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Innovative Technologies Paving New Possibilities for the Power System

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Executive Summary

- Energy policy fundamentally revolves around the S+3E principles (Safety and Energy security, Economic efficiency, and Environmental sustainability). However, the power system faces the challenging task of securing supply capacity to meet increasing electricity demand while simultaneously reducing GHG emissions from electricity generation. Expanding the introduction of clean energy sources, like renewable energy, and making existing power sources cleaner must proceed in parallel. This shift in the power supply composition creates temporal and geographical mismatches between supply and demand, necessitating adjustments in power supply and strengthening the transmission and distribution network across the entire power system.
- Currently, there is growing anticipation for innovative technologies such as perovskite solar cells (PSCs), which expand the potential of clean energy sources; storage batteries that become increasingly necessary with the expansion of renewable energy; long-duration energy storage (LDES) technologies; and demand response (DR) mechanisms. The challenges within the power system are diverse and complex, requiring the long-term development and social implementation of a broader range of technologies.

Amid urgent efforts to achieve carbon neutrality (CN) by 2050, there is an increasing need across various industries to move away from existing systems and processes.

The International Energy Agency's (IEA) "World Energy Outlook 2023" (WEO 2023) outlines three major measures needed to reduce greenhouse gas (GHG) emissions by 80% by 2030 compared to 2023 levels: 1) **tripling renewable energy capacity**, 2) doubling the rate of improvement in energy efficiency, and 3) reducing methane emissions by 75%. These measures were pledged by 118 countries at the 28th Conference of the Parties to the United Nations Framework Convention on Climate Change (COP28) in December 2023. Among these, the measure to triple renewable energy capacity has significant GHG reduction potential but requires a shift from the large-scale, centralized power systems optimized for existing power sources, alongside technological innovation, making it a challenging goal.

Technological innovation is crucial for achieving CN in an economically rational manner. According to WEO 2023, only about 20% of the technologies needed to achieve net zero emissions (NZE) by 2050 are currently mature. Approximately 45% require further cost reductions through mass production and innovation, while **the remaining 35% are technologies that do not yet exist in the market**. Strengthening the development and implementation of innovative technologies is essential for achieving CN and presents a significant opportunity to enhance the competitiveness of companies.

In Japan, GHG emissions from electricity generation account for approximately 40% of the country's total emissions, making the transition of the power system crucial for achieving CN. This report starts by identifying the challenges faced by the power system, explores the future of the power system and the necessary technologies, and reviews global corporate investment trends in these technologies.

1. Potential Increase in Electricity Demand and Decarbonization

The power system faces the difficult task of **securing supply capacity to meet the anticipated increase in electricity demand while simultaneously reducing GHG emissions from electricity generation.** To address these challenges, it is necessary to expand the introduction of GHG-free clean energy sources and make existing power sources cleaner in parallel.

In recent years, many power- and energy-related organizations, including the Organization for Cross-regional Coordination of Transmission Operators (OCCTO) in Japan and the IEA, have forecasted an increase in electricity demand leading up to 2050. Specifically, the increase in electricity demand due to electrification and digitalization, such as the adoption of electric vehicles (EVs) and heat pumps (HPs), is expected to outweigh the decrease in demand due to population decline and energy conservation efforts. Particularly significant is **the increase in electricity demand for data centers (DCs) and communication networks** driven by the expansion of IoT and the utilization of generative AI. The IEA's "Electricity 2024" report projects that global DC electricity demand will rise from 460 billion kWh/year in 2022 to over 1 trillion kWh/year by 2026.

To simultaneously address the potential increase in electricity demand and achieve decarbonization, it is essential to further expand the introduction of GHG-free clean energy sources, such as renewable energy. However, we currently face challenges, such as a lack of suitable sites and persistently high generation costs, which heighten the need for innovative technologies. For example, **perovskite solar cells (PSCs), which are lightweight and flexible, allowing for installation on building walls and lightweight roofs, and have high power generation efficiency, are attracting significant attention** as a driving force for renewable energy adoption. Similarly, in the field of wind power generation, floating offshore wind turbines, which are less affected by water depth and can be developed in regions with stable wind conditions, including Japan's vast Exclusive Economic Zone (EEZ), are key. Additionally, geothermal power, tidal power, and tidal current power, which leverage Japan's geographical features, are promising options for expanding renewable energy use.

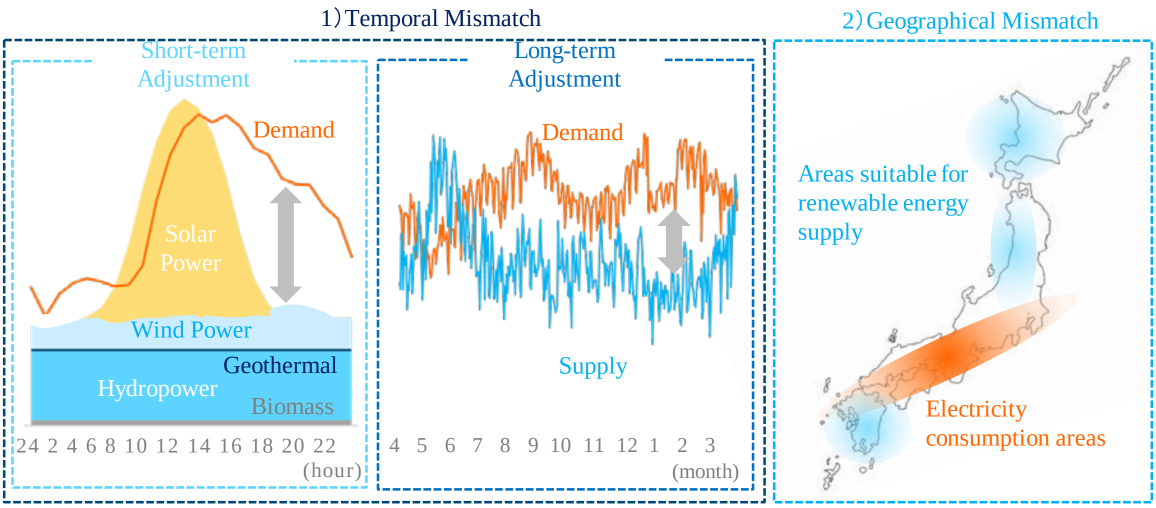
In the nuclear sector, high-temperature gas-cooled reactors (HTGRs), which can produce hydrogen using heat from nuclear fuel, and fast breeder reactors (FBRs), which are expected to reduce used fuel and radioactive waste, are gaining attention. Furthermore, although the current technological maturity is low, nuclear fusion, which uses deuterium to safely generate electricity, is also attracting attention, with many venture companies, especially in the United States, advancing technological development. Nuclear fusion technology was highlighted as a solution to global challenges such as achieving CN and ensuring energy security at the 2024 G7 Climate, Energy, and Environment Ministers' Meeting, indicating that efforts will accelerate globally in the future.

Additionally, **making existing mainstay power sources, like thermal power, cleaner is crucial**. Japanese power companies (e.g., JERA) and heavy machinery manufacturers are leading the development of combustion technologies for hydrogen and ammonia. Moreover, carbon capture and storage (CCS) to store emitted CO_2, as well as carbon offsetting through carbon credit procurement, are realistic options.

2. Mismatch Between Electricity Supply and Demand

As the introduction of clean energy sources such as solar and wind power continues to expand, **the resultant changes in the power supply composition will create temporal and geographical mismatches between supply and demand.** This necessitates adjustments in the power supply and demand balance and the strengthening of the transmission and distribution (T&D) network across the entire power system (Figure 2-1).

Figure 2-1 Mismatch in Electricity Supply and Demand



Solutions			
Supply Side	Thermal Power, ESS, etc.	Thermal Power, LDES, etc.	Electrolysis systems, etc.
Transmission	-		Strengthening network
Demand Side	Demand response (DR) and distributed energy resources (DERs)		Consumption of self-sourced electricity

(Note) Created by DBJ

2-1. Temporal Mismatch

To maintain the quality of electricity and prevent blackouts, it is essential to constantly match electricity demand with generation. However, the expansion of variable renewable energy (VRE), such as solar and wind power, whose output varies with time and weather, and the decommissioning of thermal power plants that have traditionally provided balancing functions, will make balancing supply and demand increasingly difficult. Consequently, additional balancing capacity will be needed on both the supply and demand sides.

On the generation side, in addition to traditional balancing resources like thermal power and pumped storage, **the introduction of various energy storage systems (ESS), particularly batteries, will be crucial**. As the introduction of renewable energy progresses towards 2050, the need for long-term balancing capabilities will increase, requiring not just short-term adjustments that batteries excel at, but also adjustments spanning from days to seasons. This highlights the importance of long-duration energy storage (**LDES**) technologies. LDES refers to technologies capable of storing energy for periods ranging from several hours to multiple days, ensuring reliability and flexibility in the power grid. These include redox flow batteries, which charge and discharge by circulating electrolytes and utilizing redox reactions of ions; thermal storage technologies that use temperature differences or phase changes of materials to store and generate power; and gravity storage systems that charge and discharge by using the gravitational potential energy of heavy objects like concrete. R&D and the spread of these various technologies are progressing (Figure 2-2).

Figure 2-2 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	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	8	Uses molten salts at around 300-350℃ as electrolytes. Sodium sulfur batteries (NAS batteries by NGK insulators) 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 by elevating 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.
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. Technology readiness level (TRL) indicates the maturity level of various energy technologies published by the IEA. Higher numbers indicate greater maturity, with 1–3 representing the concept stage, 4–6 as prototype, 7–8 as demonstration, 9–10 as commercial operation, and 11 as fully mature.

In addition, to reduce the cost of balancing supply and demand, **the demand side, which has traditionally been a passive consumer of electricity, is now required to actively provide balancing capabilities**. In addition to utilizing solutions such as demand response (DR), sourcing, and storage devices individually, it is essential to combine these solutions through digital technologies to function like a virtual power plant (VPP). Through these initiatives, the demand side will play a critical role in securing balancing capabilities in the future power system.

2-2. Geographical Mismatch

Another challenge is the geographical mismatch, where areas suitable for renewable energy supply are physically distant from areas of electricity consumption. This necessitates the transportation of generated electricity to consumption areas by some means. In Japan, electricity demand is concentrated along the Pacific Belt, which includes major industrial and commercial areas; whereas, regions with abundant surplus land, excellent solar radiation, and wind conditions suitable for renewable energy are located in Hokkaido, Tohoku, Kyushu, and other areas. Due to insufficient capacity in the T&D network connecting these renewable energy sites with consumption areas, renewable energy output is often curtailed.

The following possible solutions to this issue are among several being considered.

I. Construction and enhancement of the T&D network
II. Advanced and efficient energy transportation methods that do not rely on the T&D network
III. Attracting electricity-consuming facilities near power plants
IV. Installing power generation facilities in electricity consumption areas for self-sourced electricity consumption

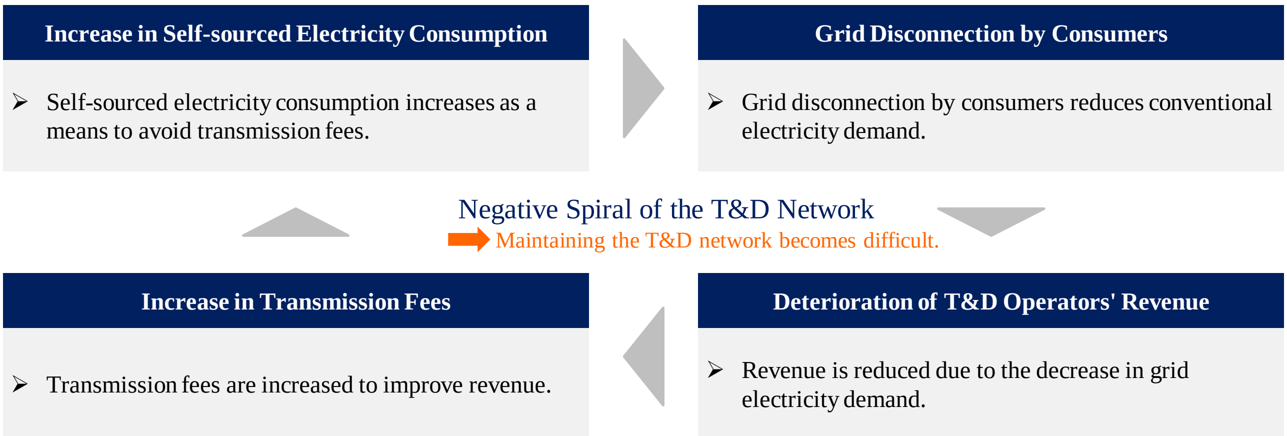
Particularly, **initiatives such as III and IV are gaining attention to minimize the system integration cost**, which includes not only the levelized cost of electricity (LCOE) related to generation but also additional costs for T&D network enhancement and supply–demand balancing.

I. Construction and enhancement of the T&D network: In 2023, the Organization for Cross-regional Coordination of Transmission Operators (OCCTO) formulated the Master Plan for the Wide-Area Interconnection System in Japan, outlining strategies for enhancing inter-regional connection lines toward 2050. Innovative technologies for this enhancement include **high voltage direct current (HVDC) transmission**, which has lower power losses compared to AC transmission, and superconducting transmission technology, which can significantly reduce power losses by eliminating electrical resistance, currently in the demonstration phase.
II. Advanced and efficient energy transportation methods that do not rely on the T&D network: This includes transporting hydrogen, ammonia, and methane produced using renewable energy, known **as power-to-gas (P2G)**, and utilizing electric transport ships equipped with batteries.
III. Attracting electricity-consuming facilities near power plants: This involves attracting high electricity-consuming facilities such as data centers and factories near renewable energy generation sites.

IV. Installing power generation facilities in electricity consumption areas for self-sourced consumption: Installing solar panels in data centers, factories and commercial facilities, and then consuming the self-sourced power can prevent congestion in the T&D network. Clean power generation technologies for self-sourced consumption include small hydrogen gas turbines and small modular reactors (**SMRs**). Perovskite solar cells (PSCs), which can be installed on building walls and lightweight roofs, are also highly anticipated. However, as with other renewable energy sources, they have variable power output. Therefore, demand response (DR) and demand-side energy storage systems (ESS) are expected for in-facility power supply–demand balancing, minimizing reverse flow and imbalance. Additionally, **self-sourced consumption of electricity in residential areas using PSCs and DR can help reduce the overall system integration cost in Japan** and promote the establishment of regional microgrids for stable local power supply.

In the current power system in Japan, an increase in self-sourced consumption of electricity by consumers can lead to a "negative spiral" in the T&D network. A negative spiral occurs when consumers disconnect from the grid, reducing the revenue of general T&D operators, resulting in these operators increasing their transmission fees, leading to further grid disconnections and making it difficult to maintain the T&D network (Figure 2-3). For consumers, self-sourced electricity consumption reduces costs by eliminating transmission fees and renewable energy surcharges associated with using the grid. However, from the perspective of general T&D operators, reduced grid power demand decreases transmission revenue. To recover the costs of maintaining and upgrading deteriorating T&D networks, as well as future enhancements, operators may be forced to raise transmission fees. This, in turn, improves the relative economics of self-sourced electricity consumption for consumers, incentivizing further grid disconnections. This spiral can increase the burden on remaining grid users and create a shortage of funds necessary for future T&D network upgrades, ultimately affecting the stable supply of electricity.

Figure 2-3 "Negative Spiral" of the T&D Network



(Note) Created by DBJ

The main cause of this negative spiral is that general T&D operators in Japan primarily recover the fixed costs of the T&D network through volumetric charges. One solution to this problem could be increasing fixed charges. Even DCs that procure all their electricity on site benefit from supply–demand balancing and reduced blackout risk through grid connections, making an increase in fixed cost recovery a reasonable option.

3. Expectations for New Technologies from Corporate Initiatives

The previous sections discussed future power system trends and necessary technologies based on electricity demand trends and the movement toward carbon neutrality (CN). This section will highlight the prominence of various technologies by examining actual corporate initiatives. This report specifically focused on approximately 300 power-related companies and projects that are the subject of this report, selected from investments by major energy companies' corporate venture capital (CVC), well-known venture capital (VC) firms, tech award-winning companies, unicorn companies, and projects adopted by the Green Innovation Fund (GI Fund) in Japan. These companies and projects were classified and aggregated based on their business content (Figure 3-1).

Figure 3-1 Aggregation of Investment Companies and Projects

Hardware	Oil & Gas CVCs	Electricity CVCs	Other VCs	Tech Awards	Unicorn Companies	GI Fund	Total
Solar	6	4	4		3	2	21
Wind	1	1	1	3	0	2	8
Other renewables	6	1	4	4	0	0	15
Nuclear	4	0	4	1	1	0	10
Thermal	1	1	3	1	0	0	6
T&D	0	3	3	0	1	0	7
Storage Battery	15	2	12	9	7	1	46
LDES	8	2	5	6	0	0	21
EV	3	3	3	1	9	0	19
HP	0	0	0	1	0	0	1
Electrification	0	2	3	3	1	1	10
Total	44	19	42	31	22	6	164
Software	**Oil & Gas CVCs**	**Electricity CVCs**	**Other VCs**	**Tech Awards**	**Unicorn Companies**	**GI Fund**	**Total**
Generation	1	5	5	8	1	0	20
T&D	9	6	4	10	1	0	30
Demand	38	12	18	18	2	0	88
Overall	3	1	4	4	0	0	12
Total	51	24	31	40	4	0	150
Overall	95	43	73	71	26	6	314

(Note) Created by DBJ

Among the CVCs of oil and gas companies, major companies facing the transition away from coal and toward electrification, such as Shell, Equinor, Chevron, and BP, are actively investing in venture companies with an eye on business transformation. The investment areas prominently include demand-side digital technologies like EV-related applications and hardware related to balancing supply and demand, such as storage batteries and long-duration energy storage (LDES). In contrast, power companies have fewer investments compared to gas companies because they mainly focus on in-house research and development.

Notable VC firms include Breakthrough Energy, founded by Bill Gates to achieve CN; Energy Impact Partners (EIP), specializing in digital technologies for the power sector; and Microsoft's Climate Innovation Fund. Investments in the power sector are fewer compared to overall climate tech investments; and they are mainly focused on storage batteries and demand-related digital technologies, similar to the main focus of oil and gas companies.

For tech awards, five prominent awards were selected, including the Global Cleantech 100, which chooses the 100 most innovative companies in the climate tech field; Deloitte's Technology Fast 500, which highlights the 500 fastest-growing companies in technology; and Fast Company's Next Big Things in Tech. Among the selected companies, those focused on visualizing power consumption and integrating EVs into the power grid stand out.

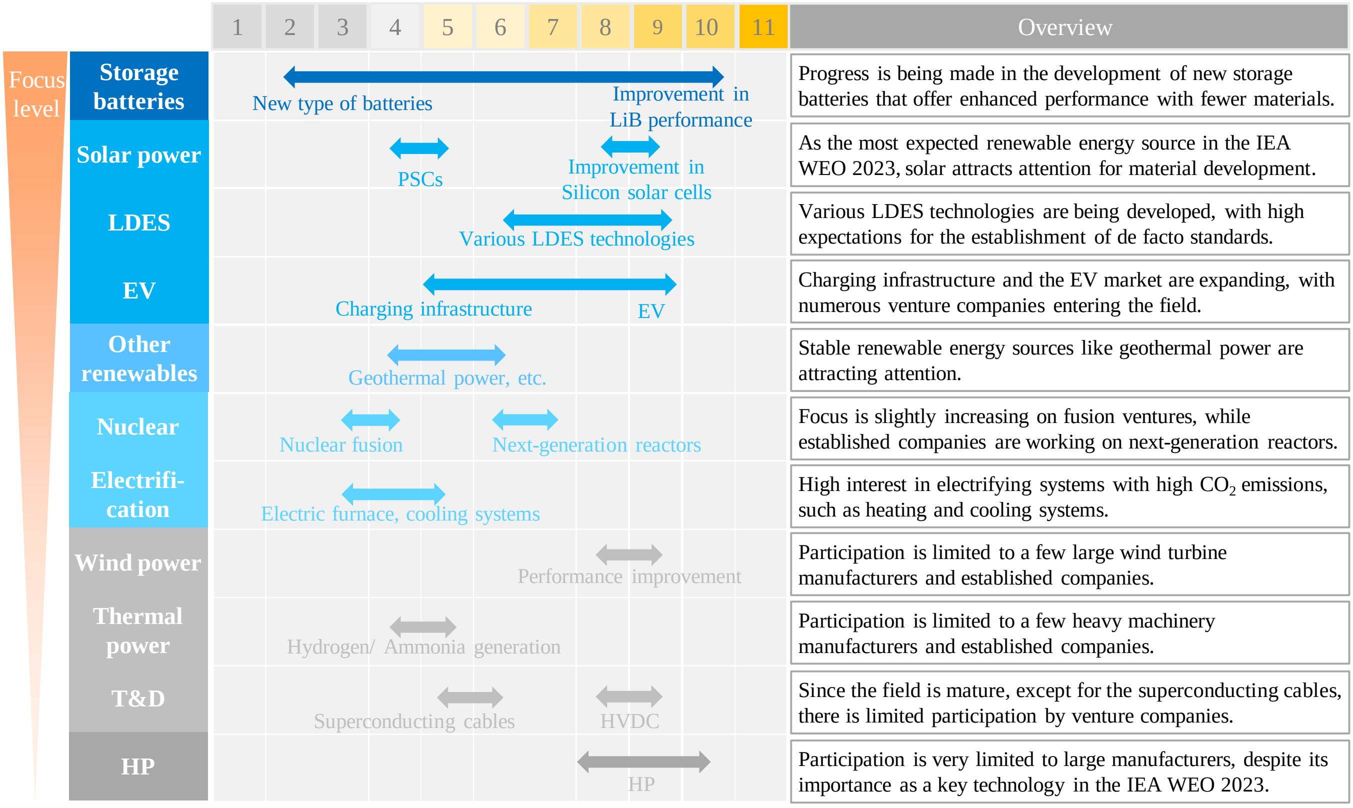
Focusing on unicorn companies, which are privately held ventures valued at over $1 billion and established within the last 10 years, reveals significant activity among battery manufacturers and EV manufacturers. Notable examples include Northvolt, a battery manufacturer that develops and sells lithium-ion batteries (LiB) with a strong emphasis on low lifecycle GHG emissions; and Hozon New Energy Automobile, which develops EVs under the brand name Neta.

In Japan, large corporations lead research and development efforts. The GI Fund, established under the New Energy and Industrial Technology Development Organization (NEDO), supports research, development, and social implementation of technologies based on 14 priority areas outlined in Japan's Green Growth Strategy. These areas include perovskite solar cells, offshore wind power, and storage batteries.

When integrating the number of initiatives in various sectors, as shown in Figures 3-2 and 3-3**, there is significant attention on storage technologies (storage batteries and LDES), solar power in the hardware sector, and demand-related digital technologies like DR in the software technology sector.** This aligns with the analysis presented in the previous sections.

However, it is important to note that the investment activities of companies analyzed in this study are likely focused on areas that are easily monetizable, known as “low-hanging fruit," considering current policy trends, economic viability, and implementation timelines. Consequently, the highlighted technologies in this report may not necessarily be the most critical for the power system**. Significant government support is required for essential technologies classified as “high-hanging fruit," which may not attract sufficient private investment.**

Figure 3-2 Focus Areas in Hardware



(Notes)
1. Created by DBJ
2. The horizontal axis is based on IEA TRL levels.

Figure 3-3 Focus Areas in Software

Focus level	Focus area		IoT	AI	Others	Examples of technologies
	Demand	DR	○	○		Automated DR (ADR) commands, IoT device control
	Demand	Energy efficiency	○		○	Visualization of electricity consumption
	Demand	EV operations		○	○	Charging spot management, charging spot display apps
	T&D	System operation		○		Imbalance adjustment
	Whole system	Equipment maintenance	○	○		Equipment maintenance using drones and image recognition
	Whole system	Integrated management			○	Integrated management of entire supply chain
	Whole system	Cybersecurity		○	○	Detection and prevention of cyberattacks, data recovery
	Genera-tion	Renewable energy	○	○	○	Mapping of areas suitable for renewable energy supply, weather forecasting
	Genera-tion	Optimization		○	○	Fuel procurement and operational optimization for thermal power generation

(Note) Created by DBJ

Conclusion

In the power system, achieving a robust and sustainable energy supply characterized by the 4As (Availability, Accessibility, Affordability, Acceptability) or S+3E used in Japanese energy policies (Safety and Energy security, Economic efficiency, and Environmental sustainability) using only existing technologies is challenging. Over eight years have passed since the Paris Agreement in 2015, during which the costs of existing technologies have significantly decreased, and the development of new innovative technologies has advanced. However, as the target year of 2050 for CN approaches, efforts must be further accelerated. In the short term, the early social implementation of clean energy technologies, such as PSCs, and balancing technologies, such as storage batteries and DR, is required. In the long term, the implementation of LDES and other demand–supply balancing technologies is essential. **The challenges within the power system are diverse and complex, necessitating the development of a wide range of technologies, including technologies not mentioned in this report.**

Major countries, including the US, China, and Japan, are pursuing strong industrial policies related to CN technologies, leading to intense international competition. Beyond achieving CN goals, capturing revenue opportunities through the early implementation of innovative technologies is desirable. **Achieving both CN and economic development will require policy support and the provision of risk capital when returns are expected**. Financially, promising technologies held by startups and large corporations are expected to see expanded investment, including carve-outs and mezzanine financing.

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