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Achieving Economic Efficiency in Power Systems through DR:
Standardization and Automation for Leveraging Low-Voltage Resources

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Executive Summary

- To address the S+3E principles（Safety plus Energy security, Economic efficiency, and Environmental sustainability）in the power system, it is crucial not only to ensure supply capacity on the generation side but also to utilize demand response（DR）to flexibly adjust power consumption.
- With technological advancements in the digital field and the expansion of variable renewable energy, opportunities for implementing DR are expected to increase in the future. However, for the utilization of DR in not only extra-high and high-voltage resources but also low-voltage resources, it is necessary to improve reliability and reduce costs and effort through efficient operation.
- To expand the adoption of DR utilizing low-voltage resources, it is important to standardize related equipment and systems and to manage groups of low-voltage resources through the automation of a series of processes. The key is the dissemination of low-voltage resources that meet the "DR Ready" requirements, and the establishment of systems related to automated demand response（ADR）.

The current power system faces the challenging task of ensuring supply capacity to meet increasing electricity demand while simultaneously reducing greenhouse gas（GHG）emissions from electricity. The introduction of various innovative technologies is expected to provide solutions. Particularly, the introduction of variable renewable energy（VRE）sources such as solar and wind power, which have fluctuating generation levels depending on the time or weather, is anticipated to contribute to GHG reduction. However, this shift in power generation composition can lead to temporal and geographical mismatches between supply and demand, necessitating the introduction of demand–supply adjustment technologies and the enhancement of transmission and distribution（T&D）networks（DBJ Research No.420 "Innovative Technologies Paving New Possibilities for the Power System" [August 9, 2024]）.

To address these challenges under the S+3E principles, it is essential for the demand side, which has traditionally been a passive consumer of electricity, to take a proactive role. Among the various measures, demand response（DR）, which involves flexibly adjusting power consumption in response to supply levels, is expected to be an economically efficient means of addressing these challenges, in addition to the ongoing efforts in energy conservation and power saving.

DR began to attract attention in the 1990s when electricity markets were liberalized in various countries. The technology saw significant social implementation in the early 2000s with the advancement of the internet and metering devices, enabling real-time monitoring and control of electricity demand. The International Energy Agency（IEA）estimates that achieving net-zero emissions by 2050 will require the global implementation of 500 GW of DR by 2030. However, as of

2020, the global DR capacity was only about 50 GW, indicating a significant potential for further expansion in the future.

In Japan, under the previous environment where the power system was regulated, the focus was on addressing power system challenges from the supply side, emphasizing reliability and stability. However, with the liberalization of the electricity market, various companies have entered the power industry, and there is increasing attention on DR as a new revenue opportunity for related entities. Additionally, changes in various regulations and shifts in the power generation mix are expected to further drive the expansion of DR. This paper will first outline the role of DR in achieving the S+3E within the power system and then focus on strategies for utilizing low-voltage resources, particularly the standardization of equipment and the automation of processes.

1. Challenges of the Power System and the Need for Demand-Side Approach

DR is a method of controlling the electricity usage of businesses and individuals in response to fluctuations in power supply. Reducing usage is referred to as “downward DR,” while increasing usage is called “upward DR.” There are three main methods for implementing DR: shifting, energy conservation, and substitution. Shifting involves adjusting the operational timing of facilities such as factories to achieve downward or upward DR. Energy conservation implements downward DR by reducing the power consumption of lighting, air conditioning, and other equipment that do not significantly impact business operations or daily life. Substitution involves adjusting the ratio of power procurement from the grid and in-house generation facilities to achieve downward or upward DR. As an example of substitution, increasing in-house generation when power demand is stable reduces the relative use of grid power, thus serving as a means of downward DR. Through shifting, energy conservation, and substitution, DR can create adjustment capacity（ΔkW）and effective supply capacity（kW）, as well as avoid grid congestion and voltage rises. This contributes to the stability, economic efficiency, and environmental sustainability of the power system（Figure 1-1）.

Figure 1-1 The Role of DR

<table>
<tr><th rowspan="2"></th><th colspan="2">Provision of Adjustment Capacity（ΔkW）</th><th rowspan="2">Suppression of Maximum Power Demand（kW）</th><th rowspan="2">Avoidance of Grid Congestion, Voltage Fluctuations, etc.</th></tr>
<tr><th>Downward DR</th><th>Upward DR</th></tr>
<tr><td>Stability</td><td colspan="2">Contributes to stable power supply</td><td>Avoidance of supply shortages</td><td>-</td></tr>
<tr><td rowspan="2">Economic Efficiency</td><td colspan="2">No need for large-scale equipment investment</td><td rowspan="2">Reduces the need for low-utilization, stable power sources</td><td>-</td></tr>
<tr><td>Reduces electricity prices during supply shortages</td><td>-</td><td>Suppresses the need for strengthening transmission and distribution networks</td></tr>
<tr><td>Environmental Compatibility</td><td>Reduces fuel usage during supply shortages</td><td>Efficient use of surplus variable renewable energy during surplus periods</td><td>-</td><td>-</td></tr>
</table>

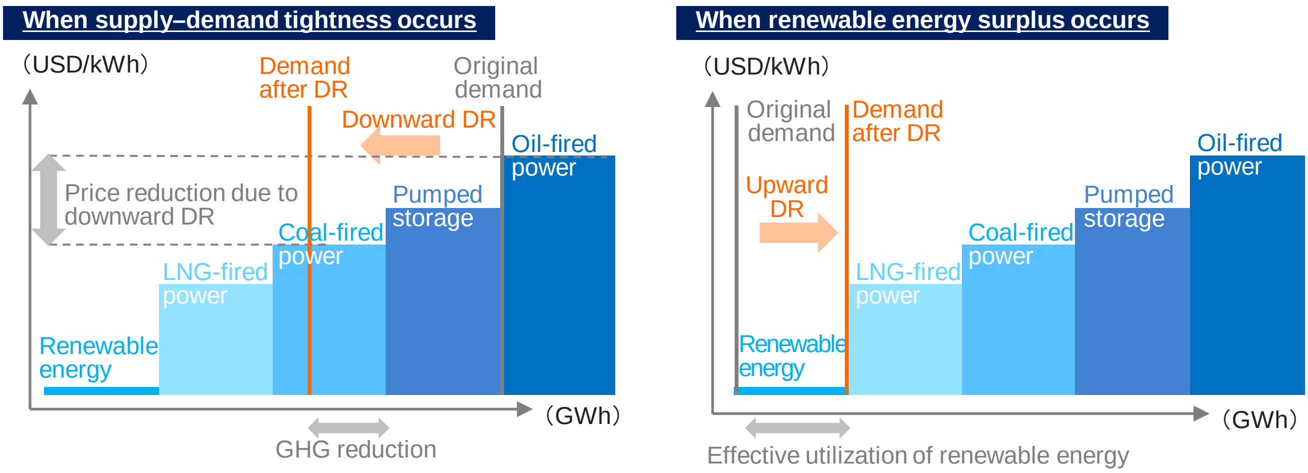
（Note）Created by DBJ.

The importance of adjustment capacity（ΔkW）is expected to increase as the introduction of variable renewable energy（VRE）expands and the decommissioning of thermal power plants, which have traditionally provided adjustment capacity, becomes more common. In addition to adjusting the operation of thermal power plants, the use of batteries for charging and discharging electricity and long-duration energy storage（LDES）technologies are also anticipated. It is necessary to combine these various technologies with DR. Unlike batteries and LDES, DR does not require the introduction of new equipment, making it a potentially economically efficient means of providing adjustment capacity if used skillfully.

With the large-scale introduction of VRE, there is a growing trend of time periods where electricity supply exceeds demand, leading to regulations limiting output, especially in areas like Kyushu and Hokkaido during favorable weather conditions. Implementing upward DR in such situations can effectively utilize surplus renewable energy that would otherwise be curtailed. Additionally, as the continuous introduction of renewable energy reduces the relative position of thermal power in the spot market, and its operation rate is kept consistently low, there is a concern about the lack of downward adjustment capacity. Therefore, the importance of upward DR during periods of surplus renewable energy increases. Upward DR during periods of electricity surplus is beneficial, but so too is the implementation of downward DR during times of low reserve margins, such as in the evening, contributing to the avoidance of power supply shortages.

Furthermore, the implementation of such DR can ultimately lead to a reduction in prices in the spot market. In Japan’s spot market, bids from sellers are made based on marginal costs, and a single-price auction is adopted where the intersection of the demand curve and the supply curve determines the uniform clearing price for all sources. During supply shortages, high marginal cost sources like oil-fired power plants operate, raising the price for all cleared sources. In such cases, if downward DR shifts the demand curve to the left, the clearing price for all sources will decrease. Additionally, downward DR reduces the required generation amount, lowering the operation rate of high-marginal-cost thermal power plants, thereby reducing fuel costs and GHG emissions（Figure 1-2）.

Figure 1-2 Reduction of Market Prices and GHG Emissions by DR



（Notes）1. Created by DBJ.
2. The bid prices on the generation side are just examples, and in reality they vary depending on the fuel prices, etc.
3. The bid prices on the demand side are also factors in determining prices in the spot market, but they are omitted here.

One of the benefits of utilizing DR is the suppression of maximum power demand（kW）. Nationwide power generation facilities need to secure sufficient capacity to respond to the highest demand that occurs several times a year due to severe weather conditions. However, the peak hours are extremely short within a year, and power plants with limited utilization opportunities are being maintained and managed. Therefore, by implementing downward DR during peak hours and suppressing the annual maximum power demand, it is possible to reduce the maintenance and management costs of such power plants and new equipment investments. However, due to uncertainties in future power demand caused by abnormal weather from global warming and rapid digitalization of society, it is necessary to secure a certain scale of supply capacity by appropriately evaluating DR while also utilizing new power source development and maintaining dormant power sources.

The utilization of DR is also expected to address issues in the distribution network, such as insufficient capacity and voltage demand rise due to the growing number of EV chargers and solar power generation. When the capacity of the distribution network becomes insufficient due to the increase in power demand and the introduction of distributed power sources, the connection of new demand and power sources to the system is constricted, necessitating the reinforcement of the distribution network. Additionally, when a large amount of solar power generation and storage batteries are introduced into the distribution network, increasing the inflow of electricity to the system side（reverse power flow）, the voltage rises and power quality deteriorates, requiring the installation of voltage control devices to limit the deterioration. By securing local flexibility using DR to adjust the demand and power flow of the distribution network, it is possible to solve issues without the need for large-scale equipment investment.

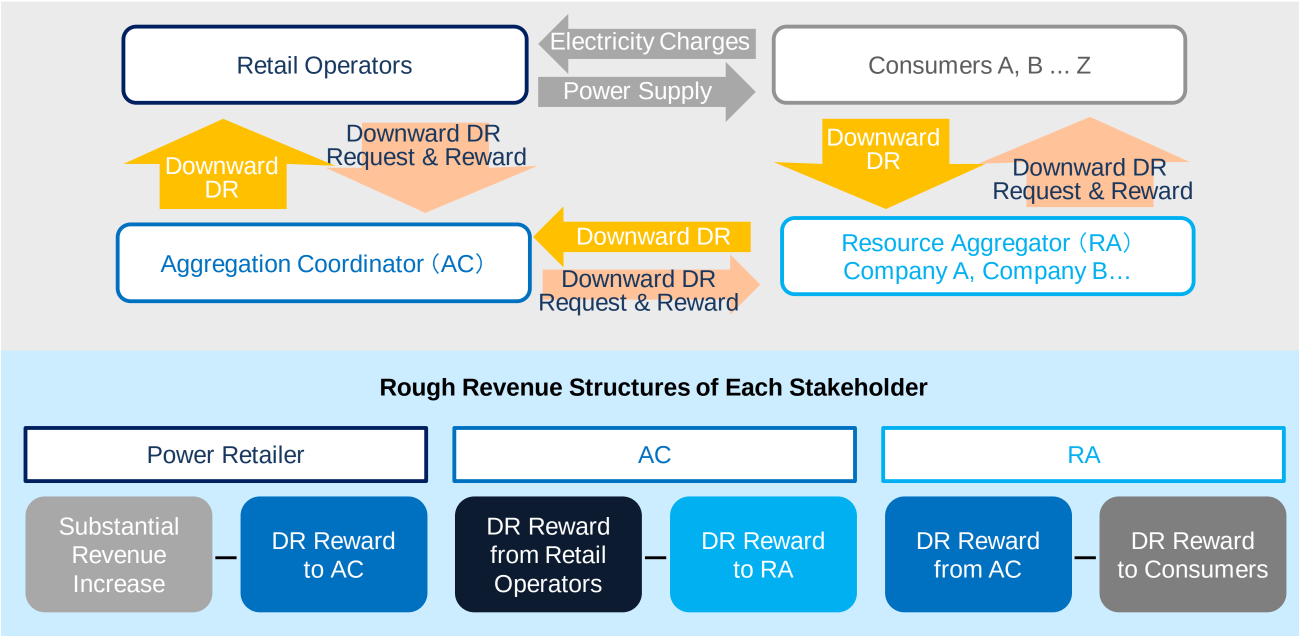
2. Business Model of DR

2.1. Overview of the DR Business Model

DR is implemented by shifting, conserving, or substituting the power consumption of equipment and storage batteries owned by power consumers such as companies and individuals. However, it is not easy for individual consumers to analyze market price trends and efficiently and effectively consider and implement DR; so, an integrated operation that bundles multiple consumers is carried out. In addition to DR, the framework that operates self-generation facilities and storage batteries connected to the grid is called a virtual power plant（VPP）.

The business of bundling multiple consumers and providing various services such as adjustment power provision, imbalance avoidance, and electricity cost reduction to trading partners such as T&D operators, power retailers, and consumers is called an energy resource aggregation business（ERAB）. In this business, there are resource aggregators（RA）, who directly contract with consumers and equipment manufacturers to implement DR, and aggregation coordinators（AC）, who oversee the entire ERAB（Figure 2-1）. As of October 2024, various players such as new power retailers and energy service providers（ESPs）have registered, and further market activation is expected through the entry of ambitious operators and the healthy competition among operators（Figure 2-2）. Aggregators can benefit from DR through two main means: market transactions and economic DR.

Figure 2-1 Example of ERAB Implementation for Downward DR



（Note）Created by DBJ.

Figure 2-2 Classification of Aggregators

Former General Electric Utilities	Power Generation Operators	Retail Electricity Operators	Energy Service Providers	Gas Operators	Energy-related Operators	Total
7 companies	8 companies	39 companies	22 companies	3 companies	4 companies	83 companies

（Note）Created by DBJ based on the “List of Specified Wholesale Supply Operators,” Ministry of Economy, Trade and Industry（as of October 17, 2024）.

2.2. Utilization of DR in Market Transactions

In market transactions, aggregators and retail electricity operators bid the adjustment power and supply capacity generated by DR in various markets to obtain compensation. Previously, the opportunities for monetizing DR in each market were limited, but with various system changes, these opportunities are expected to continue expanding.

The supply–demand adjustment market is a market where T&D operators procure adjustment power, and there are multiple product categories based on response speed and duration. Currently, the adjustment power generated by DR mainly bids in the relatively slow-response adjustment power categories, but in the long term, it is expected to bid in faster-response production. Additionally, under the current system, market participation requirements are limited to special-high-voltage and high-voltage resources, and low-voltage resources such as household storage batteries and EVs are not allowed to participate. However, a governmental committee has shown that the participation of low-voltage resources in the supply–demand adjustment market can provide significant benefits, and from fiscal year 2026, the participation of low-voltage resources is going to be allowed, raising expectations for the expanded role of DR in the supply–demand adjustment market.

The capacity market is a market aimed at securing supply capacity four years in advance, and currently, DR can only bid as a dispatchable resource if it can provide a supply capacity of 1MW or more. In response to the high power demand during the hot summer of 2024, dispatchable resources centered on DR were utilized as a supply capacity securing measure, and DR has already built a certain track record in suppressing maximum power demand. Furthermore, in the additional supply capacity tenders held when a severe supply–demand balance is expected, DR is also eligible as a target facility alongside various power sources. Although there were no successful DR bids in the most recent additional supply capacity tender for the summer of fiscal year 2023, there is a sufficient possibility that DR will win bids in future tenders.

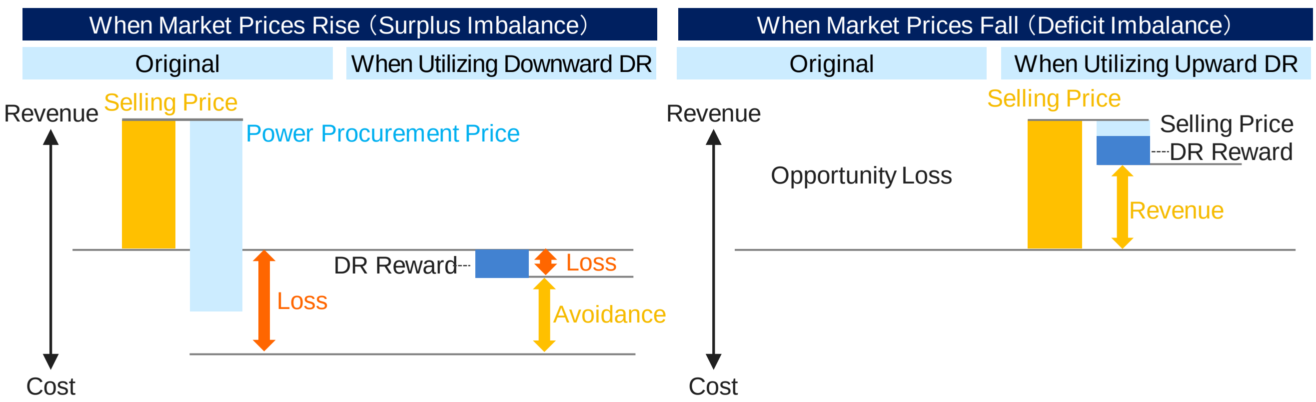
2.3. Implementation of Economic DR

In addition to obtaining compensation through market transactions, DR is also used to secure revenue and avoid losses in response to power supply–demand and market price fluctuations. This approach is called economic DR, and the opportunities for its implementation are expected to expand further with the increase in variable renewable energy（VRE）introduction rates towards 2050.

Retail electricity operators stabilize the procurement price of electricity by using the baseload market and bilateral contracts with power generation operators, while also procuring a certain amount from the spot market, which has high price volatility. However, many retail electricity operators adopt fixed-price rate plans for consumers, which can result in losses when market prices soar. Additionally, retail electricity operators are required to match supply and demand on a 30-minute basis, and they must settle imbalance charges with T&D operators if actual power demand exceeds the planned value or falls below the planned value.

Economic DR is an effective means to avoid risks related to such price discrepancies and imbalances, as well as to secure additional revenue. For example, if spot prices soar and the electricity procurement price exceeds the selling price, the operator can request downward DR related to the payment of compensation to the consumers. Although the DR reward incurs a cost, the operator can partially avoid the losses that would have occurred if the electricity had been procured from the market. Conversely, if market prices fall, the operator can implement upward DR, allowing them to sell the cheaply procured electricity at a fixed contract price, thereby securing revenue（Figure 2-3）.

Figure 2-3 Methods for Earning Revenues through Economic DR



（Note）Created by DBJ.

The greater the fluctuation in spot market prices and imbalance charges, the stronger the incentive for retailers to implement economic DR. Currently, both prices are stable, but as the VRE increases, the fluctuation range is expected to grow, expanding opportunities for economic DR implementation. Institutional measures to promote the spread of economic DR include introducing time-of-use tariffs in the T&D network usage fee system and lowering the floor price of the spot market to a negative value. However, while negative prices encourage the introduction of DR and storage batteries, careful consideration is required from the perspective of their impact on the business profitability of power sources, and the consistency with various policies.

In addition to the market transactions and economic DR mentioned so far, the promotion of DR through the introduction of dynamic pricing that links the selling price of electricity to consumers with market prices can also be considered. These initiatives are referred to as electricity tariff–based DR, which encourages voluntary behavioral changes among consumers, and have become more active since 2022 due to the surge in fuel prices and spot market prices caused by events such as Russia’s invasion of Ukraine. While electricity tariff-based DR is relatively easy to implement, it lacks enforceability, posing challenges in terms of the scale and reliability of DR.

3. Specific Examples of DR

As mentioned earlier, DR methods are classified into three categories: shifting, energy saving, and substitution. Various resources are expected to be utilized in both special-high-voltage and high-voltage（6,600V and above）applications, mainly used by industrial consumers, and low-voltage（100V and 200V）application, mainly used by general households（Figure 3）.

Figure 3 Major Devices and Adjustment Methods for DR Implementation

Main Location Of Resources	Device Name		Feasibility		Implementation Method		
			Upward DR	Downward DR	Shifting	Energy saving	Substitution
Special-High-Voltage & High-Voltage Applications	Production line		○	○	○	-	-
	Factory equipment	Self-generation	○	○	-	-	○
		Industrial storage battery	○	○	-	-	○
	Water electrolysis equipment		○	△	-	-	○
Low-Voltage Application	Household storage battery		○	○	-	-	○
	EV charger		△	○	-	-	○
	Heat pump（HP）	Water heater	○	△	○	-	-
		Air conditioning	△	△	△	○	-
	Household fuel cell（Ene-Farm）		○	△	-	-	○

（Notes）1. Created by DBJ.
2. Legend: ○ = feasible, △ = conditionally feasible, - = not feasible.

3.1. Initiatives in Special-High-Voltage & High-Voltage Resources

Currently, DR is mainly implemented for large consumers, such as manufacturers, providing substantial adjustment or supply capacity by shifting the operating hours of their factory equipment. For example, Tokyo Steel Manufacturing Co., Ltd., an electric furnace steel manufacturer, contributes to the effective utilization of surplus renewable energy by creating demand through additional operations in response to requests for upward DR from Kyushu Electric Power. On the other hand, when using factory production lines as DR resources, adjusting operating schedules and changing employee work shifts are not easy tasks, and there are limits to the frequency and scale of implementation. Therefore, DR utilizing factory equipment such as self-generation and storage batteries within the factory, which are easy to implement, relatively, is also an important means. In the trend towards decarbonization, while there is a movement in the manufacturing industry to suspend the use of coal-fired self-generation that was traditionally used, the number of businesses introducing storage batteries from the perspective of utilizing business continuity plans and on-site power sources is increasing. Therefore, it is expected that in the future, the use of storage batteries will become more mainstream than self-generation in the implementation of DR.

Furthermore, with the anticipated increase in electricity demand due to the advancement of digital transformation, it is also expected that data centers（DCs）, which consume large amounts of electricity, will be utilized for DR. For example, Tokyo Electric Power Grid and Hitachi, Ltd. provides upward and downward DR by implementing distributed control of computational loads（spatial shift between DCs）based on the supply and demand conditions of multiple areas and adjusting computational loads based on the output conditions of VRE（temporal shift between DCs）. Besides digital processing, other methods for utilizing surplus renewable energy include implementing upward DR using various facilities such as water electrolysis equipment to produce hydrogen, seawater desalination facilities, water and sewage facilities, and soda electrolysis equipment.

3.2. Utilization of Low-Voltage Resources

In the low-voltage range, mainly consisting of general households, various DR resources exist, and their expanded utilization is expected in the future. Additionally, the International Energy Agency analyzes that key clean energy technologies for achieving carbon neutrality（CN）, such as EVs, heat pumps（HP）, fuel cells, and water electrolysis equipment, will play an important role in DR.

Firstly, household and commercial storage batteries, which are rapidly being introduced for the effective utilization of surplus power from on-site solar power generation, and onboard storage batteries in EVs are expected to be resources for substitution. Particularly for EVs, if users concentrate charging during certain times such as mornings and evenings, it can strain the overall power supply and demand, causing issues such as grid congestion and voltage rise in the distribution network. Therefore, it is desirable for society to be able to distribute and control the timing of charging. The means for this are classified into V1G, which adjusts only the amount and timing of charging to EVs; and V2G, which also utilizes discharging from EVs to the power grid in addition to charging. While V1G, which is currently being introduced, has lower implementation and operational costs, its impact on supply and demand adjustment is limited. There are high expectations for V2G, which can significantly contribute to grid stabilization. The CHAdeMO Association, established in 2010 with Toyota Motor Corporation, Nissan Motor Co., Ltd., Mitsubishi Motors Corporation, Subaru Corporation, and Tokyo Electric Power Company as managing companies, issued the CHAdeMO standard with bidirectional charging specifications ahead of the rest of the world in 2014, and it is widely used in mass-produced, V2G-compatible models currently on the market. Through the global spread of the CHAdeMO standard, it is expected that those companies will acquire knowledge and data related to the increasingly important V2G and engage in DR business utilizing V2G.

Furthermore, with the rapid spread of HP technology that creates temperature changes by expanding and compressing atmospheric heat using electricity, driven by the surge in gas prices due to the invasion of Ukraine and the trend towards achieving CN, especially in Europe. Operating HP water heaters during periods of power surplus（upward DR）is relatively easy to implement and has minimal impact on users' daily lives. In Japan, household fuel cells like Ene-Farm can also be utilized as DR resources through substitution. Ene-Farm generates electricity by chemically reacting hydrogen extracted from gas with oxygen in the air, thereby reducing grid power demand.

4. Prospects for DR Business and Required Initiatives

As mentioned earlier, while DR implementation is progressing mainly in the special-high-voltage and high-voltage ranges, the opportunities for DR implementation are expected to expand due to technological advancements in the digital field, the expansion of VRE introduction, and the progress of related policies. However, to further promote the spread of DR, including in the low-voltage range, it is necessary to reduce the costs and efforts through efficient operation.

Although there is high DR potential in the low-voltage range, the resources are dispersed among approximately 20 million consumers in Japan, and the scale of each implementation is small. On the other hand, since data communication and processing incur certain costs regardless of the scale of DR resources, DR utilizing low-voltage resources often does not meet the cost–benefit criteria. Additionally, in the case of general households in the low-voltage range, compared to industrial consumers in the special-high-voltage and high-voltage ranges, there are challenges such as lower reliability in the execution of planned DR and difficulty in estimating baselines. To overcome these challenges, it is effective to manage multiple low-voltage resources as a large group through standardization of related equipment and systems and automation of the entire process.

4.1. Standardization of Equipment（DR Ready）

To manage low-voltage resources as a group, the various resources present in each household must be connected to some system, enabling data transmission and reception and resource control. If the communication functions and standards of each resource are not aligned, new costs will arise each time equipment or systems are developed and introduced. Therefore, standardizing these aspects is crucial for the spread of DR.

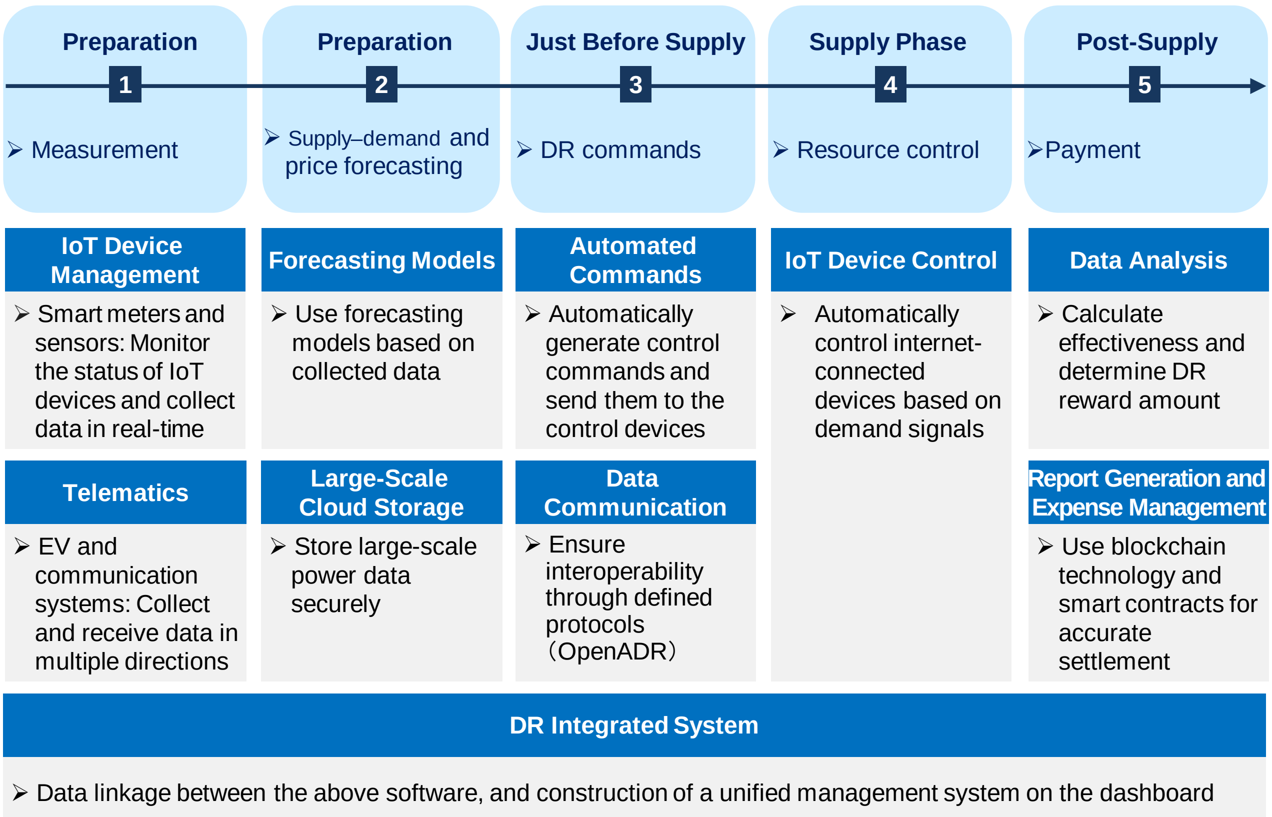
The Ministry of Economy, Trade and Industry（METI）has established the “DR Ready Study Group,” which works on formulating “DR Ready requirements” related to communication and external connection functions so that the aggregators can easily identify and control low-voltage resources. Additionally, considering increases in cyberattacks targeting the vulnerabilities of IoT devices, etc., the “Cybersecurity Guidelines for ERAB” established in 2017 are also expected to be revised.

Based on discussions in the “DR Ready Study Group” and other forums, the government plans to indicate the sales ratio of equipment that meets the DR Ready requirements to relevant equipment manufacturers and importers, promoting the spread of DR Ready low-voltage resources. Considering the period for establishing institutional frameworks and the development period by manufacturer, the spread of equipment that meets the DR Ready requirements is expected to occur after 2030.

4.2. Automation of Processes

In the medium to long term, to maximize the potential of low-voltage DR, the key will be to improve the efficiency of DR systems through the automation of DR processes—that is, automated DR（ADR）. The necessary technologies for realizing ADR are mostly developed, and going forward it will be necessary to integrate each technology related to i）measurement, ii）supply–demand and price forecasting, iii）DR commands, iv）resource control, and v）settlement into one system, keeping an eye on DR Ready progress（Figure 4）.

Figure 4 Digital Technologies Required for ADR



（Note）Created by DBJ.

Regarding measurement, it is necessary to utilize smart meters and sensors to understand the baseline of power demand, DR potential, and the locations of resource installations. In the special measurement system enacted in 2022, it has become possible to conduct power transactions using special measurement devices such as power conditioners and EV chargers, in addition to certified meters based on the long-standing Measurement Act. Furthermore, the next-generation smart meters, scheduled to be introduced nationwide from fiscal year 2025, will be capable of collecting data from special measurement devices using IoT. The combination of special measurement devices and next-generation smart meters will make real-time data collection easier. However, EV-related data management via next-generation smart meters alone is difficult, because the grid connection points are not limited to a single demand location. Therefore, it is considered necessary to also utilize telematics systems installed in the vehicles to collect and manage information.

Supply and price forecasting involves using forecasting models to determine which options, such as spot market bidding, intraday market transactions, and imbalance payments, are the most economically rational compared to DR. This is an area where business development, such as creating forecasting models using power data, is expected.

After such preparations, DR commands are automatically sent to consumers at the appropriate timing, and resource control is performed based on these commands. While the upstream communication command system is unified by OpenADR 2.0, a global communication international standard first introduced in Japan, different communication protocols and command systems are used by each company for downstream equipment and gateway connections. Alongside discussions on DR readiness, future standardization through OpenADR 2.0 is anticipated.

After DR implementation, aggregators calculate the amount of DR implemented by each consumer based on data received from measurement devices, in accordance with METI’s ERAB guidelines, and determine the DR reward amount. It is necessary to manage reports and settle expenses for various entities such as consumers, RAs, and ACs, and it is expected that settlement efficiency will be improved using smart contracts with blockchain technology.

These are the main software and devices required to realize ADR, but it is also necessary to build a system for data linkage between these software and devices, and for integrated information management on the dashboard by aggregators.

To further activate ADR in the future, while competition among companies for the advancement of digital technologies is important, it is also necessary to standardize and unify the foundational aspects of ADR, such as communication technologies. Demonstration projects in Japan have already achieved cross-industry collaboration involving not only aggregators but also software, measurement device, automotive, communication, and home appliance manufacturers, as well as large consumers. However, to expeditiously introduce the ADR system globally, it is crucial to further deepen such collaborations.

Conclusion

As mentioned earlier, solving the challenges faced by the power grid under the principle of S+3E requires not only securing supply capacity and technological advancements on the generation side but also significantly expanding the use of DR on the demand side. With the introduction of variable renewable energy expanding, digital technologies rapidly progressing, and reporting of DR performance being mandated by the revised Energy Conservation Act, an environment supporting DR implementation is being established. It is hoped that appropriate understanding of the value of DR will spread throughout society, and through initiatives such as standardization and automation mentioned in this article, the utilization of DR resources, including those in the low-voltage range, will expand.

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