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Securing Grid Flexibility for Renewable Energy Integration

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Executive Summary

- The expansion of the share of variable renewable energy in the power supply mix increases the variability and uncertainty of supply. Therefore, it is necessary to ensure flexibility by utilizing demand response (DR), storage batteries, long-duration energy storage (LDES), and grid-forming (GFM) inverters.
- Regarding storage batteries, technological developments aimed at breaking the stagnation in manufacturing costs and improving safety are progressing. In the short term, lithium iron phosphate (LFP) batteries, which use inexpensive lithium, iron, and phosphorus as cathode materials, are attracting attention. For LDES, technologies such as redox flow batteries, sodium–sulfur (NaS) batteries, thermal storage technologies, and iron–air batteries are anticipated. Additionally, securing inertia and synchronization is crucial for grid stabilization, and the use of GFM and motor–generator (MG sets) is also proposed.

The role of renewable energy in achieving decarbonization economically in the power system is significant. In Japan, in the draft of the 7th Basic Energy Plan, published in December 2024, it is indicated that the share of renewable energy in total power generation will reach 40–50% by 2040. Among renewables, solar and wind power, which are expected to be prominent due to their low levelized cost of electricity (LCOE) and ease of installation, are types of variable renewable energy (VRE) that experience significant fluctuations in generation depending on time and weather. The expansion of these VRE sources introduces various challenges, such as temporal and geographical mismatches in power supply and demand, and a reduction in inertia.

In this context, maintaining and operating the power system will require securing flexibility to manage fluctuations and uncertainties in supply and demand. This can be achieved by utilizing demand response (DR), as discussed in DBJ Research No.427 “Achieving Economic Efficiency in Power Systems through DR: Standardization and Automation for Leveraging Low-Voltage Resources,” as well as storage batteries and long-duration energy storage (LDES), which are capable of economically charging and discharging electricity for more than six hours. This paper examines the overall picture of flexibility and the promising technologies.

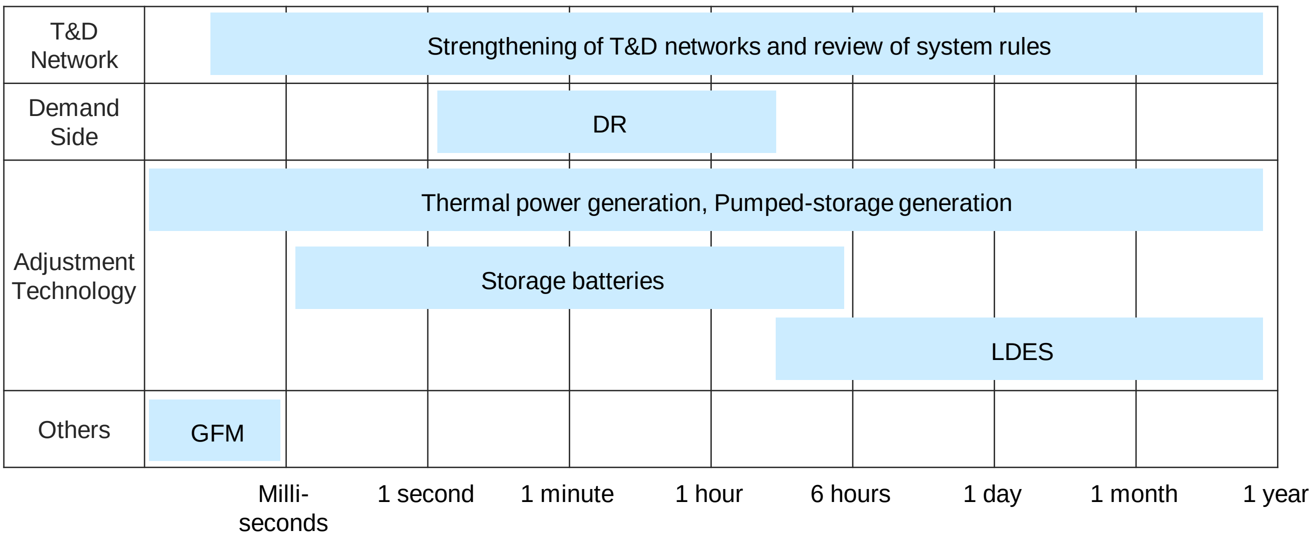
1. The Importance of Securing Flexibility in Anticipation of Renewable Energy Integration

Flexibility refers to the set of functions that the power system must possess to manage fluctuations and uncertainties in power supply and demand over various time scales while maintaining reliability and economic rationality. In the power system, it is necessary to constantly match supply and demand to ensure power quality and prevent blackouts. For example, when supply exceeds demand, it is necessary to either curtail the output of generation facilities or increase power consumption to match supply and demand. Flexibility enables such responses, and traditionally, thermal power and pumped storage power have been the main providers of this flexibility.

In the future, as the share of VRE in the power supply mix increases, the variability and uncertainty of supply will also rise. At the same time, the share of thermal and pumped-storage power generation is expected to decrease relatively, making the assurance of flexibility a significant challenge. Thermal power generation is an excellent source of flexibility over a wide range of time units, but it is also the primary source of CO_2 emissions in the power system. On the other hand, pumped-storage power generation can provide adjustment capabilities without emitting CO_2, but most suitable sites in Japan have already been developed, and new development is difficult from the perspectives of profitability and environmental assessment.

Given this situation, it is necessary to comprehensively implement strategic development of transmission and distribution (T&D) networks, DR, and the introduction of storage batteries and LDES, considering the technical characteristics and economic feasibility of each (Figure 1-1).

Figure 1-1 Corresponding Technologies, by Time Unit



（Note）Created by DBJ based on the International Energy Agency's *Status of Power System Transformation 2018*.

There is a clear correlation between the amount of VRE introduced and the need for flexibility. The International Energy Agency (IEA) analyzes this correlation by dividing it into six phases (Figure 1-2). Considering the future amount of VRE introduction, it is expected that Japan will reach Phase 4 by 2030, at which point there may be prolonged periods of surplus or shortage of electricity depending on weather conditions and power demand. Therefore, in addition to the short-term adjustment capabilities that have been implemented so far, such as strengthening T&D networks and securing short-term adjustment capabilities using thermal, pumped-storage, and storage batteries, it is also necessary to secure long-term adjustment capabilities using LDES and inertia and synchronization using grid-forming (GFM) and other technologies.

Figure 1-2. Changes in Phases, by VRE Share and Required Flexibility

Phase	VRE share in Total Power Generation	T&D networks	Short-term Adjustment	Long-term Adjustment	Inertia and Synchroni-zation	Countries and Regions by 2024	Countries and Regions by 2030
1	5% or less					Thailand	-
2	5-10%					USA, India, Kenya	Thailand, USA
3	10-25%					Japan, UK, Vietnam, Chile	India, Kenya, Vietnam
4	25-60%					Iceland, UK, Denmark	Japan, UK, Chile
5	60-90%					South Australia	Iceland, Denmark South Australia
6	90-100%					-	-

High Requirement　Low Requirement

（Notes）1. Created by DBJ based on the International Energy Agency's *Integrating Solar and Wind*.
2. Short-term adjustment capability is defined as charging and discharging for less than six hours, and long-term adjustment capability is defined as charging and discharging for ix hours or more.

(1) Strategic Development of T&D Networks and Review of System Rules

The strategic development of transmission and distribution (T&D) networks that connect power plants and demand areas is an important measure to ensure flexibility in anticipation of the expansion of VRE introduction, which causes a geographical mismatch between power supply and demand. Unlike Europe and China, where transmission networks are widely spread, Japan, being a long island nation from north to south, has an elongated and narrow transmission network that is not interconnected with other countries. Therefore, it is currently difficult to ensure flexibility through the flexible exchange of electricity among regions in the country when large-scale supply and demand fluctuations occur.

Considering this situation, the Organization for Cross-regional Coordination of Transmission Operators (OCCTO) created the "Master Plan for Cross-regional Interconnection Systems" in March 2023. This plan aims to make renewable energy a main power source and strengthen the T&D networks, presenting a long-term outlook for cross-regional system development towards 2050. If there is insufficient transmission line capacity, it may lead to increased curtailment of renewable energy output and delays in the introduction of renewables. Therefore, planned reinforcement of the transmission network in line with the master plan is expected. Additionally, considering that many small-scale distributed power sources are also located within the distribution network in Japan, it is necessary to respond by combining distribution network reinforcement and DR.

In addition to strengthening the transmission and distribution networks, it is also important to maximize the use of existing T&D networks by reviewing system utilization rules. In Japan, as part of the Japanese version of *Connect & Manage*, efforts such as rationalizing assumed power flows and N-1 power control have been sequentially implemented since 2018.

（2）Introduction of Supply–Demand Adjustment Technologies

Technologies that provide the adjustment capability necessary to ensure flexibility for periods longer than a few seconds include not only thermal and pumped-storage power generation and DR, but also storage batteries and a wide range of other LDES technologies (Figure 1-3).

Figure 1-3 Overview of Various Technologies Providing Balancing Power

	LNG thermal	Pumped-storage	Storage batteries	LDES	DR
Potential	Possible	Limited additional introduction in Japan	Possible	Possible, except for some	High potential
Short-term adjust-ment	Possible through governor-free operation, etc.	Possible through variable-speed generators	Possible	Slow response speed for some	Not performed, due to reliability issues
Long-term adjust-ment	Possible if fuel is available	Depends on precipitation and operational plans	Possible, though high cost	Possible	Difficult
Cost	High fuel costs; prices are volatile	Low marginal cost	Inexpensive for short-term adjustment	Inexpensive for long-term adjustment	Inexpensive due to no CAPEX required
Sustaina-bility	Emits GHG	No GHG	No GHG	No GHG	No GHG

（Notes）1. Created by DBJ.
2. Short-term adjustment is defined as charging and discharging for around one second, and long-term adjustment is defined as charging and discharging for six hours or more.
3. Blue-shaded areas indicate the advantages of the technology.

While the spread of storage batteries for electric vehicles (EVs) and hybrid electric vehicles (HEVs) is leading the way, the introduction of stationary storage batteries for power-related applications is also progressing, including (i) co-location with power plants, (ii) connection to T&D networks, and (iii) on-site installation by power consumers. Regarding (i), under the feed-in premium (FIP) system that started in 2022, unlike the feed-in tariff (FIT) system, there is no imbalance exemption; so, power producers need to settle imbalances when there is a discrepancy between the power generation plan and the actual generation. Additionally, under the FIP system, the profitability of the business varies greatly depending on the generation profile, which is driving the co-location of storage batteries with renewable energy power plants. Regarding (ii), connection contracts for grid storage batteries are being concluded one after another, especially in regions with high VRE penetration, such as Hokkaido and Kyushu. Regarding (iii), storage batteries are also spreading in households and industries from the perspective of effective utilization of on-site solar power generation and business continuity planning (BCP).

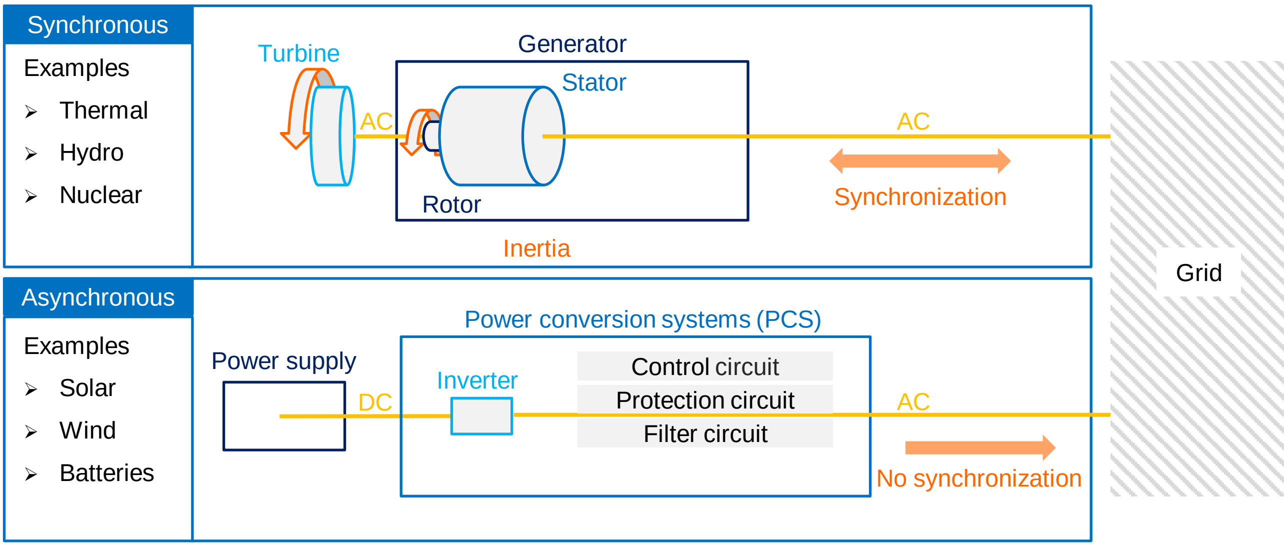
For longer-term and scale adjustments, there is growing interest not only in conventional storage batteries but also in a wider range of LDES. While storage batteries are cost-effective in terms of output (kW), they are expensive in terms of capacity (kWh), making them unsuitable for long-term, large-scale supply–demand adjustments. Therefore, technologies that are cost-effective per kWh and capable of storing large amounts of energy for long periods are needed, and social implementation of various LDES is progressing. According to the 7th Basic Energy Plan, the share of renewable energy, mainly VRE, is expected to reach 40–50% by 2040. Thus, it is considered necessary to respond with storage batteries and DR by 2030, and to promote the introduction of LDES with a view to 2040 and beyond to 2050.

(3) Ensuring Inertia and Synchronization Capability Contributing to Stable Supply

In ensuring flexibility for extremely short periods, inertia and synchronization are important. Inertia refers to the total amount of kinetic energy possessed by rotating machinery such as generators and motors, while synchronization refers to the characteristic of generators connected within the same alternating current (AC) system operating at the same frequency. Both play a significant role in suppressing sudden frequency fluctuations during system disturbances and ensuring the stability of the power system.

Power sources that use rotating magnetic fields, such as thermal, hydro, and nuclear power generation, are called synchronous power sources. They operate in parallel by being coupled with other synchronous power sources through synchronization capability and maintain the frequency of the power system through the inertia of the rotating bodies. VRE, on the other hand, is an asynchronous power source that discharges power into the power system after converting direct current (DC) output power to AC using power conversion systems (PCS) and does not possess inertia or synchronization (Figure 1-4).

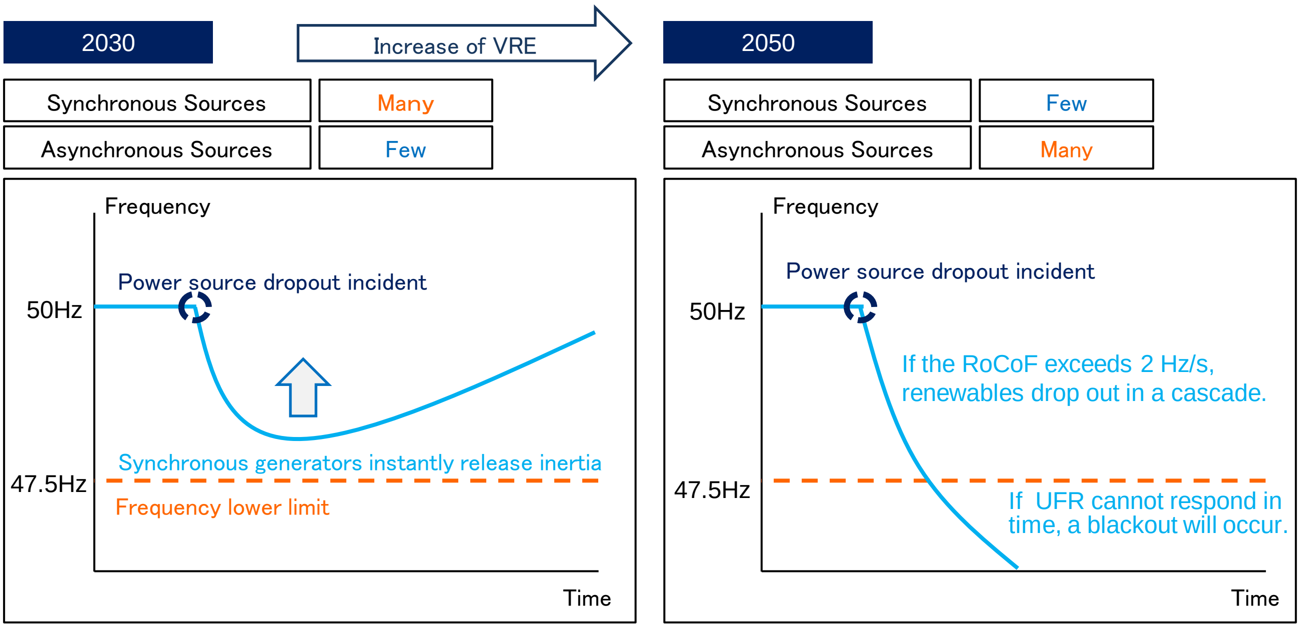
Figure 1-4 Differences between Synchronous and Asynchronous Power Sources



(Note) Created by DBJ.

When the VRE ratio reaches 40–50%, the entire power system will lack inertia and synchronization. Additionally, the protection functions of PCS will cause cascading disconnections of renewable energy sources, leading to an increase in the rate of change of frequency (RoCoF). If the frequency drops below the lower limit during an incident, the under-frequency relay (UFR) will activate to disconnect part of the demand side. However, if the RoCoF increases and the UFR cannot respond in time, widespread blackouts or equipment damage may occur (Figure 1-5).

Figure 1-5 Concerns about Stable Supply Due to Lack of Inertia



（Note）Created by DBJ.

It is said that the probability of a blackout increases when the RoCoF exceeds 2 Hz/s. According to the power supply composition for 2030 indicated in the 6th Basic Energy Plan, there are no areas where the RoCoF is expected to exceed 2 Hz/s. On the other hand, in the base scenario of the OCCTO's Master Plan for Cross-regional Interconnection Systems, which envisions the realization of carbon neutrality by 2050, the RoCoF in East Japan and middle West Japan is expected to exceed 2 Hz/s. Therefore, ensuring inertia and synchronization will be a critical issue towards 2050.

In addition, synchronous power sources can instantly supply fault current (high current) during a short circuit, allowing the system to detect the fault location. However, using PCS with VRE involves semiconductor components that are vulnerable to high currents and rapid current changes, limiting their response to fault currents. Therefore, it is necessary to strengthen protection relay systems and take other measures.

2. Expectations and Measures for Storage Batteries in 2030

（1）Overview of Storage Batteries and Notable Technologies

The storage battery market is rapidly expanding in response to the increased introduction of EVs and renewable energy, which play a crucial role in achieving carbon neutrality. There are many types of storage batteries, differing in materials used, and when considering actual implementation, it is necessary to comprehensively consider technical characteristics, maturity, and issues related to commercialization. In the fields of automotive and stationary applications, ternary lithium-ion batteries (LiB), which have high energy density and a long cycle life and have achieved cost reductions through mass production, are mainstream. However, ternary LiBs use a lot of critical materials, making the supply chain unstable and limiting theoretical cost reductions. Additionally, since the electrolyte is a flammable liquid, appropriate measures are needed to prevent fires (Figure 2-1).

Figure 2-1 Required Specifications for Storage Batteries and the Status of Ternary LiB

Technical Specifications					
Volumetric Energy Density	Gravimetric Energy Density	Safety	Energy Loss	Charge Speed	Cycle Life
200～500 Wh/L	70～200 Wh/kg	UN38.3 compliant	Around 10%	Less than 1C	1,000 - 2,000 cycles
◎	◎	△	○	○	○

Time Axis	Issues Related to Commercialization				
Maturity	Supply Chain	Scalability	Manufacturing Cost	Maintenance	Recycling
TRL10	Unstable	Easy	Normal	Easy	Easy
◎	△	◎	○	○	○

（Notes）1. Created by DBJ.

2. In comparison with other batteries, points that are very superior are marked with ◎, superior points are marked with ○, and points that are considered to have issues are marked with △.

To both break through the stagnation in manufacturing cost reductions and improve safety, various storage batteries with innovations in cathode and anode materials are being developed (Figure 2-2).

Figure 2-2 Major Storage Battery Technologies and Maturity Levels

Types	TRL (2023)	Description
Lead–acid battery	11	A rechargeable battery using lead oxide as the positive electrode and lead as the negative electrode. While the energy density per unit weight is low, the manufacturing cost is economical, making it suitable for stationary applications.
Nickel–metal hydride battery	11	A rechargeable battery with a positive electrode of nickel hydroxide and a negative electrode of metal hydride alloy. It is widely used for long cycle life and rapid discharge capabilities, such as in HEVs.
Lithium-ion battery (LiB)	10	With positive electrode materials like nickel manganese cobalt (NMC), lithium iron phosphate (LFP), etc., LiB is the predominant battery technology. The International Energy Agency (IEA) estimates a high probability of replacement by new technologies before 2030.
Sodium-ion battery (NiB)	8	Utilizing LiB as a basis for design, sodium, which is affordable and readily available, is used in the electrodes and electrolytes. However, challenges include cost reduction and difficulties in rapid discharge.
Silicon-containing LiB	6	An LiB with silicon, which has 10 times the energy density of graphite, as the negative electrode. The swelling of silicon and short cycle life are key challenges.
All-solid-state lithium-ion battery	5	A battery that replaces liquid electrolytes with solid electrolytes, expected to significantly improve energy density and safety. According to the IEA, commercialization is expected in the second half of the 2020s.
Lithium–sulfur battery (Li-S battery)	4	A battery using sulfur, which is affordable and widely available, as the positive electrode. Its high energy density is a feature, but challenges include short cycle life and polysulfide generation.
Zinc–manganese oxide battery	4	A battery using zinc and manganese oxide as the electrodes. It is expected to enhance energy density, but challenges include short cycle life and low voltage output.
Potassium-ion battery	3	A battery using potassium, which belongs to the same alkali metal group as lithium and sodium. Cost reductions are expected, but challenges include short cycle life and difficulties in rapid discharge.
Multivalent-ion battery	2	A battery using multiple types of ions, such as magnesium, calcium, and aluminum. Challenges include ensuring stable charge–discharge cycles and overcoming short cycle life.

（Notes）1. Created by DBJ.
2. TRL (technology readiness level) is based on the International Energy Agency’s classification.
3. TRL 1–3 = basic research stage, TRL 4–6 = applied research stage, TRL 7–8 = demonstration stage, TRL 9–10 = commercialization stage, TRL 11 = mature technology.

When selecting stationary storage batteries, it is considered important to focus on three aspects among the evaluation items shown in Figure 2-1: safety, maturity, and cost competitiveness. Regarding safety, since stationary storage batteries are connected to the power grid, which is a critical infrastructure, and may be adjacent to residential areas, it is necessary to minimize the probability of accidents such as fires as much as possible. From the perspective of maturity, considering mass production and social implementation in the 2030s, it is desirable for the technology to be at least at the demonstration stage (TRL 7 or higher) at present. Furthermore, cost competitiveness, which is a crucial factor for widespread adoption, can be evaluated using the levelized cost of storage (LCOS), which is calculated by dividing the total cost by the total discharge amount. To reduce the total cost, the use of inexpensive raw materials and the simplification of maintenance and recycling are effective, while increasing the total discharge amount can be achieved by improving cycle life and reducing energy loss rates. Given their significant impact on LCOS, it is important to focus on the cost of raw materials and cycle life in the evaluation. Since high energy density per volume and weight, which is required for batteries in vehicles, is not as necessary for stationary storage batteries, cost competitiveness is a more important factor.

Considering these perspectives comprehensively, apart from ternary LiB, the lithium iron phosphate (LFP) battery, which uses lithium, iron, and phosphorus as cathode materials, is already a mature and cost-effective technology and is gaining attention. The characteristics of LFP include a cycle life of 2,000 to 4,000 cycles, which is longer compared to ternary systems; limited use of rare metals; and lower raw material costs. However, regarding safety, while the cathode material is more stable compared to ternary systems, the electrolyte uses flammable solvents similar to those in ternary systems, and thus the safety issues in LiB have not been completely eliminated. Recently, with improvements in energy density per weight, the use of LFP in automotive applications has increased, and R&D as well as mass production are accelerating, leading to expectations for further performance improvements and cost reductions.

3. Expectations for LDES by 2050

（1）Overview of LDES and Notable Technologies

Long-duration energy storage technology becomes increasingly necessary when the VRE penetration rate exceeds approximately 30% (Phase 4 as defined by the IEA). It is expected to see full-scale adoption across Japan after 2030. Many LDES technologies are those that either have been developed, demonstrated, and implemented over time or apply combinations of existing technologies. Many of these technologies, such as pumped hydro storage, are already relatively mature (see Figure 3-1).

Figure 3-1 Major LDES Types and Their Technology Readiness Levels (TRLs)

Types	TRL (2023)	Description
Pumped storage hydropower (PSH)	11	Broadly utilized. Advancing research and development in areas such as drop shafts and seawater utilization, as well as small modular systems.
Redox flow batteries (RF batteries)	9	Circulates electrolytes with pumps and charges/discharges via ion redox reactions. Vanadium redox batteries (VRBs) are currently being developed.
Electrolysis & fuel cells	9	Uses solid oxide electrolyzer cells (SOECs) to produce and solid oxide fuel cells (SOFCs) to generate electricity from hydrogen.
Flywheel energy storage	8	Minimizes air resistance and rotational friction, storing electrical energy in a flywheel in a vacuum.
Molten salt batteries (NaS batteries)	8	Uses molten salts at around 300–350℃ as electrolytes. Sodium–sulfur batteries (NaS batteries) by NGK Insulators, Ltd. are already in use.
Thermal storage	8	Stores energy by heating materials with high thermal resistance, such as metal, bricks, or molten salts.
Liquid air energy storage (LAES)	7	Stores energy by liquefying air at extremely low temperatures and generating electricity by regasifying and expanding it through turbines.
Gravity storage	7	Stores energy through elevation of heavy objects, like concrete blocks, and generates electricity upon their release, a concept similar to PSH.
Latent heat storage	7	Stores energy by using phase changes (solid, liquid, gas) of specific materials at certain temperatures.
Iron–air battery	7	Uses oxygen from the atmosphere and iron and charges and discharges through the oxidation-reduction reaction of iron.
Compressed air energy storage (CAES)	6	Stores energy by compressing air in underground spaces. Lower cost; however, more geographically constrained compared to LAES.

（Notes）1. Created by DBJ.
2. Since the IEA has not published regarding iron–air batteries, it is listed as TRL 7 based on the current situation.

LDES stores electricity in various ways, and there are significant differences in cost, output scale, and discharge time. However, in evaluating the technology, safety and price competitiveness are as important for LDES as they are for batteries. Although the energy loss rate varies greatly depending on the technology in LDES, if electricity is stored appropriately when market prices are low, the impact of the energy loss rate on LCOS becomes minimal. Therefore, it is not necessary to overly consider the energy loss rate in technology evaluation. Additionally, unlike countries like the United States, which are ahead in LDES technology development and deployment, Japan has limited surplus land and suitable installation sites, and it is not easy to introduce technologies such as pumped hydro storage, gravity storage, and compressed air energy storage, which are theoretically expected to have low LCOS. Thus, flexibility in installation locations also needs to be considered.

Taking these factors into account, the following four technologies are highlighted as those expected to be introduced in the future: (i) redox flow batteries (RF batteries), (ii) molten salt batteries (NaS batteries), (iii) thermal storage technologies (sensible and latent heat storage), and (iv) iron–air batteries. However, it should be noted that the technologies that can be introduced vary depending on location constraints, and this is a field where future technological innovations and new approaches are expected. Therefore, it is necessary to maintain a diverse range of options without narrowing down to specific technologies at this point.

（2）Redox Flow Batteries (RF Batteries)

RF batteries are a technology that charges and discharges by circulating electrolyte with a pump and utilizing the redox reaction of ions. The practical implementation of this technology is represented by vanadium redox flow batteries (VRF batteries), developed by companies like Sumitomo Electric, which use vanadium as the electrolyte. The key features of RF batteries include the use of non-flammable vanadium, making the risk of fire very low. Additionally, the electrolyte has a virtually infinite lifespan, and the product itself can be used for about 20 years. Another strength is the ability to adjust capacity by varying the size of the electrolyte tanks, allowing for flexible equipment installation based on the available site area and market trends.

On the other hand, the current manufacturing cost is relatively high; so, there is a focus on reducing LCOS through the modularization of electrolyte tanks and cell stacks, as well as through the development of electrolytes using cheaper raw materials. Regarding the revision of electrolytes, alternatives to the rare metal vanadium, such as titanium–manganese systems that use different elements for the positive and negative electrodes, and organic compound systems that offer high energy density and can be produced at low cost, are attracting attention.

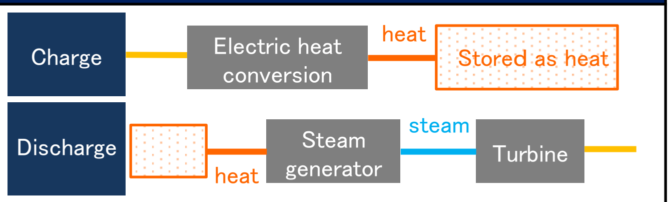
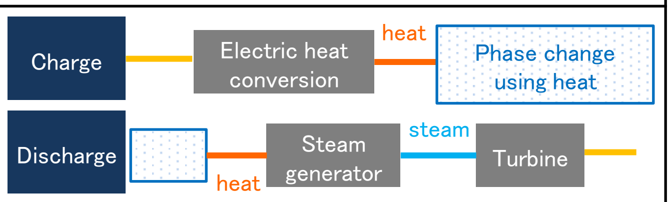
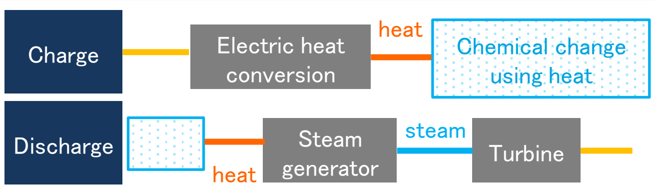
(3) Molten Salt Batteries (NaS Batteries)

Molten salt batteries use molten salt as the electrolyte at high temperatures. Currently, the only commercially operating molten salt battery is the sodium–sulfur (NaS) battery developed by NGK Insulators, Ltd. NaS batteries have high energy density, making them less constrained by installation area at the deployment site. They do not require rare resources for the positive and negative electrodes, and their cycle life is about 7,300 cycles, which is longer compared to other batteries, theoretically providing cost competitiveness. However, from a safety perspective, sodium is classified as a water-reactive substance and sulfur as a flammable solid under the Fire Service Act, necessitating the appointment of hazardous materials handlers and securing open space. NaS batteries’ long operational track record and various certifications ensure that they are safe.

(4) Thermal Storage Technologies

Thermal storage technologies are attracting attention not only for their safety and LCOS advantages but also for their ability to supply both electricity and heat. In fact, many thermal storage–related companies have been selected for the "Global Cleantech 100," which identifies promising startups contributing to climate change mitigation, an indication of high interest in this field. Thermal storage technologies can be broadly classified into three types: sensible heat storage, which utilizes temperature differences in materials; latent heat storage, which utilizes phase changes; and chemical storage, which utilizes chemical reactions or adsorption heat (Figure 3-2). Among these, many companies are working on the development of sensible heat storage, which has relatively low technical difficulty.

Figure 3-2 Classification of Thermal Storage Technologies

Types	Overview	Diagram
Sensible heat storage	A technology that utilizes temperature differences in materials, already commercialized in solar thermal power generation.	
Latent heat storage	A technology that utilizes phase changes in solids and liquids, offering high energy density and reduced heat loss for long-term storage, but with limited capacity due to container requirements.	
Chemical storage	A technology that utilizes chemical reactions or adsorption heat in materials, providing the highest energy density and reduced heat loss for long-term storage, but with safety concerns and limited lifespan of chemical materials.	

(Note) Created by DBJ.

Approximately 40% of Japan's energy consumption is used for heat supply via gas and other sources, and decarbonizing heat is a major challenge for achieving carbon neutrality. While electrification using heat pumps is a solution for low-temperature ranges around 150° C, medium to high-temperature heat sources fall into the so-called hard-to-abate areas. In addition to hydrogen, ammonia, and e-methane, thermal storage technologies are also considered promising if heat is stored during periods when electricity prices are low due to surplus renewable energy.

（5）Iron–Air Batteries

Iron–air batteries use oxygen from the air as the positive electrode and iron as the negative electrode, performing charging through the oxidation reaction of iron and discharging through the reduction reaction. This technology is expected to have cost competitiveness due to its simple structure and the abundance of iron on Earth. However, challenges include the higher electrical resistance of iron compared to lithium and other materials, and the degradation of electrodes due to redox reactions, which shortens the cycle life.

4. The Necessity of Ensuring Inertia and Synchronization Power Towards 2050

（1）Notable Technologies

To ensure inertia and synchronization, efforts are being made to explore various technologies that do not solely rely on existing synchronous power sources such as thermal and hydro power (Figure 4).

Figure 4 Overview of Technologies to Improve Inertia and Synchronization

	Overview	Inertia	Synchro-nization	Maturity
Synchronous generators	Thermal and hydro power plants	○	○	Commercially implemented
Synchronous condensers	Generation of inertia and synchronization without fuel costs but incurring maintenance costs	○	○	Commercially implemented
MG sets	Motor–generator combinations that incur energy efficiency decreases due to additional equipment requirements	○	○	Commercially implemented
Flywheels	Devices that store energy using rotational disks. Used with LDES, they generate inertia and synchronization	○	○	Demonstration phase
GFL, GFM	Power conversion systems that provide inertia and synchronization by controlling the rotational speed of the inverter	○	○	Demonstration phase
System strengthening	Measures to strengthen the system, such as reducing impedance, which can improve synchronization	×	○	Commercially implemented
STATCOM	Devices that use power electronics to control reactive power and improve voltage stability	×	○	Commercially implemented

（Notes）1. Created by DBJ based on papers from Transmission and Distribution Grid Council (TDGC).
2. Impedance refers to the total of resistance and reactance (the phase difference between current and voltage caused by coils or capacitors) in an AC system.

Technologies being researched include motor–generator (MG sets), which combine a motor and a synchronous generator; pseudo-inertia power conversion systems (PCS), which replicate the movement of synchronous generators in inverters; flywheels, which are a type of LDES that provide inertia and synchronization due to their rotating mass; system strengthening; and self-excited static synchronous compensators (STATCOM) using semiconductor switches. In the STREAM Project conducted by Japan’s New Energy and Industrial Technology Development Organization (NEDO), many universities and private companies are developing pseudo-inertia PCS and MG sets as countermeasures to frequency fluctuations caused by reduced inertia.

There are two types of pseudo-inertia PCS: the current control method (grid-following [GFL]), which can be introduced by adding functions to conventional PCS; and the voltage control method (grid-forming [GFM]), which requires new installation. GFM has characteristics similar to synchronous generators, such as instantaneous response speed, off-grid operation capability, and high inertia response, making it necessary to gradually transition from GFL to GFM. Considering the various characteristics and cost perspectives, pseudo-inertia PCS and MG sets are regarded as notable technologies. However, it is necessary to explore the potential use of various technologies, given the expected global demand growth and further technological innovations.

（2）Direction of Efforts for Expansion

To ensure the maintenance of inertia and synchronization, it is necessary to mandate frequency change suppression measures in grid codes or procure inertia and synchronization in the balancing market. In the UK, for example, there is a minimum inertia maintenance requirement for power generation systems, and the North American Electric Reliability Corporation (NERC) requires frequency fluctuation countermeasures in electrical grid areas such as those operated respectively by Electric Reliability Council of Texas, Inc. (ERCOT) in Texas and Northeast Power Coordinating Council, Inc. (NPCC) in the northeastern United States. In 2023, the German Federal Network Agency (BNetzA) discussed a market-supported inertia procurement model that pays fixed premiums to providers of inertia and Australian Energy Market Operator (AEMO) launched a fast frequency response market ancillary service.

In Japan, the Organization for Cross-regional Coordination of Transmission Operators (OCCTO) is revising the grid code in five stages. By around 2030, when the renewable energy ratio is expected to reach 50–60% in terms of capacity, system changes will be implemented to contribute to balancing power, inertia, and system protection and control. Specifically, rate of change of frequency (RoCoF) tolerance will be set, including for solar and wind power connected to low-voltage networks, and inertia supply will be mandated. Therefore, technology development and demonstration projects aimed at meeting these requirements in the coming years are necessary.

Conclusion

In Japan and globally, rapid adoption of VRE is progressing, leading to various challenges in power systems, such as daytime output suppression and evening supply–demand tightness. As the expansion of VRE, particularly solar power, is expected to continue towards achieving carbon neutrality, the development and social implementation of various technologies to ensure flexibility are urgent.

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