoring of the charge status and degradation status.[12] Further enhancements to these technologies and products led to the release in 2013 of a specialized BMS product for industrial lead-acid batteries. To make this product suitable for use with large-scale storage battery equipment of the sort used in broadcasting or data centers, consideration was given to reducing the work involved in equipment installation and to safety measures such as simplifying the wire harnesses and avoiding short circuits caused by contact between harnesses, resulting in the adoption of wireless communication. In addition, in light of the characteristics of lead-acid batteries, degradation estimation technology using impedance measurement data for the high- and low-frequency ranges was employed.[13] In anticipation of extension to accommodate the IoT, second-generation BMS was developed that uploads data from multiple installation points to a cloud server to enable remote monitoring at all times. These technologies developed by EW are not limited to applications such as lead-acid battery status detection for broadcasting and data centers but have expanded to include status detection and remote monitoring for energy storage devices used in fields such as renewable energy, electric forklifts, and mobility.[7] In the field of electric forklifts specifically, EW has started a new service called withBMS.[14] It works by transferring battery measurement data from monitoring systems mounted on the lead-acid batteries of forklifts to a service platform hosted on a cloud server, and the battery measurement data stored on the service platform is used as the basis for generating and supplying battery malfunction alerts and regular status reports.

Moving forward, applications for these technologies will expand to include areas such as AI-based status detection and predictive diagnostics, energy storage devices using battery types such as nickel-zinc (Ni-Zn), and products and services employing energy storage devices. EW hopes to be involved in the evolution of even safer and more secure solutions based on stronger links with IoT, mobile communications, and more.

5 Contributing to the realization of a carbon-free, recycling-oriented society

The lead-acid battery is a good example of a product that can help in the realization of a circular economy, and more than 90% are recycled. This is far superior to the resource recovery rates for nickel-cadmium or nickel-metal hydride batteries (76% and 77%, respectively).[15]

Table 2. Melting points of major electrode materials

Electrode material	Melting point (°C)
Lithium	180.5
Cadmium	321.1
Lead	327.5
Antimony	630.5
Aluminum	660.3
Calcium	839
Copper	1085
Manganese	1246
Nickel	1455
Cobalt	1495
Iron	1538

Table 2 lists the melting points of major electrode materials. Lead melts readily at a comparatively lower temperature than most other materials, and it is easy to separate from other substances. There are actually reports that the recycling rate for lead from lead-acid batteries is 99.8%,[16] and this is one reason why recycling of lead-acid batteries continues to advance.

According to the ecoinvent database, the global warming potential (GWP) for typical lead-acid batteries is 2.320 (t-CO2eq/t-lead), but this is reduced to 0.652, or approximately 1/3, when recycled lead is used. In addition, special facilities such as dry rooms are not required when manufacturing lead-acid batteries, there is no need to consider special cooling structures, etc., in the product design of applications, and no forced cooling is necessary during use. This makes the lead-acid battery a storage device with a superior CFP over its entire life cycle, from procurement of materials through manufacture, operation, disposal, and recycling.

Furthermore, a look at lead imports shows that the countries from which Japan imported lead ore (percentage) in 2020 break down as follows: 1st place — U.S.A. (32%), 2nd place — Australia (31%), and 3rd place — Bolivia (13%). For other metals the breakdown is: 1st place — Australia (45%), 2nd place — Taiwan (26%), and 3rd place — South Korea (24%).[17] From the standpoint of the recent focus on the comparative geopolitical risk of materials procurement, lead can be considered a low-risk material.

EW has a subsidiary in Thailand, Thai Nonferrous Metal Co., Ltd., that is building out its recycling business for discarded lead-acid batteries. At the same time, we are strengthening our collaboration with recycling companies in Japan. As part of our efforts to actively promote green transformation (GX), EW is aggressively advancing recycling efforts aimed at making the most of the abovementioned advantages of lead-acid batteries.

6 Conclusion

This report discussed aspects of the proposal-based energy storage solution promoted by EW from our viewpoint as energy storage devices system services provider. Moving forward, we expect to further expand our efforts to provide new products and system services tailored to the societal trends toward DX and GX by leveraging the roles and benefits of energy storage devices. We are committed to deepening our understanding of the needs of our customers and of how products and system services can better meet them, and we will continue our evolution into a company offering proposal-based energy storage solution, based on EW's technology and expertise in the field of energy storage devices, as we work with suppliers and customers to help create a carbon-free, recycling-oriented society.

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Development of Core Technologies for Providing One-Stop Solutions in Renewable Energy Storage Systems

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1 Abstract

To prevent global warming, renewable energy sources, such as PV (photovoltaic) and wind power, are becoming throughout the world. However, power generated from renewable energy fluctuates depending on weather conditions and time. To address this issue, renewable energy storage systems have been installed.

At Energywith Co. Ltd, we are developing renewable energy storage systems, which have our LL Series of stationary valve-regulated lead-acid batteries for cycling use and power conditioning systems (PCS) for targeting buildings, convenience stores, factories, and other facilities. Furthermore, to enhance the reliability of these systems and optimize their entire lifecycle, we are developing a remote monitoring system to collect and analyze battery operations and energy management systems (EMS) to achieve both electric cost optimization and battery lifecycle control.

In this report, we present the elemental technologies of these renewable energy battery storage systems.

2 Evolving landscape of renewable energy

As part of worldwide measures to deal with global warming, the first Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change[1] in 1992 was followed by the Kyoto Protocol in 1995 (COP3) and the Paris Agreement in 2015 (COP21). Most recently, in 2024 (COP29), the following targets for worldwide efforts to limit global warming were adopted.[1)]

- Limiting global warming to less than 2°C compared to pre-industrialization levels (with 1.5°C as a non-binding target).
- Ensuring that worldwide emissions of greenhouse gases (GHG)[2] peak out by 2025 and drop to net zero by the latter half of the 21st century.
- Increasing the adoption of renewable energy worldwide to 11,000 GW or greater, or at least three times the current level, by 2030.

The Japanese government has followed the COP in the targets it has adopted in its Seventh Strategic Energy Plan,[2)] and these are to form the basis for government and municipal policies moving forward.

- Reducing emissions of greenhouse gases (GHG) by 46% (compared to 2013) by 2030 and to net zero by 2050.
- Increasing the adoption of renewable energy worldwide to 38% by 2030 and to 50% by 2050.

On the other hand, the main sources of renewable energy, solar power generation (PV) and wind power generation (wind power), are what is termed variable renewable energy (VRE), meaning that the amount of power generated varies under the influence of

1 As of 2025 198 countries, almost all the countries on Earth, are parties to the United Nations Framework Convention on Climate Change, and Conferences of the Parties have been convened every year since 1995.

2 Greenhouse gases (GHG) are gases that have an effect on global warming. In addition to carbon dioxide, they include methane, nitric monoxide, and alternative CFCs.

factors such as the season or the weather. For this reason, as the amount of VRE increases, it can be difficult to absorb the fluctuations on the power grid side, making it hard to maintain a stable supply of power. In fact, the power companies have a licensing system for new renewable energy installations, and prior consultation (power grid interlinkage consultation) is required. Attention has turned to storage systems as a solution to the problem of variability, and such systems on the scale of several MWh have already gone into service. Also, subsidies for new renewable energy deployment that are conditional on the installation of storage systems have increased in recent years. **Figure 1** shows three patterns for the use of renewable energy storage systems in applications.

① Battery storage for anti-fluctuation co-located with renewable power generation: In the case of wind power in particular, the amount of power being generated is constantly changing due to variations in wind conditions. When such a source of power is connected to the grid, a storage system is used to suppress variability in the generation output.

② Battery Storage for power grid: Such systems are mainly installed at transformer substations to help balance power supply and demand. Also called storage stations or ancillary services.

③ Self consumption system[3]: Such systems are installed alongside PV in homes, factories, etc. The storage system suppresses reverse power flow, allowing more efficient utilization of power generated by PV. A configuration that includes control functionality is called an energy management system (EMS).

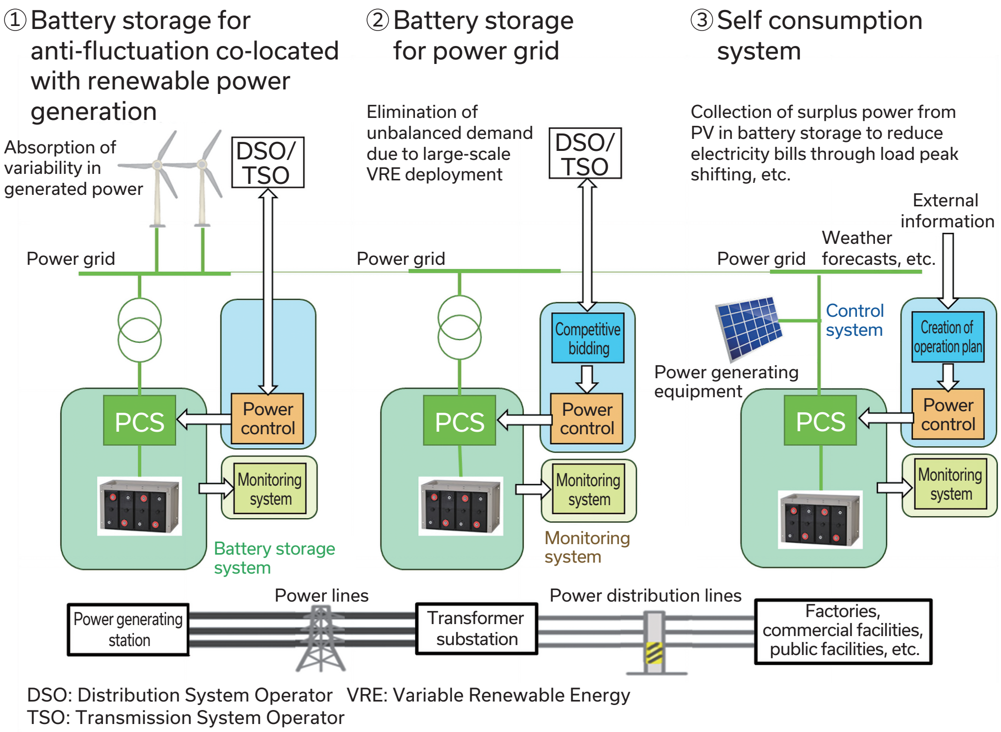
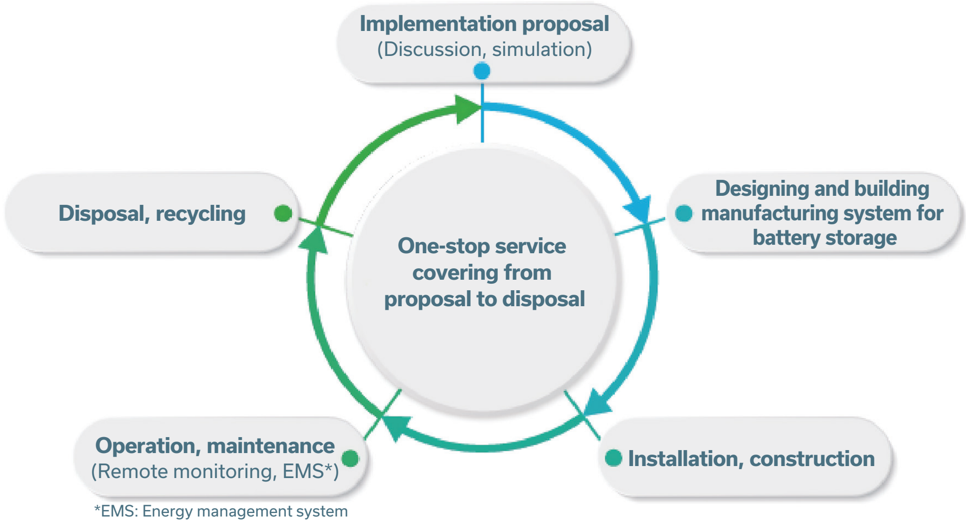


Figure 1. Patterns of battery storage installation in systems

3 Core technologies composing renewable energy storage systems

Figure 2 illustrates aspects of the provision of one-stop solutions encompassing the entire life cycle of renewable energy storage systems. The technical components composing these systems are described below.

1. Storage system
2. Control system, simulation
3. Monitoring system



❶ Discussion, simulation, implementation proposal

How the system will be used and its goals are discussed with the customer, a simulation of the economic effects of sunlight and storage system deployment is undertaken based on power demand data, and the most appropriate system configuration is proposed.

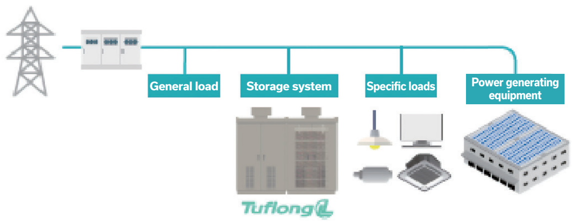
●**Example simulation results**

Item	Solar power generation equipment	Tuflong LL storage system	Cost reduction	CO_2 reduction	Optimal proposal
Simulation 1	35kW	–	¥430k/year	3.1 t/year	△
Simulation 2	35kW	25kW–112kWh	¥1080k/year	4.9 t/year	○

Note: For customers who already have a solar power generation system in place, a simulation can be made of the effects once a storage system is added.

❷ System design, manufacture of battery storage, system building

An entire power generation and storage system, along with crucial load backup capability for emergencies, is built by combining a Tuflong LL storage system and solar power generation equipment.



❸ Installation/construction, operation support, maintenance

Remote monitoring technology is used to oversee the status of the Tuflong LL storage system, and predictive maintenance is performed. This also boosts maintenance efficiency and lowers the cost. In addition, advice is provided on operating procedures that will extract maximum battery storage performance, based on analysis of operation data.

❹ Disposal, recycling

A subsidiary in the Energywith Group collects battery storage after use, allowing for proper processing or sale of waste batteries and relieving the customer of burdens (labor and cost) related to disposal. Since Tuflong LL batteries are nearly 100% recyclable and are produced at EW factories in Japan, resources are recycled domestically, contributing to the realization of a sustainable society.

Note: Energywith has obtained wide area certification (certification No. 331) and secondhand goods business certification (Tokyo Metropolitan Public Safety Commission license No. 301032420929).

Figure 2. One-stop solution flow for medium- and small-capacity renewable energy storage systems

(1) Storage system (battery storage + PCS)

The storage system is configured as a Power Conditioning System (PCS) due to the need for bidirectional conversion between direct and alternating current in order to connect EW's LL series batteries (valve regulated stationary lead-acid batteries for cyclic applications) and battery storage to the power grid. The Tuflong LL system is a renewable energy storage system employing EW's LL series batteries.

LL series batteries form the basis of the system, and since these are lead-acid batteries, although inferior to lithium-ion batteries from the standpoint of energy density, they deliver superior safety (the electrolyte is an aqueous solution, and it contains no dangerous substances as defined under The Fire Service Act) and recyclability (the main material is highly recyclable). As for expected service life, the development in 2001 of the LL1500, rated for 3,000 cycles, was followed by numerous improvements, with the appearance in 2011 of the LL1500-W,[4] with a service life of 17 years, the appearance in 2014 of the LL1500-WS, with output characteristics 1.5 times better than its predecessor, and the appearance in 2016 of the LL1500-G, with rated discharge of 1.0 C and service life of 5,250 cycles. For small-capacity applications, development work continues on a compact LL type product that retains the format and installation method of the LL1500. It is expected to go on the market in 2026.

Figure 3 summarizes the features of Tuflong LL systems and presents installation examples. One advantage of Tuflong LL systems is their suitability for installation in existing buildings or facilities, due to their use of lead-acid batteries having an extensive track record for safety. **Figure 4** presents examples of medium-capacity and small-capacity Tuflong LL storage systems. Note that the PCS is procured externally. The necessary functions of lead-acid batteries are constant-voltage charging to enable uniform charging and suppression of overvoltage and overcurrent.

Tuflong LL features

Superior safety

The electrolyte of Tuflong LL batteries is an aqueous solution, which is not defined as a dangerous substance under The Fire Service Act.

Reduced CO_2 emissions

Further reduction in carbon dioxide emissions can be achieved in combination with a solar power generation system.

Support for BCP

The system routinely operates in a mode designed to lower electricity costs. It is a multi-use storage system that supports BCP operation mode in case of emergency to deal with power supply risk.

Recyclability

Tuflong LL batteries can be collected after use by an Energywith Group subsidiary and are nearly 100% recyclable.

Example Tuflong LL installation

Output (kW)	Operating capacity (kWh)	Installation format	Main applications
25~50	100	Dedicated cubicle	Local governments, small retail stores, hospitals
50~100	~350	20 ft container × 1	Large retail stores, general hospitals, hotels, condominiums, small/midsize factories
100~200	~700	40 ft container × 1	
200~300	~1,400	Partitioned shelter or 40 ft container × 2	
300~500	~2,100	Partitioned shelter or 40 ft container × 3	Factories, distribution warehouses
500	2,000	Industrial tent, covered structure, etc.	
1,000	4,000	Industrial tent, covered structure, etc.	Power companies
10,000	40,000	Industrial tent, covered structure, etc.	

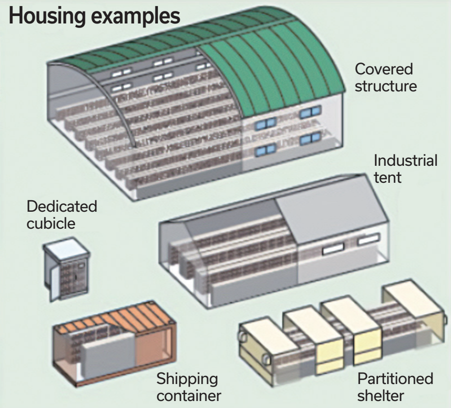
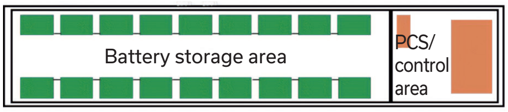
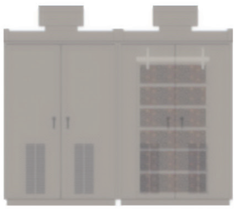


Figure 3. Tuflong LL features and installation examples



40 ft container system for outdoor installation
Size: 12200×2500×2900mm
Capacity: 200kW (PCS)-864kWh (battery storage)
Weight: Approx. 5.0 t

(a) Medium-capacity Tuflong LL system



Cubicle for outdoor installation
Capacity: 25kW (PCS)-68kWh (battery storage)
Size*: 1700×1000×2750mm (battery storage)
1500×1000×2530mm (PCS)
Weight: Approx. 3.8 t
*Not including ventilating tower

(b) Small-capacity Tuflong LL system

Figure 4. Tuflong LL storage system configuration examples

(2) Control system, simulation

The advantage of a renewable energy storage system is that it allows shifting of the timing of power generation from renewable energy, power purchasing, and power consumption, thereby enabling peak power reduction (load peak shifting).[3] In other words, the cost of power can be reduced by charging the storage system with surplus power from PV and power purchased during time periods when the price is low, and then discharging it during time periods when the unit price of power is high or during peaks in power purchasing. In addition, by using making effectively use of advance purchasing of power based on weather forecasts, it is possible to minimize the effects of the weather.

EW has developed a simulation, based on a previously developed HEMS engine,[5)] that enables quantitative evaluation of the effects of deploying a renewable energy storage system. **Figure 5** shows an example of the results of such calculations. Part (a) shows operation results for one day under fair conditions (left) and rainy conditions (right), and part (b) shows the effects of deployment for an entire year.

By charging the system with surplus power generated by PV in the morning when conditions are fair and discharging power in

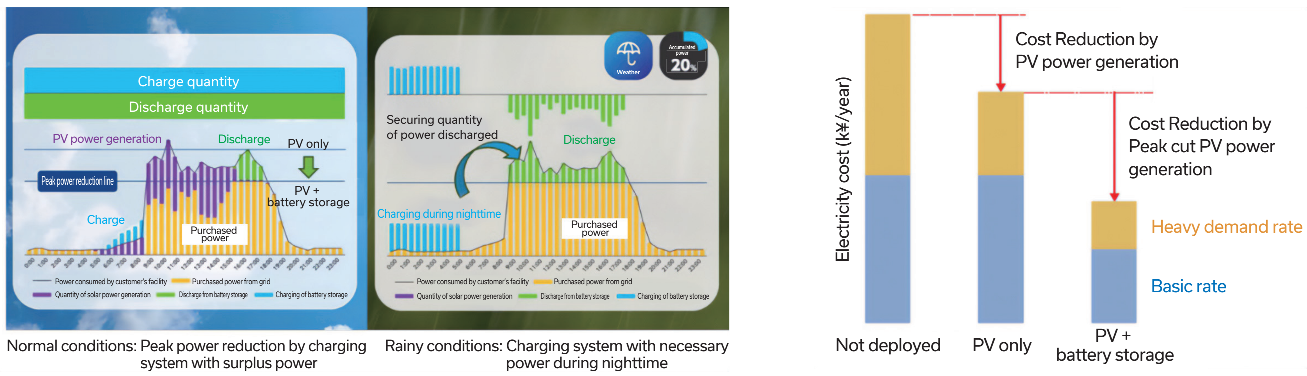
3 In this report, the phrases "peak power reduction" and "load peak shifting" are used interchangeably. In this section, "peak power reduction" is used to emphasize the sense of reducing peaks in power purchasing.

the evening during peak power purchasing time, or by purchasing and charging the system in the evening with power necessary to reach the peak power reduction line during rainy conditions, the maximum value of purchased power (peak power reduction line) can be lowered and the amount of contracted power reduced.

Part (b) summarizes the effects of renewable energy storage system deployment by adding up the cost reductions over an entire year.

Figure 6 illustrates an EMS concept (EW-EMS) with simulation technology developed by EW at its core. EW-EMS comprises two parts: A Planning EMS, which creates an operation plan based on estimated PV power generation and power demand data that was input to the simulation, and an Operating EMS, which issues charge-discharge instructions to the storage system based on the operation plan and actual PV power generation and power demand data. EW-EMS is scheduled to go on the market within the 2025 fiscal year.

In addition, in or after fiscal 2026 EW plans to release an EMS that lowers electricity costs and extends the service life of battery storage by incorporating battery storage degradation estimation functionality into the Planning EMS.



(a) Results of simulation of results for fair and rainy conditions

(b) Annual reduction in electricity costs

Figure 5. Renewable energy storage system simulation results

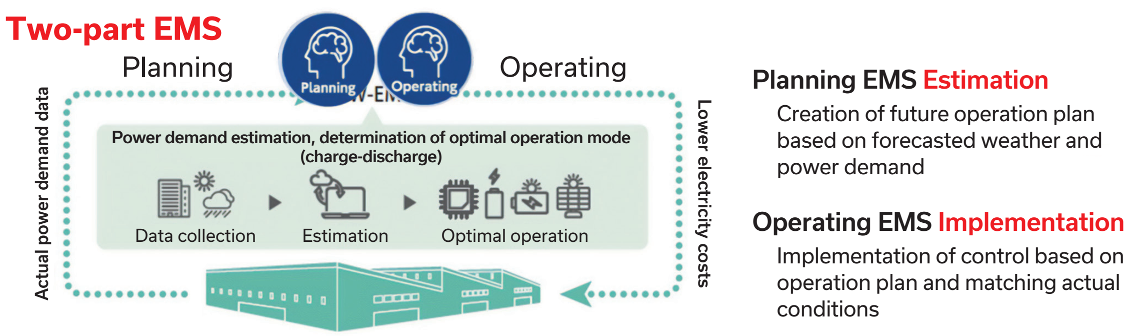


Figure 6. EW-EMS features

(3) Monitoring system

The renewable energy storage system is equipped with a remote monitoring system. This remote monitoring system allows EW service personnel to check the health, performance, and economic efficiency of the system in real time and respond to issues in a timely manner. In particular, since performance degradation depends on factors such as the temperature conditions under which the battery storage is used and charge-discharge quantities, preventive safety to control system service life is carried out by checking whether the system is operating as originally designed and making adjustments as necessary.

Figure 7 illustrates the functions and advantages of the remote monitoring system. EW service personnel constantly monitor the renewable energy storage system and analyze operation data. This enables them to respond quickly when problems occur, to carry out preventive safety to avoid malfunctions and premature degradation of battery storage, and to provide advice regarding system operation.

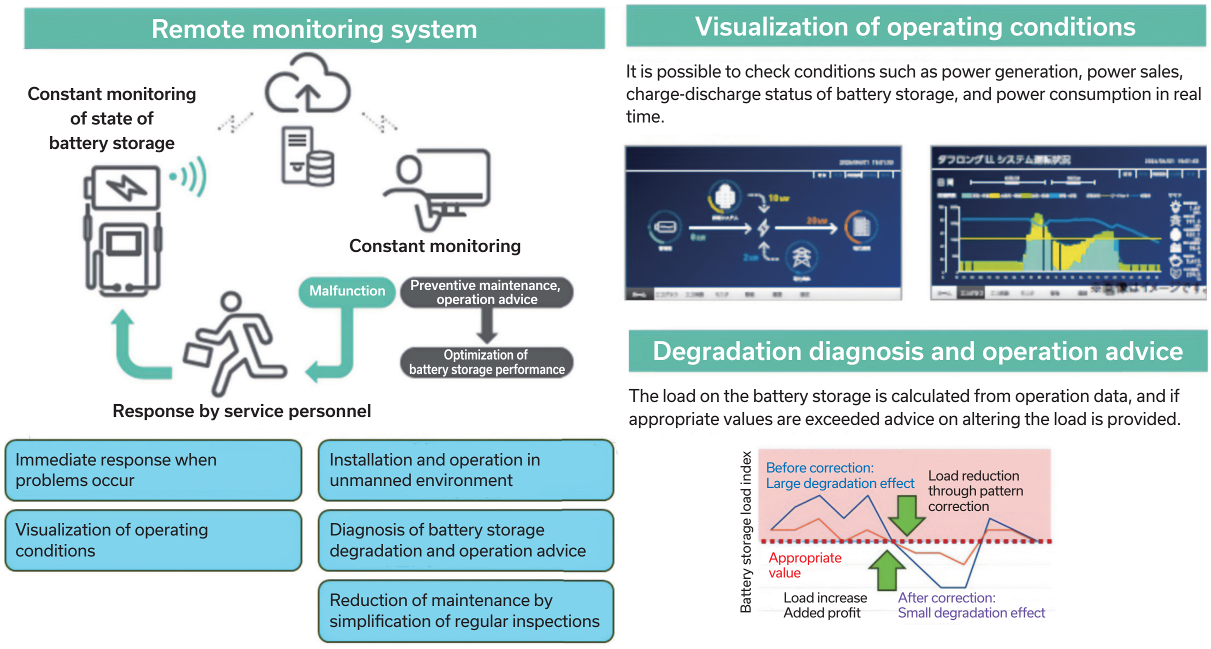


Figure 7. Functions and advantages of remote monitoring system

4 Conclusion

This report described the core technologies of EW's renewable energy storage systems, which are built around the LL series of valve regulated stationary lead-acid batteries for cyclic applications designed for safety and recyclability. EW has developed remote monitoring technology and a linked EMS that enables optimization over the entire life cycle of the system. In addition to contributing better system reliability, we can expect this to lead to an expansion of new products and services in line with corporate trends such as DX and GX. Moving forward, EW will continue to expand its range of renewable energy storage systems, while deepening our understanding of customer requirements, products, and system services.

5 Future developments

1) Enhancement of EW's lineup of the products comprising renewable energy storage systems
2) Stronger linkage of remote monitoring and EMS through use of cutting-edge technologies such as AI

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Decomposition and Evaluation of Battery Performance Variation Based on Statistical Interpretation

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1 Abstract

Our company conducts periodic sampling inspections for each type of battery to ensure quality assurance. We have established a method to decompose performance variation of the batteries into variations within the same production lot and between different production lots for evaluation, by applying statistical theories such as the Law of Large Numbers. This method has clarified the characteristics of performance variation for each product, making it easier to see the whole picture of the variations and their origin. The analyzed results are expected to enhance the quality of our products by being applied to the improvement of product development and manufacturing processes.

2 Technical features

- We have applied statistical theory to create a method for analyzing and evaluating variability in battery performance within the same production lot and between different production lots.

3 Development details

The corporate philosophy of EW mentions a "focus on quality," and we consider quality to be one of the key elements in our business operations.[1] We have long conducted regular sampling inspections of each type of battery to ensure that charge-discharge performance reference values are met. The inspection data is all recorded in the EW's in-house quality control system and used to determine the causes when quality problems arise. This process plays an important role as "quality on defense" for maintaining product quality.

EW is in the process of evolving into an "energy storage solution business" by using our knowledge of storage batteries to provide value in forms such as our service for monitoring the battery status of electric forklifts and our renewable energy storage battery systems.[2] To accomplish this, EW is pursuing technical innovation related to quality as part of our digital transformation (DX) initiative. An example of the fruits of this effort is the improvements in quality achieved through the deployment of image inspection technology in the manufacturing process.[3] This is "quality on offense" that goes a step beyond "quality on defense" by actively promoting quality improvement and is a tangible embodiment of EW's "focus on quality" philosophy.

To give this philosophy still more tangible form, we are studying ways to bring "quality on offense" to regular inspections as well by treating data from regular inspections conducted over time as "big data" and applying data analysis driven by statistical and AI technology as we attempt to create new quality improvement methods. These efforts have already produced a method allowing deeper evaluation of the causes of performance variability as a result of the incorporation of machine learning techniques such as exploratory data analysis (EDA), cluster analysis, and decision tree analysis.

This report presents an example of the application of statistical theory to break down and analyze battery performance variability within the same production lot and variability between different production lots, enabling us to gain an overall picture of the performance variability affecting each product and understand its causes.

In regular inspections, multiple batteries are sampled from the same production lot at regular intervals, and their charge-discharge performance is measured. **Figure 1 (a)** is a graph of regular inspection results. This graph shows two performance data values each month for a specific battery over a range of five months.

Generally, to evaluate the variability of the collected data, the standard deviation is calculated (**Figure 1 (b)**). The standard deviation quantifies the amount of distance of the individual values from the average value of all the data in the group, and in this example the standard deviation is 2.39. The factors causing performance variability can generally be divided into two classifications: variability factors arising from the components of the product and variability factors arising from the environment of the product. However, it is difficult to narrow down these factors using the standard deviation, which expresses overall variability.

With this in mind, we considered ways to break down the two types of factors causing performance variability. Information on the same production lot was obtained from data collected in the same month of regular inspections, and information on different production lots was obtained from data collected in different months. Based on this, we evaluated variability within the same production lot (variability within lots) and variability between different production lots (variability between lots) using the data from **Figure 1 (a)**. The results are shown in **Figure 1 (c)**. Variability within lots is shown by the differences in sample performance (green arrows) for the same month, which represents a standard deviation of 1.85. Variability between lots is shown by the change in sample average values for the same month (blue line), which represents a standard deviation of 2.18.

Since the products produced in the same lot were manufactured under the same conditions, meaning that changes in the production environment were exceedingly small, we can say that variability within lots arises mainly from the components of the product, namely differences in factors such as pole plate thickness or electrolyte concentration. In contrast, variability between lots comprises variability arising from differences in factors such as the time of production and the operators, in addition to the abovementioned variability within lots. Since variability due to changes in the production environment includes variability arising from the components of the product, it is difficult to precisely separate out and quantify this one type of variability alone through analysis. Nevertheless, we can say that if variability between lots is greater than variability within lots, we cannot simply ignore the effects on performance variability of changes in the production environment. Therefore, since the results shown in **Figure 1 (c)** show greater variability between lots than variability within lots, we can conclude that changes in the production environment have a major effect on performance variability.

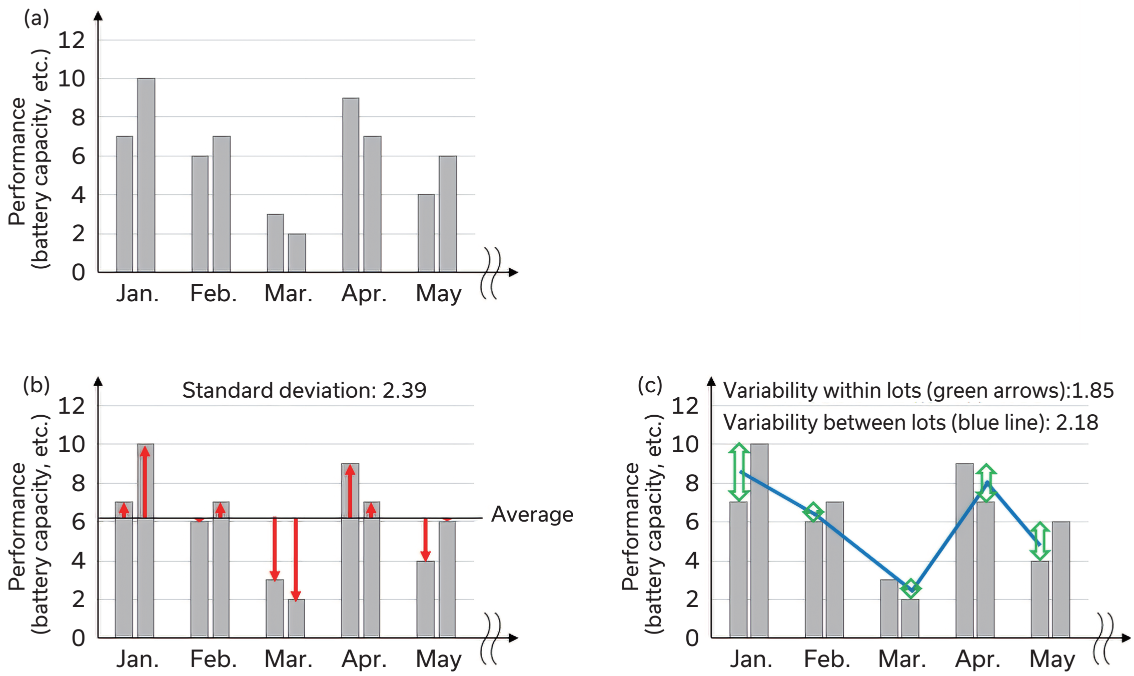

Figure 1. (a) Graph of regular inspection results (data for same month shown in sampling order from left)
(b) Performance shift (deviation) from average value over 5 months and standard deviation
(c) Variability within lots, variability between lots, and their respective standard deviations

The examples shown in **Figure 1** were for five months' worth of sampling data. By accumulating more data, it is possible to calculate each type of variability more precisely. **Figure 2** illustrates the principle of improved estimation accuracy of variability within lots through data accumulation. Here, the distribution of data for the entire production lot (population) including all the sampled batteries is narrowed down to provide a comparison between storage battery A and storage battery B. In this case there was a higher probability that storage battery A's performance difference among the sampled batteries would be smaller, but due to sampling error storage battery B's performance difference was smaller when one month's worth of sampling data was used. However, based on the "law of large numbers," accumulating more data so that the sample average approaches the average of the entire production lot raises the estimation accuracy for the population, and an accurate result of smaller variability within lots is obtained for storage battery A.

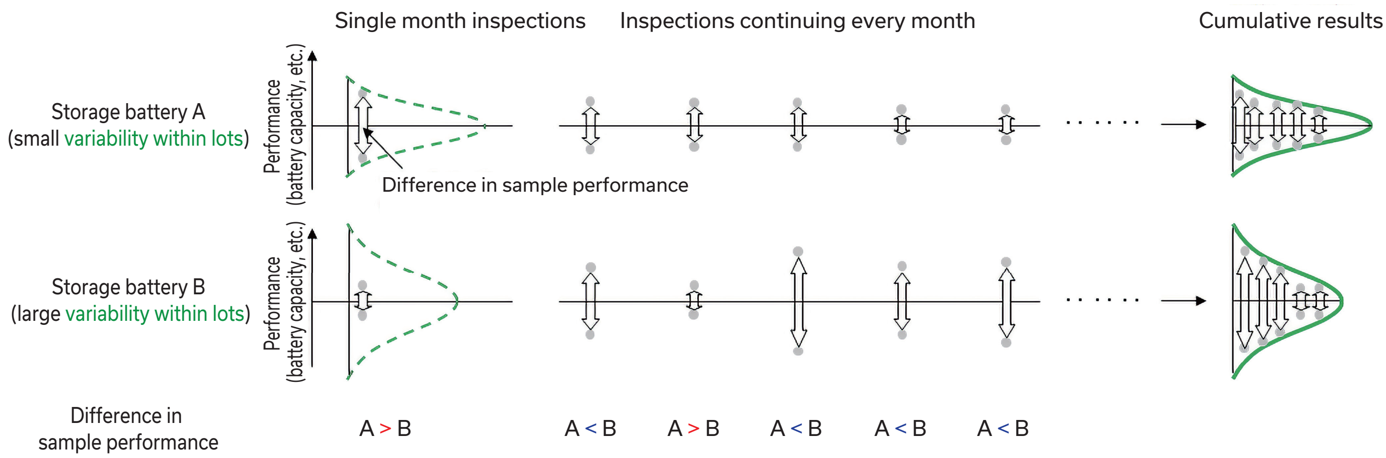

Figure 2. Principle of improved estimation accuracy of variability within lots through data accumulation

For variability between lots as well, it is possible to raise the estimation accuracy based on the "law of large numbers." **Figure 3** shows the principle of improved estimation accuracy of variability between lots through data accumulation. We can assume that the effects of variability within lots and sampling error may lead to cases of large divergence from actual values in the measured values for variability between lots. However, by accumulating a large amount of sampling data it is possible to obtain highly accurate values for variability between lots that are closer to the actual values.

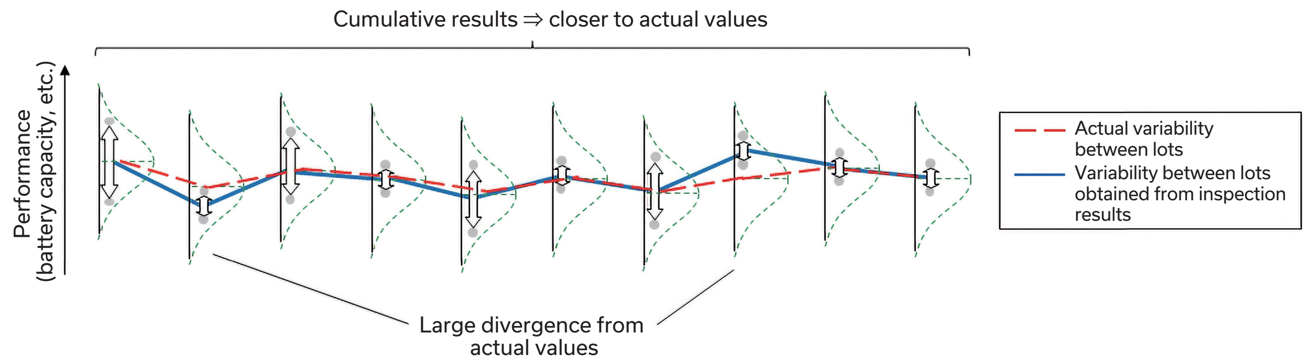

Figure 3. Principle of improved estimation accuracy of variability between lots through data accumulation

EW has been carrying out regular inspections for many years, and it is possible to calculate variability within lots and variability between lots with a high degree of accuracy based on the accumulated data. **Figure 4** shows the relationship between variability within lots and variability between lots of discharge test results for specific batteries. The item "Control No." in the figure refers to the control numbers used to differentiate among products. A coefficient of variation obtained by dividing the standard deviation by the average value is used to make relative comparisons among multiple products. Plotting the coefficient of variation of variability for each control number to categorize them into four quadrants allows us to gain an understanding of battery characteristics. First, the two areas on the right side in **Figure 4** contain batteries for which the coefficient of variation of variability within lots is higher than the average value. The variability arising from product components is higher than the average for these batteries, so it is likely that initiating design changes would be an effective way of reducing the performance variability of these products. Next, the two areas at the top in **Figure 4** contain batteries for which the coefficient of variation of variability between lots is higher than the average value. For these batteries the variability arising from the production environment is large, so it is likely that making improvements to the manufacturing process would be effective in reducing performance variability. In addition, the effectiveness can be expected to increase the most in cases where the variability within lots is small.

By breaking down and evaluating performance variability within lots and between lots in this way, we can gain an overall perspective of the variability of each product and an understanding of the causal factors. Linking variability within lots and between lots to improvements and product design and the manufacturing process based on the analysis results can be expected to enable us to improve the performance variability of each product and improve quality by reducing defects.

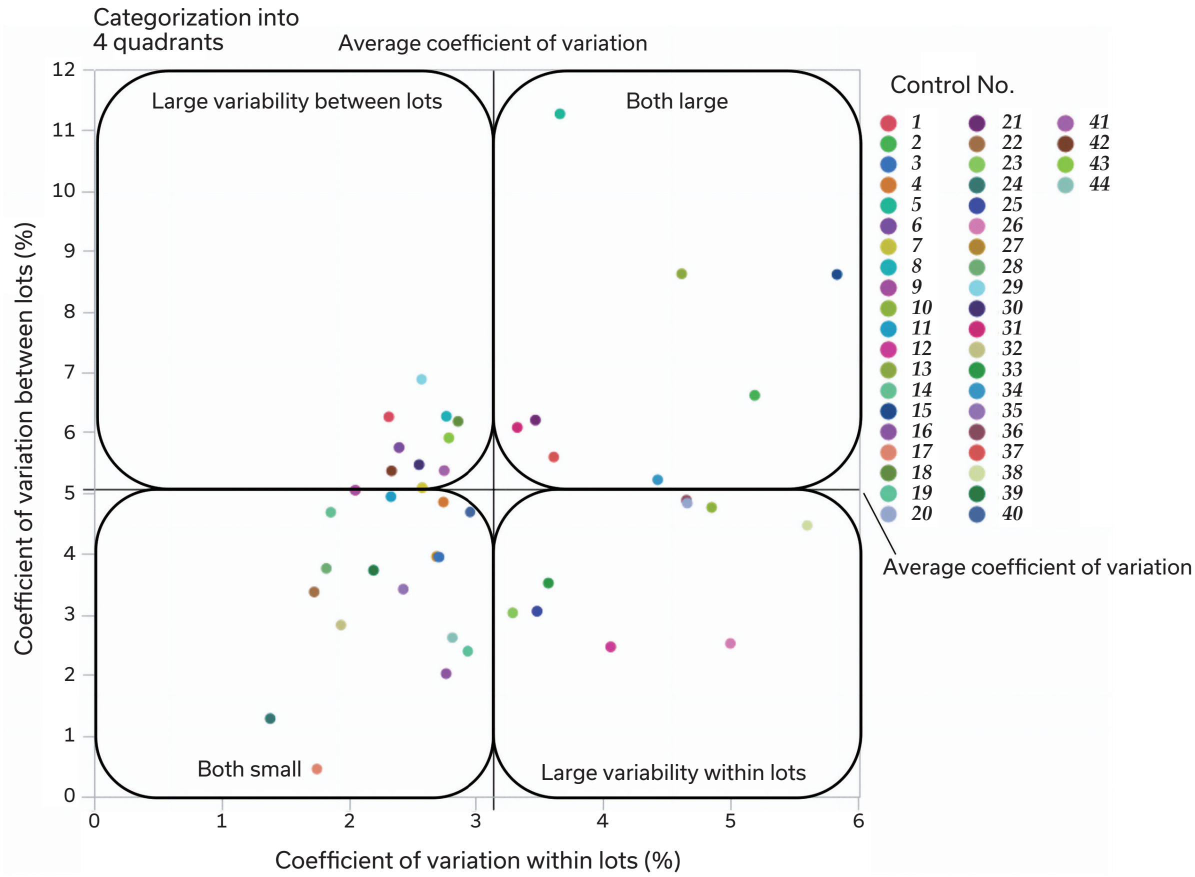

Figure 4. Relationship between variability within lots and variability between lots of discharge test results for specific batteries

5 Conclusion

This report described quality assurance–related aspects of the proposal-based energy storage solution promoted by EW. By creating a method of breaking down and evaluating battery performance variability within lots and between lots, we have made it easier to understand the characteristics of each product and the factors affecting them. Moving forward, we will use this technology to optimize product design and the manufacturing process in order to improve performance variability.

[Reference]

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Contact information

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