Social Implementation of Vanadium Redox Flow Batteries

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To achieve a carbon-free society, the goal is to halve greenhouse gas emissions by 2030 and aim for carbon neutrality by 2050 worldwide, while in Japan, the targets are to achieve net-zero emissions by 2050 and reduce emissions by 46% by 2030 (compared to FY 2013).(1) The use of renewable energy is essential, while to effectively utilize such variable power sources, utility-scale energy storage devices are indispensable. In particular, there is an increasing demand for Long Duration Energy Storage (LDES) that can absorb differences in electricity supply and demand due to seasonal and diurnal changes.(2) Sumitomo Electric's vanadium redox flow batteries (VRFBs) are stationary energy storage batteries that excel in safety, have very little decline in lifespan due to charge and discharge cycles, and are capable of storing a large amount of energy for a long time. The adoption of VRFBs is progressing in Japan and around the world, making significant contributions to the efficient utilization of renewable energy, the construction of local energy systems, and the enhancement of power resilience. In this paper, specific examples are introduced to show how VRFBs contribute to a cleaner and more stable energy future.

Keywords: Vanadium Redox Flow Battery (VRFB), storage battery, net-zero, Long-Duration Energy Storage (LDES), circular economy

1. Introduction

Globally, renewable energy (RE) adoption is advancing to realize a decarbonized society. Since RE sources like solar and wind power fluctuate in output depending on time of day, weather, and season, increasing their deployment necessitates greater importance in balancing supply and demand. Vanadium Redox Flow Batteries (VRFBs) are anticipated as grid stabilization technology essential for expanding RE adoption, and their deployment has accelerated in recent years. This paper introduces specific examples of VRFBs in use both in Japan and internationally.

2. Principle and Equipment Configuration of VRFBs

VRFBs are electrolyte circulation-type batteries that store an electrolyte solution—vanadium, the active material, dissolved in dilute sulfuric acid—in external tanks. This electrolyte is supplied to the cells via pumps for charging and discharging. The battery reaction involves only the oxidation-reduction of vanadium ions in the electrolyte. In principle, this eliminates active material degradation, making it a storage battery with extremely low degradation dependent on charge/discharge cycle numbers or patterns. Figure 1 shows a schematic diagram. Figure 2 illustrates an example of the VRFB equipment configuration. One positive electrolyte tank container and one negative electrolyte tank container, each storing electrolyte in the lower layer, are arranged side by side. A battery container housing the cells, pumps, piping, etc., is placed in the upper layer. The electrolyte stored in the tank containers is circulated to the cells by pumps. Energy is charged and discharged within the cells by utilizing the redox reaction of the active material in the electrolyte.

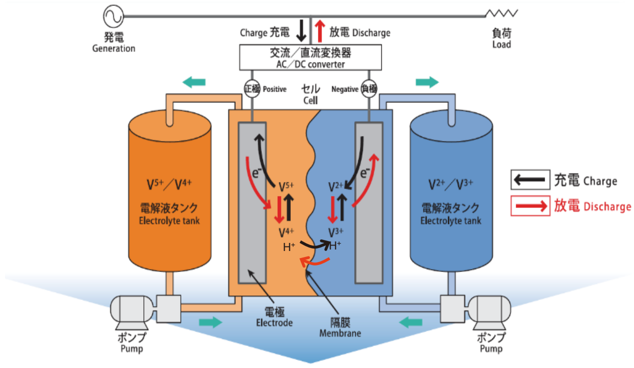

Fig. 1. Operating principle of a VRFB

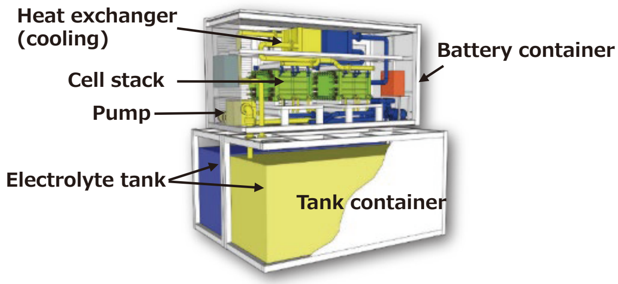

Fig. 2. VRFB configuration example

3. Features and Applications of VRFBs

VRFBs offer high level of safety, long lifespan, and eco-friendliness. Table 1 compares these characteristics with lithium-ion batteries.

Table 1. Comparison of VRFB features

Item		Vanadium Redox Flow Battery (VRFB)	Lithium-ion battery
Safety	Fire safety	• Non-flammable electrolyte	• Separation distance required during installation
	Fire suppression equipment	• Minimal fire suppression equipment	• Special fire suppression equipment required
Service life	Operational period	• 30 years (new model) • 20 years (current model)	• 10 to 20 years
	During the operational period	• No major equipment replacement required	• Battery addition / replacement required
	Charge/discharge cycle count	• No restrictions	• Restrictions apply
Environmental impact	At the end of life (EOL)	• Electrolyte is reusable • Over 99% reusable or recyclable (†) • Circular economy	• Dispose of as industrial waste

† Participation in the GX League administered by the Ministry of Economy, Trade and Industry of Japan (METI), and certification under the Wide-Area Industrial Waste Certification System administered by the Ministry of the Environment of Japan (MOE).

3-1 Features of VRFBs

(1) High Level of Safety

The electrolyte is a non-flammable aqueous solution, and other components are made of non-flammable or flame-retardant materials. Consequently, the fire risk is extremely low, and the system is not classified as a hazardous material under Japan's Fire Service Act. As a result, approval from fire authorities or the appointment of a dedicated fire safety manager in Japan is not required. The necessary fire suppression equipment is minimal, typically requiring only ABC fire extinguishers. For this reason, the system has attracted significant attention from users who prioritize fire safety. As described later, VRFB systems have been adopted in coal mines handling combustible resources and on remote islands.

(2) Long Service Life

In principle, degradation of discharge capacity is minimal, and by applying long-life materials in new VRFB models, an operational lifespan of 30 years can be achieved.[3] With no limit on charge/discharge cycles, it is suitable for multi-use applications. This includes simultaneous operation of long-cycle operation—storing excess RE during surplus periods and discharging during high-demand periods—and short-cycle operation, typically represented by ancillary services (frequency regulation, peak shifting, etc.). Furthermore, conventional models have undergone technical evaluation by major reinsurance companies, enabling the application of insurance systems with 20-year performance guarantees.

(3) Eco-Friendly

The electrolyte, which constitutes approximately 80% of the VRFB's weight (for a 6-hour capacity battery), does not degrade in principle, enabling semi-permanent reuse. In practice, electrolyte used for about 10 years in one VRFB has been successfully transferred to another VRFB and operated for another 10 years. Figure 3 illustrates initiatives toward a circular economy for the electrolyte.

Components containing the electrolyte are, in principle, over 99% reusable or recyclable, reducing industrial waste at

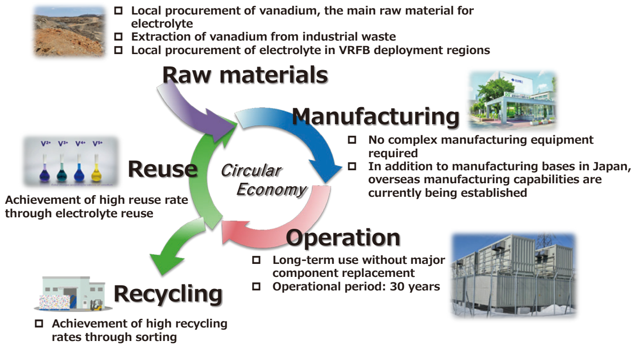

Fig. 3. Initiatives toward a circular economy

disposal to less than 1%. In Japan, the system has obtained certification under the Ministry of the Environment's Wide-Area Industrial Waste Certification System.

(4) Lifecycle Cost Advantage

VRFBs allow independent design of the power output section (cell) and the capacity section (tank). Capacity can be extended for longer durations simply by increasing the amount of electrolyte. Consequently, as shown in Fig. 4, the longer the duration capacity is, the lower the lifecycle cost is (initial cost + maintenance cost). Furthermore, due to their long lifespan and low degradation characteristics, they do not require cell stack replacement, electrolyte replacement, or expansion during operation. Consequently, as shown in Fig. 5, the longer the operational period is, the

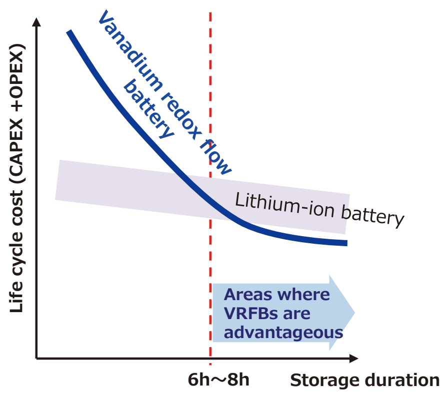

Fig. 4. Life cycle cost vs. storage duration

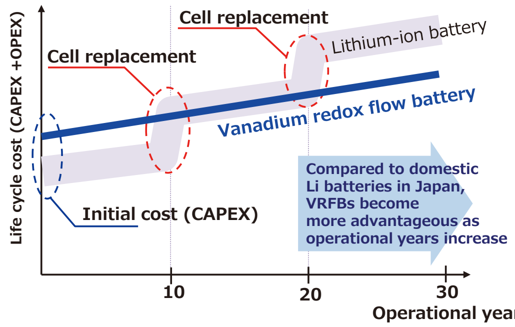

Fig. 5. Life cycle cost vs. operational years (6 h capacity)

greater the lifecycle cost advantage is.

Furthermore, during facility decommissioning after operation, the electrolyte is reusable, and most other components are also reusable or recyclable. Since the battery is not classified as hazardous material, its disposal cost is lower than that of hazardous waste. These factors make VRFBs highly competitive in terms of lifecycle cost for long-duration applications and easily adaptable for extended durations, making them the optimal storage battery for Long-Duration Energy Storage (LDES) applications. They are adopted in LDES systems both in Japan and internationally, including by regional power companies like Kashiwazaki IR Energy, as well as power companies in the U.S., Italy, Australia, and others.

3-2 Applications for VRFBs

VRFBs have lower energy density than lithium-ion batteries, requiring a larger installation area. However, they have no separation distance requirements during installation and offer higher level of safety with a lower risk of thermal runaway or ignition due to overcharging, a concern with lithium-ion batteries. Consequently, they are adopted particularly by users prioritizing safety or in environments handling flammable resources.

Furthermore, operators of grid-connected storage batteries engaged in power market transactions require batteries with high charging management accuracy and high responsiveness capable of addressing instantaneous supply-demand fluctuations. VRFBs meet customer requirements for grid-connected storage systems because they can measure open-circuit voltage using dedicated, non-contributing cells, enabling real-time, high-precision State of Charge (SoC) management even during charging/discharging. They also possess responsiveness, capable of charging/discharging within approximately 100 ms after receiving a charge/discharge command.

As a key technology for enhancing RE integration and power supply stability, LDES is expected to play a central role in future energy systems. VRFBs, which can extend time capacity by increasing electrolyte volume, are being applied as optimal storage solutions for LDES in RE transitions, microgrids,*2 and sustainable mining operations globally. Specific implementation cases are introduced in the next chapter.

Table 2. Major VRFB deployment cases

Customer	Application	Output	Year of completion	Appearance
Hokkaido Electric Power Network [Transmission and distribution operator]	Grid-side battery storage - Grid stabilization (LFC, etc.)	60 MWh (15 MW, 4 h)	2015	
Taiwan Power Company [Electric power company]	Microgrid demonstration	750 kWh (125 kW, 6 h)	2017	
San Diego Gas & Electric [Electric power company (U.S.)]	Grid-scale battery storage - Market operations - Microgrid power source	8 MWh (2 MW, 4 h)	2017	
Maeda Corporation [Construction industry (research institute)]	Consumer Equipment - Peak shaving - Stand-alone operation	750 kWh (250 kW, 3 h)	2018	
John Cockerill [Government-affiliated organization (Belgium)]	Grid-scale battery storage - Microgrid demonstration	1.7 MWh (500 kW, 3.4 h)	2019	
Sumitomo Corporation Taiwan [Government-affiliated organization (Taiwan)]	Consumer equipment - Battery storage demonstration - BCP	750 kWh (250 kW, 3 h)	2020	
Hokkaido Electric Power Network [Transmission and distribution operator]	Grid-side battery storage - Enhancing balancing capacity for wind power grid integration	51 MWh (17 MW, 3 h)	2022	
Nippon P.S [Manufacturing (factory)]	Consumer equipment - Improvement of renewable energy self-consumption rate - BCP	750 kWh (250 kW, 3 h)	2023	
Kashiwazaki IR Energy [Regional electric power company]	Grid-scale battery storage - Market operations - Improvement of renewable energy utilization rate	8 MWh (1 MW, 8 h)	2024	
Energy Queensland [Electric power company (Australia)]	Grid-scale battery storage - Solar power co-location - Demand response	750 kWh (250 kW, 3 h)	2024	
San Diego Gas & Electric [Electric power company (U.S.)]	Grid-scale battery - Market operations - Microgrid power source	4 MWh (500 kW, 8 h)	2024	
Minamikyushu City, Kagoshima Prefecture [Local government]	On-site installation for consumers - Solar power co-location - Microgrid, BCP	1.125 MWh (250 kW 4.5 h)	2025	
Kashiwazaki IR Energy [Regional electric power company]	Grid-scale battery storage - Market operations - Solar power co-location	8 MWh (1 MW 8 h)	2025	
Kashiwazaki IR Energy [Regional electric power company]	Grid-scale battery storage - Market operations - Solar power co-location	8 MWh (1 MW 8 h)	2026	
Idemitsu Australia [Energy industry (Australia)]	Grid-scale battery storage - Green Transformation (GX) in mining	12.6 MWh (2 MW, 6.3 h)	2026 (planned)	
Chugoku Electric Power Transmission & Distribution Company [Transmission and distribution operator]	Grid-scale battery storage - Improvement of renewable energy ratio - BCP for remote islands	12.5 MWh (4 MW, 3.125h)	2026– (planned)	

4. VRFB Adoption Cases

Table 2 shows major VRFB adoption cases globally. As of March 2026, these projects span seven countries including Japan, the U.S., Australia, Taiwan, and Europe, totaling 54 MW and 202 MWh. Applications include power quality stabilization through frequency regulation for utilities, grid-scale market trading, increasing RE ratios for consumers, and forming regional microgrids.

4-1 General transmission and distribution operators: grid-scale batteries

Hokkaido Electric Power Network, Inc. completed construction of a VRFB system with a capacity of 60 MWh (15 MW × 4 h, Max 30 MW) at the Minami-Hayakita Substation in Hokkaido in December 2015. The system aims to demonstrate the performance of large-scale batteries as a new balancing resource for RE output fluctuations and to establish optimal control technology. It underwent three years of demonstration testing[(4)-(7)] and has been in actual operation since 2019. While the rated output is 15 MW, it can operate at twice the rated capacity, 30 MW, for short-term fluctuations. Figure 6 shows a test example of short-term fluctuation suppression control, confirming the effectiveness of frequency deviation suppression through battery control.[(8)] Furthermore, during the Eastern Iburi Earthquake that occurred in the early hours of September 6, 2018, this VRFB facility, installed just 16 km from the epicenter, resumed operation the day after the earthquake. It functioned as a balancing power source for wind power generation, contributing to the reconnection of 103 MW of wind power generation.[(9)]

Furthermore, aiming to expand wind power genera-

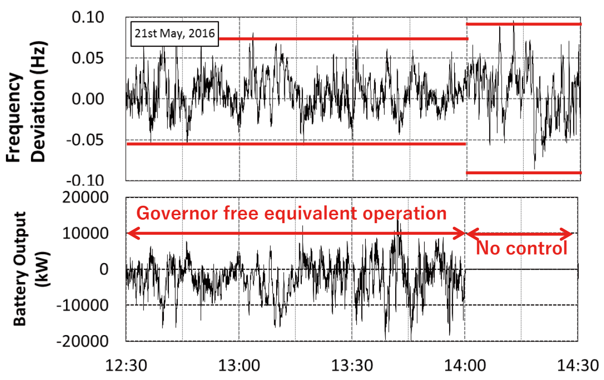

Fig. 6. Example test results for Governor-free equivalent control

tion, an RFP (Request for Proposals) for the Grid-Side Battery-Based Wind Power Procurement Process (Phase I) was issued to provide the necessary balancing power for connecting 162,000 kWh of wind power generation facilities. This project, encompassing equipment installation, operation (21 years), maintenance, and disposal, was selected based on a lifecycle cost evaluation. A 17 MW / 51 MWh VRFB system commenced operation in April 2022.(10) In addition to load frequency control commands from the Central Power Dispatching Center, it performs autonomous operation (governor-free control) based on grid frequency, smoothing the output of connected wind power generation facilities and adjusting frequency. Figure 7 illustrates the operational concept. This facility was recognized for contributing to grid stabilization by eliminating the need for individual storage batteries at power generation sites through the introduction of large-scale VRFBs on the grid side, receiving the 2023 New Energy Award from the New Energy Foundation (NEF) of Japan.(11)

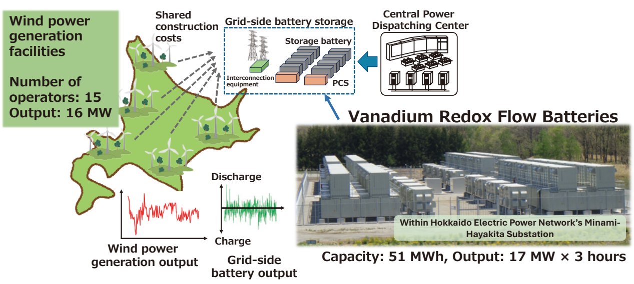

Fig. 7. Operational concept

4-2 Regional electric power company: LDES and grid-scale batteries

Kashiwazaki City, Niigata Prefecture, Japan is proactively promoting RE utilization with a vision to become a "Decarbonized City." Sumitomo Electric supports the realization of a sustainable local community by leveraging the energy storage and supply capabilities of VRFBs. Specifically, during periods of excess power supply from solar generation, such as daytime, the VRFBs are charged. During periods of high-power demand, the batteries discharge, maximizing RE utilization within Kashiwazaki City and ensuring stable power supply in the region.

Kashiwazaki IR Energy Co., Ltd.'s 1 MW / 8 MWh VRFB system has been adopted for three consecutive years as a grid-scale battery for regional electric power companies (two units are in operation, one is under construction).(12) Utilized as an 8-hour capacity LDES, the system promotes RE use, local power generation and consumption, and enhances energy security. Figure 8 shows an operational concept diagram.(13) Leveraging its 8-hour capacity, the system reduces procurement costs from the wholesale electricity market, stabilizes prices, and purchases electricity to charge the system when prices are low, and discharges it for sale when prices are high. This is expected to maximize RE utilization and stabilize electricity costs by improving wholesale electricity market revenues.

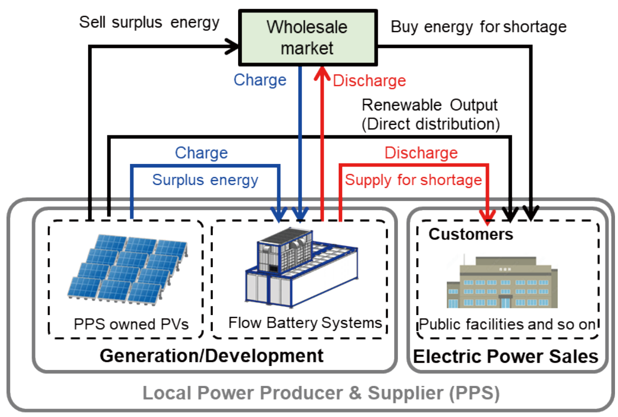

Fig. 8. Operational concept

4-3 U.S. Utility: LDES, grid-scale batteries, market operations, and microgrids

A multi-use demonstration was conducted using a 2 MW / 8 MWh VRFB installed at the facility of San Diego Gas & Electric (SDG&E) in California, the U.S. As shown in Figs. 9 and 10, the following were demonstrated: stabilization of supply and demand and voltage control in the distribution system, operation in the wholesale market, and demonstration of microgrid operation in an actual distribution network. All these use cases proved the system's operational feasibility.(14)-(16) After the demonstration concluded, the ownership of the facility was transferred to SDG&E. During normal operations, the VRFB generates revenue by participating in the California wholesale electricity market (CAISO market).*3 In addition, during disasters or planned outages, it is used as a voltage source for microgrid operations. This demonstration project has been highly regarded for its contribution to ensuring the resilience of the power grid, receiving the ISGAN Award 2024.(17) Furthermore, in 2024 an additional 0.5 MW / 8 MWh VRFB was reordered from SDG&E for the same purpose. During Public Safety Power Shutoff (PSPS)*4 events, where power is temporarily shut off to prevent wildfire occurrence and spread, it will be utilized as a community microgrid, integrated with adjacent solar power generation facilities. It provides an extended capacity of 8 hours and, like the existing VRFB, operates in the CAISO market during normal conditions. The results of this demonstration were obtained through the commissioned project "Demonstration Project for Combined Transmission and Distribution Operation of Storage Batteries in California, USA" (JPNP93050) by the New Energy and Industrial Technology Development Organization (NEDO).

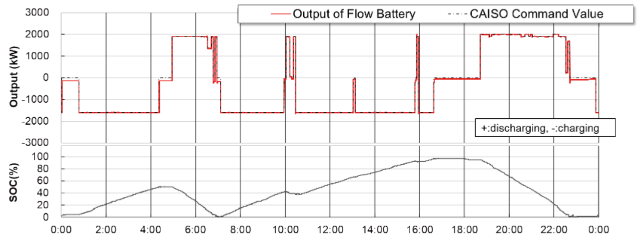

Fig. 9. Example of operation in the CAISO Market

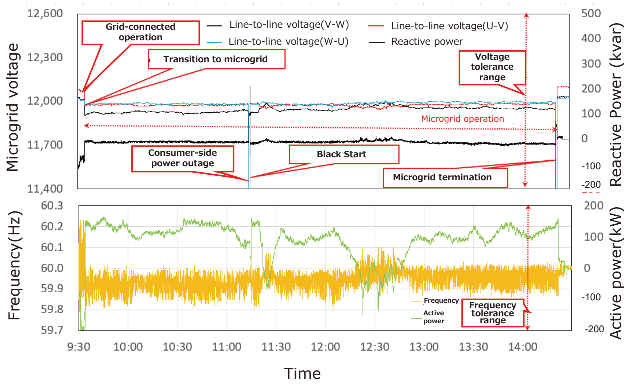

Fig. 10. Microgrid operation results

4-4 Consumer (Factory): RE utilization and BCP

To maximize the consumption rate of solar self-generated power within the factory's electricity supply, a 250 kW / 750 kWh VRFB was installed on the premises of Nippon P.S Co., Ltd.(12) For this facility, the VRFB system was selected because it offers a long lifespan, is not classified as a hazardous material, does not require special fire prevention equipment, and provides high level of safety. Figure 11 shows a daily operation overview.

Figure 12 shows the RE utilization rate from the factory's monthly power consumption and solar power generation over two years following the introduction of the solar power generation system (700 kW) and VRFB system. The VRFBs were particularly utilized during summer when surplus solar power generation was high, achieving a maximum RE utilization rate of 67% and an average of 42.8%. They are also used for multiple purposes, including reducing electricity costs through peak shaving and operating as an independent power source to supply critical equipment during power outages.

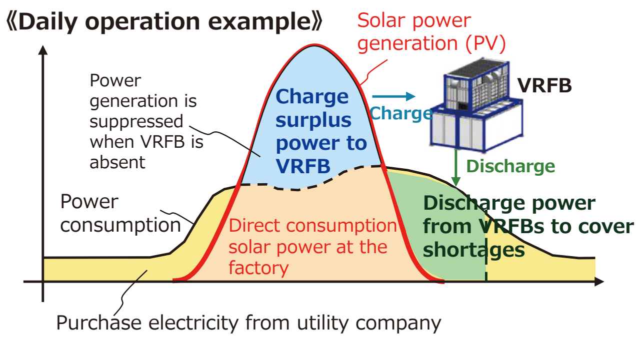

Fig. 11. Operational concept

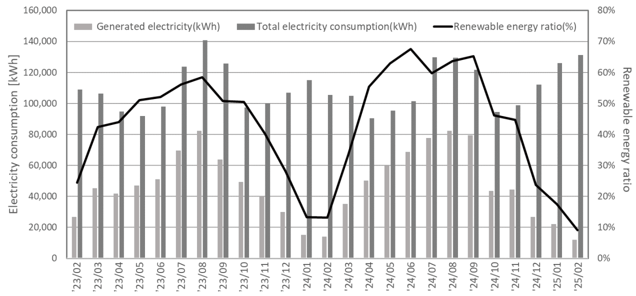

Fig. 12. Changes in the RE ratio

4-5 Coal mine: LDES and high level of safety

Australia, which aims to achieve an 82% RE share of baseload power by 2030 and net zero by 2050, is accelerating the introduction of RE, including solar power generation facilities. Australia is one of the world's leading resource exporters and is promoting the transition to green metals*5 and decarbonization in its key mining sector to ensure future competitiveness. The Australian government is promoting Green Transformation (GX)*6 in the mining sector through subsidies for RE adoption in mining operations and for flow batteries using minerals such as vanadium.(18)

Within the mining sector, environments handling combustible resources like coal mines demand high level of safety standards. VRFBs contain no flammable materials, carry a low risk of thermal runaway, and offer significantly higher level of safety compared to other storage batteries. Recognizing this advantage, a 2 MW / 12.6 MWh VRFB system is planned for installation at Boggabri coal mine operated by Idemitsu Australia Pty Ltd. To accelerate the mine's decarbonization, solar power generation facilities and VRFBs will be introduced. The plan is to utilize electricity stored during daytime generation at night, with installation scheduled for the second half of 2026.(19)

Knowledge gained from this mining GX project is expected to be applied to other mines.

4-6 Remote islands: high level of safety and microgrids

Remote islands face challenges such as high fuel costs due to the difficulty of transporting fuel from the mainland, ensuring power supply during disasters, and the need for efficient RE utilization to achieve a decarbonized society. Chugoku Electric Power Transmission & Distribution Co., Inc. is promoting the introduction of storage batteries in the

Oki Islands to accelerate the realization of a decarbonized society and as a power source for independent operation (microgrid) during disasters, aiming to enhance carbon neutrality and power resilience in island regions.[20] VRFBs were selected due to their high level of safety, eliminating the need for a hazardous materials handler to be present during installation and operation, making maintenance and operation easier on remote islands, and their long lifespan.†

† Supported by the Project to Support Equipment Introduction for Mainstreaming RE in Remote Islands and Other Areas (Japanese Ministry of the Environment)

5. Conclusion

This paper introduces case studies of VRFB deployment advancing toward a decarbonized society. As the government advances policies aiming for long-term decarbonization, such as further expanding RE adoption and conducting long-term decarbonization auctions for power sources, the role of VRFBs—suited for long-duration energy storage—will become increasingly important. Furthermore, VRFBs, which are safe, long-lasting, and environmentally friendly, are highly suitable technologies for enhancing power resilience on remote islands and promoting GX initiatives in coal mines. They will continue to contribute to realizing a decarbonized society through implementation across various sectors of society.

Technical Terms

*1 Long Duration Energy Storage (LDES): A system that stores energy for extended periods (generally 8 hours or more) and releases it as needed.

*2 Microgrid: An energy system that normally leverages local RE sources while receiving power supply through the transmission and distribution network, and in emergencies can be disconnected from the transmission and distribution network to autonomously supply power by combining distributed power sources within the region.

*3 CAISO Market: California Independent System Operator (CAISO). A non-profit corporation that manages the transmission grid and is responsible for grid stability, infrastructure planning, and market operations.

*4 Public Safety Power Shutoff (PSPS): A preventive power supply shutdown by electric power companies to ensure the safety of the power transmission and distribution network and prevent large-scale fires under weather conditions that greatly increase the risk of wildfires.

*5 Green Metal: Metals procured and manufactured using methods that generate no or very little greenhouse gases, and metals referred to as a wide range of low-carbon, sustainable metals, including battery materials and RE-related materials.

*6 GX (Green Transformation): The transformation of the conventional fossil fuel-centered industrial structure into a sustainable society utilizing RE and energy-saving technologies.

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