Hitachi-UTokyo Lab. 5th Industry-Academia Collaboration Forum
Toward Realizing Energy Systems to Support Society 5.0

Energy Simulation Assuming Carbon Neutrality by 2050

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Challenges in Decarbonization of Electricity Systems

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The main challenges in achieving decarbonization of electricity systems are: stable power supply, enhancing resilience, utilization of decarbonization technologies, advancement of electricity system operations, and utilization of data and digital technologies.

The power supply and demand simulation model is an important tool that contributes to the quantification and objective evaluation of mitigation technologies.

Reinforcing stable power supply

Reinforcing measures for the large-scale introduction of renewable energy

Securing supply capacity, adjustment capacity, and inertia; maintaining, managing, maximizing, and enhancing the transmission and distribution network; optimizing the supply-demand balance; securing investments; and controlling electricity costs.

Enhancing resilience

Strengthening ability to respond in normal times and during supply shortages

[Progress in electrification increases importance of electricity in society].

Further improvement of reliability of supply in normal times and response to unexpected rare-frequency risks such as natural disasters and severe weather.

Decarbonization of electricity systems

Quantification, improvement of efficiency, and innovation of electricity systems through the development of open data infrastructure and use of digital technologies.

Use of decarbonization technologies

Accelerating technology innovation

Shift to renewable energy as main power source (solar and wind power), power storage (grid-use storage batteries, EV batteries, thermal storage power generation, etc.), hydrogen and ammonia power generation (co-firing, mono-fuel combustion), distributed power sources (fuel cells, cogeneration), transmission and distribution networks (high-voltage direct current transmission, microgrids, etc.), demand response, nuclear power (innovative light water reactors, small reactors), CCUS (CO_2 capture, utilization, and storage) technology, sector coupling technology (methanation, etc.)

Sophistication of electricity system operation

Operational sophistication for the use of DER such as renewable energy

Sophistication of power grid operation (bidirectional power flow [between regions and upstream/downstream]), more flexible power demand (DER utilization [EV, heat pumps, PV+ storage batteries, change in consumer behavior, etc.])

CCUS: Carbon dioxide Capture, Utilization and Storage, DER: Distributed Energy Resources, EV: Electric Vehicle, PV: Photovoltaic

Power Supply and Demand Operations (Kyushu region: Apr 2021)

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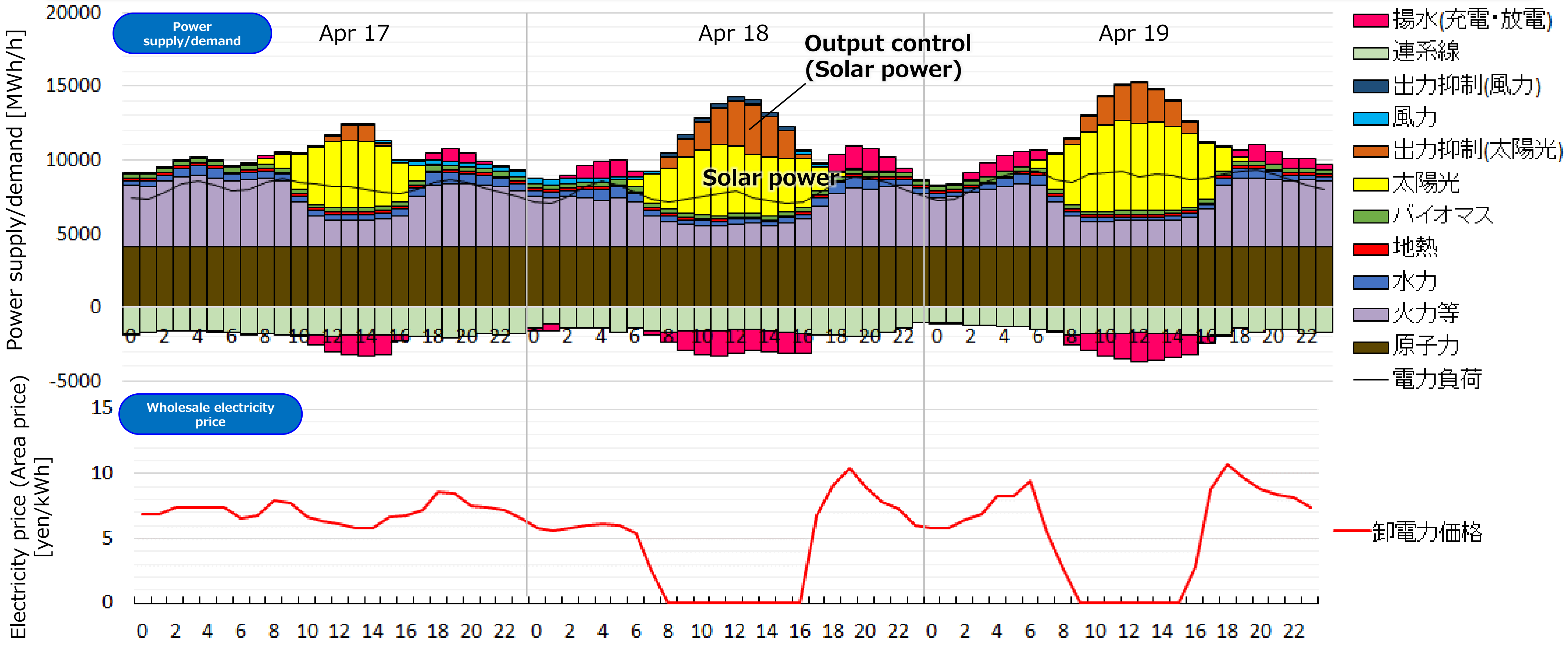
Large-scale output suppression has been implemented in Kyushu, where the ratio of renewable energy use is high. There is a need to plan and implement measures early on to maximize the use of renewable energy.

- Ensuring adjustment capacity, maximizing and increasing transmission capacity, expanding power storage capabilities, and increasing flexibility in power demand.
- Fluctuation and decline in wholesale electricity prices -> decline in incentives for increase and maintenance of power sources, and concerns over future supply shortages.

There is a need for multifaceted and quantitative visualization of issues and for evaluation of countermeasures.



(Source) Prepared based on actual supply and demand in the Kyushu Electric Power Area

Large-scale Numerical Simulation of the Power Grid

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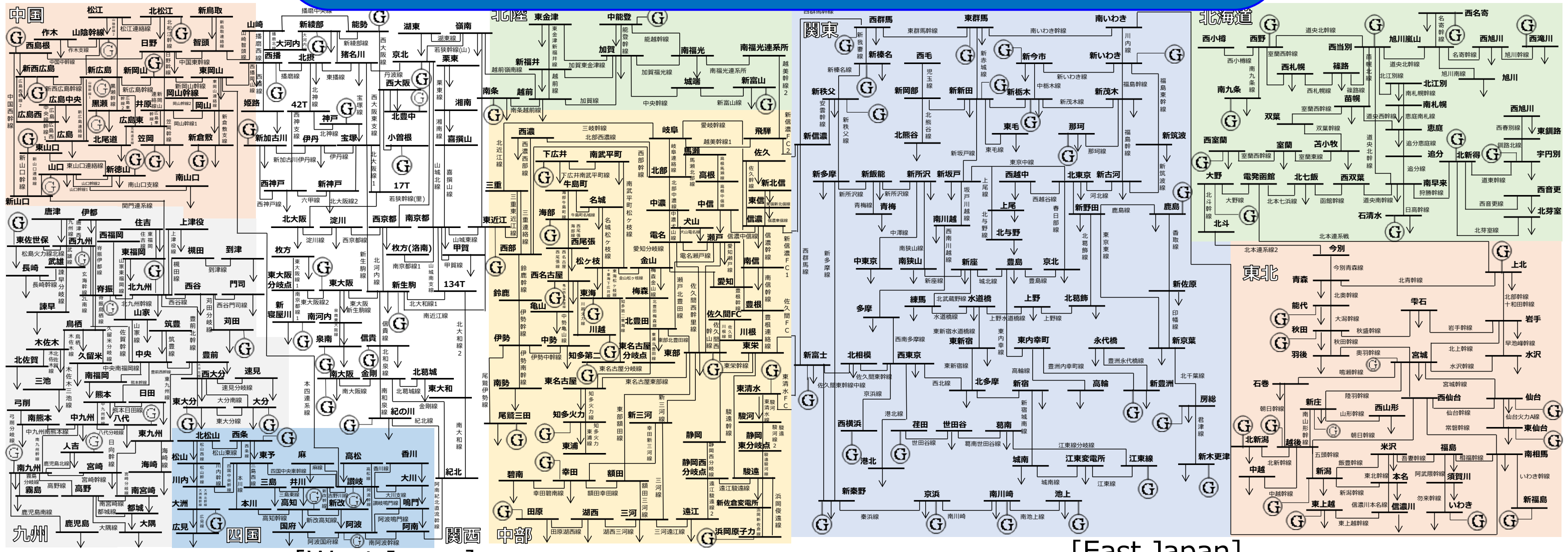
Numerical simulation of power supply and demand using an optimized power supply/demand model (developed by Fujii-Komiyama Lab, University of Tokyo).

Analysis of the best mix of power sources under various technical conditions and CO_2 constraints for the entire bulk power supply grid in Japan.

- Geographical resolution -> 383 bus lines and 475 core transmission lines -> detailed consideration of power grid constraints and renewable energy weather conditions.
- Time resolution -> analyzed by 1-hour value and 8,760 hours annual time -> detailed consideration of fluctuations in renewable energy output.
- Consideration of various technical factors such as innovative technologies: Coal, coal-ammonia co-firing, coal-CCS, gas composite, gas-fired steam power, gas-hydrogen co-firing, gas-CCS, petroleum, hydrogen, nuclear power (large reactor, small reactor), general hydropower, geothermal, biomass, ocean, solar, onshore wind power, offshore wind power, pumped water, NAS battery (for long period variation), and Li-ion batteries (for short-cycle fluctuations) *CO_2 that cannot be recovered by CCS thermal power is assumed to be offset by negative emission technologies in other sectors.
- Main assumptions: Solar power (can be newly installed without setting an installation capacity limit), wind power (upper limit is set based on evaluation of potential for introduction by the Ministry of the Environment), hydrogen power generation (maximum 20M ton capacity per year, import price 20 yen/Nm3), nuclear power generation (60-year operation scenario [23.7GW], no new additions), etc.
- (Actual) Materials of the Strategic Policy Committee of the Advisory Committee for Natural Resources and Energy, METI (43rd Meeting, 2021), METI Contracted Industrial and Economic Research Project "Simulation Survey Using Power Supply and Demand Models" (2016), etc.

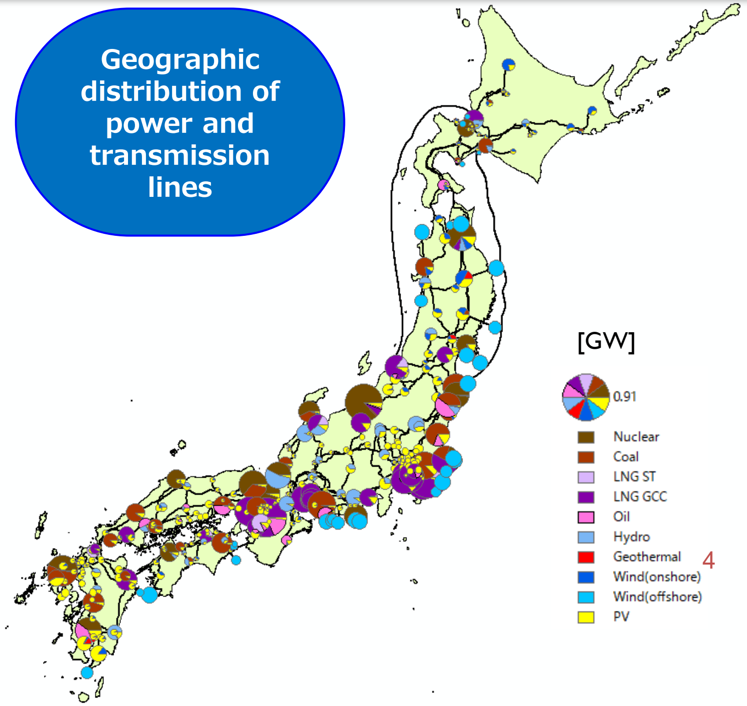
Point of the report: Importance of quantification and congestion management for inertia measures by digitally solving grid constraints and detailed modeling of renewable energy weather conditions.

Nationwide bulk power supply grid model (383 bus lines, 475 transmission lines)



[West Japan] [East Japan]

Geographic distribution of power and transmission lines



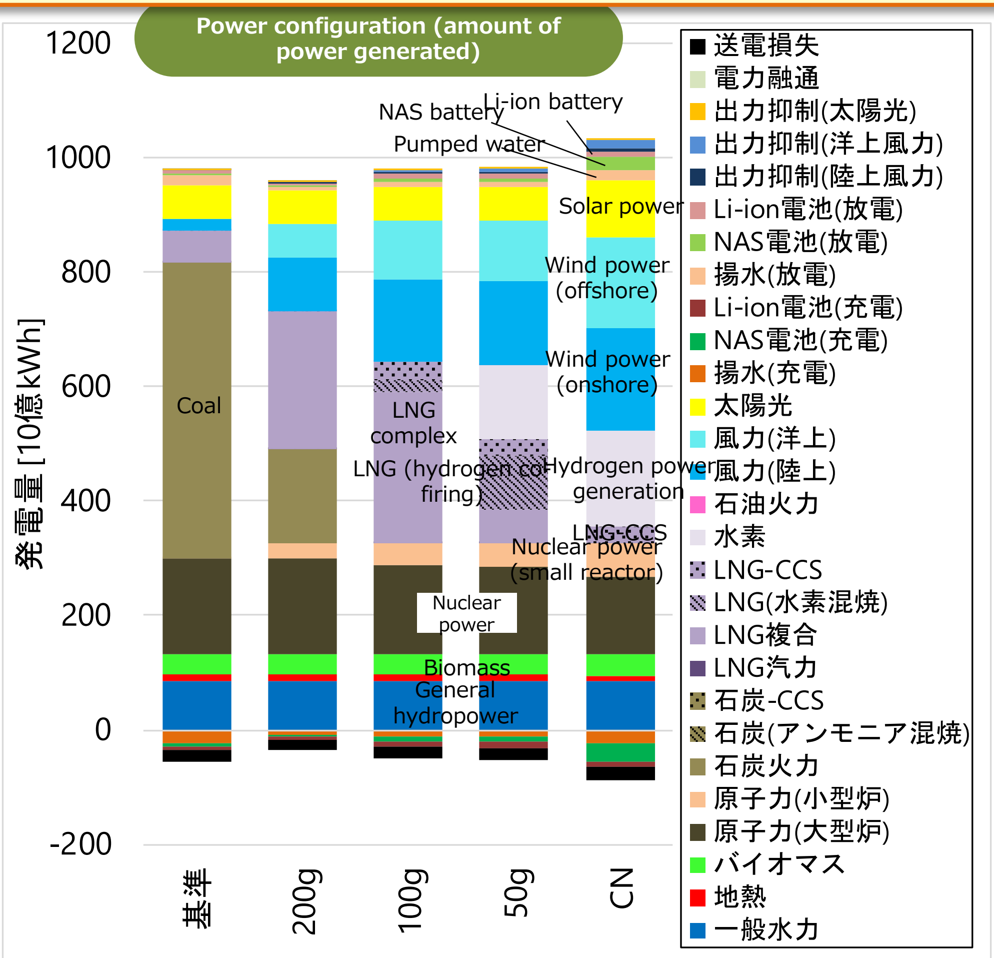
(Reference) Komiyama, R., Fujii, Y., *Energy Policy*, 101(2), 594-611 (2017); Komiyama, R., Fujii, Y., *Renewable Energy*, 139, 1012-1028 (2019), etc.

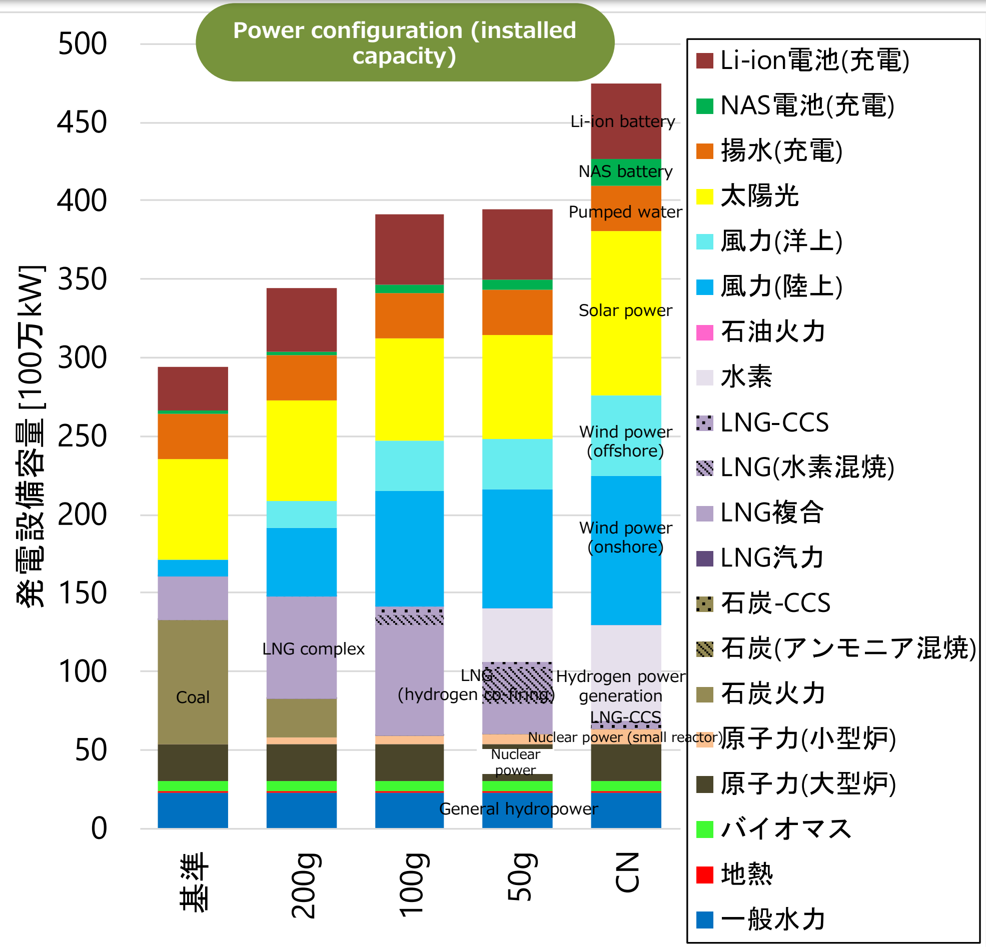
Tool Key Function 1: Power Analysis

Under transmission and resource constraints, derive the power supply configuration with the lowest social cost and the amount of power generated to achieve the target CO_2 emissions.

- Case settings (CO_2 emission limit): Standard (no CO_2restrictions), 200g-CO_2/kWh, 100g-CO_2/kWh, 50g-CO_2/kWh, CN (limit at zero CO_2 emission).
- Carbon neutrality restrictions -> Expand the introduction of solar power, wind power (onshore and offshore), clean thermal power (hydrogen power generation, etc.), grid storage batteries, etc.

Coupled analysis of supply-demand simulation and grid simulation with a geographical resolution of 383 points



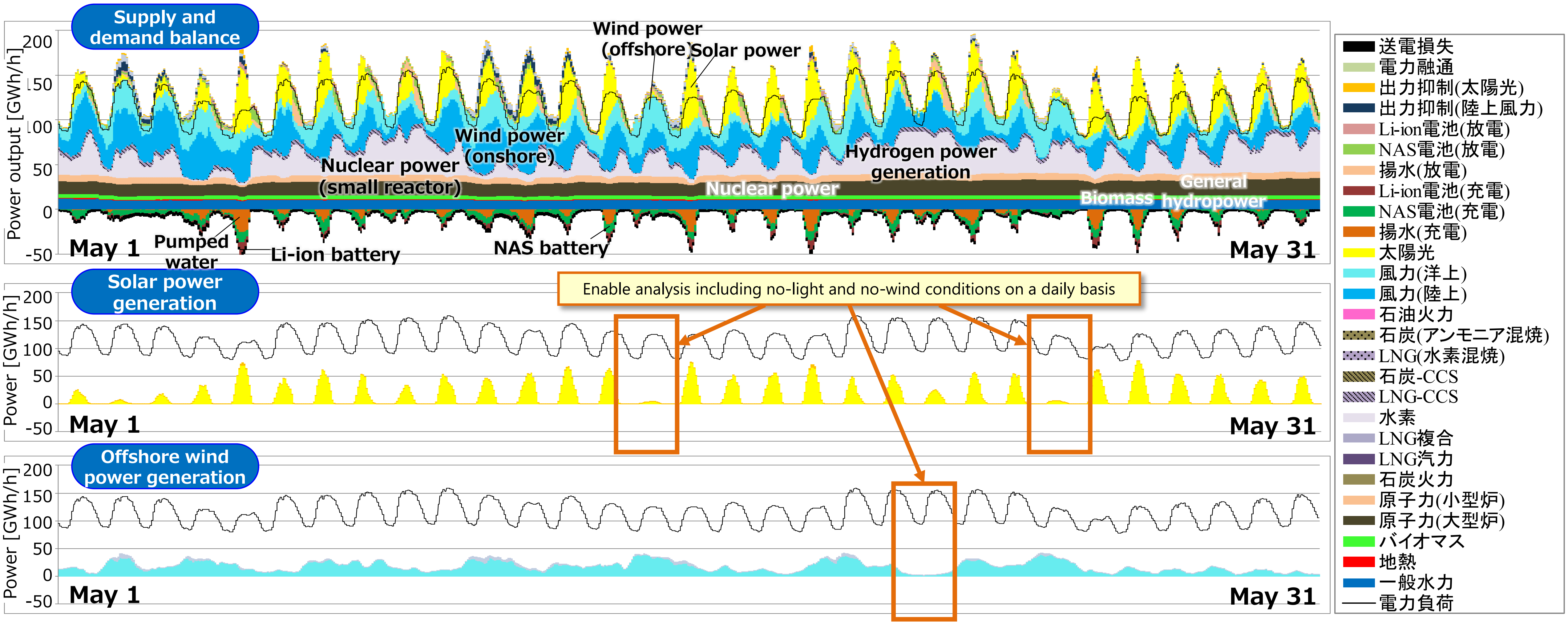


CN: Carbon Neutrality, CCS: Carbon dioxide Capture and Storage

(Source) Komiyama, Fujii, (Symposium Lecture) Power Supply and Demand Analysis in the Age of Carbon Neutrality, Institute of Electrical Engineers of Japan (2022)

Tool Key Function 2: High Temporal Resolution

Sectional analysis at 8,760 [hours/year] enables supply/demand analysis for power, energy storage, and demand by incorporating hourly, daily, and seasonal fluctuations.



(Source) Komiyama, Fujii, (Symposium Lecture) Power Supply and Demand Analysis in the Age of Carbon Neutrality, Institute of Electrical Engineers of Japan (2022)

Tool Key Function 3: Quantification of Power Generation Cost

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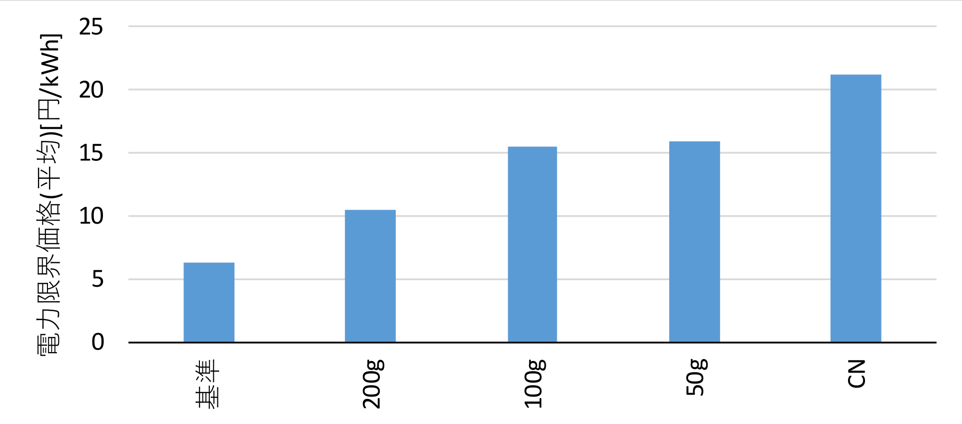
Enables calculation of change in electricity costs over time, including power generation, storage, and transmission losses
Visualization of cost changes according to the transmission network reinforcement plan.

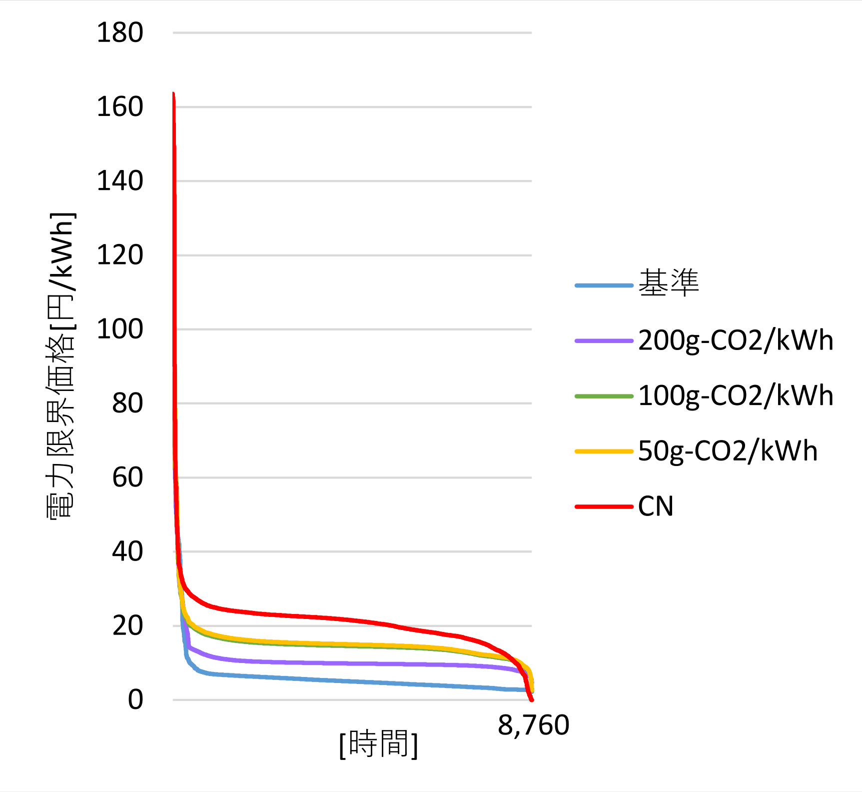
- Due to CO_2 constraints and the uptake of renewable energy, the average level of electricity prices will rise, and the range of fluctuations may also expand.
- Uptake of renewable energy -> securing adjustment capacity (grid-use storage batteries, clean thermal power); strengthening power transmission lines -> rise in power prices.

Electricity price (Marginal price)



[yen/kWh]	Electricity marginal price	Average electricity price	Standard deviation	Highest price	Lowest price
Standard	6.4	8.4	8.2	99.4	2.2
200g-CO_2/kWh	10.5	9.5	8.7	122.7	4.2
100g-CO_2/kWh	15.5	10.7	9.2	141.0	2.9
50g-CO_2/kWh	15.9	11.9	9.0	138.3	2.6
CN	21.2	13.4	10.9	163.6	0.0

Annual trend in electricity prices (Marginal price)



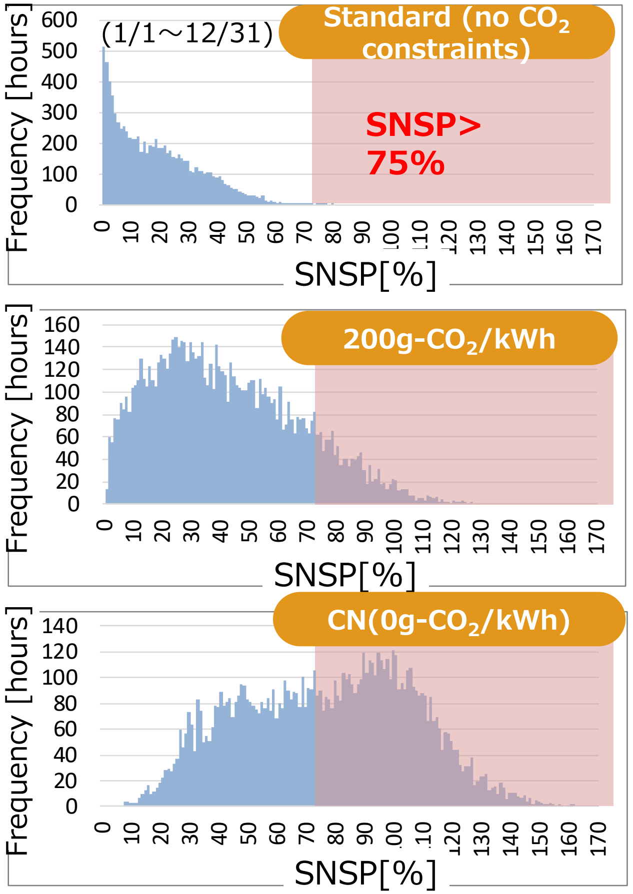
(Source) Komiyama, Fujii, (Symposium Lecture) Power Supply and Demand Analysis in the Age of Carbon Neutrality, Institute of Electrical Engineers of Japan (2022)

Tool Key Function 4: Renewable Energy Ratio Evaluation Over Time

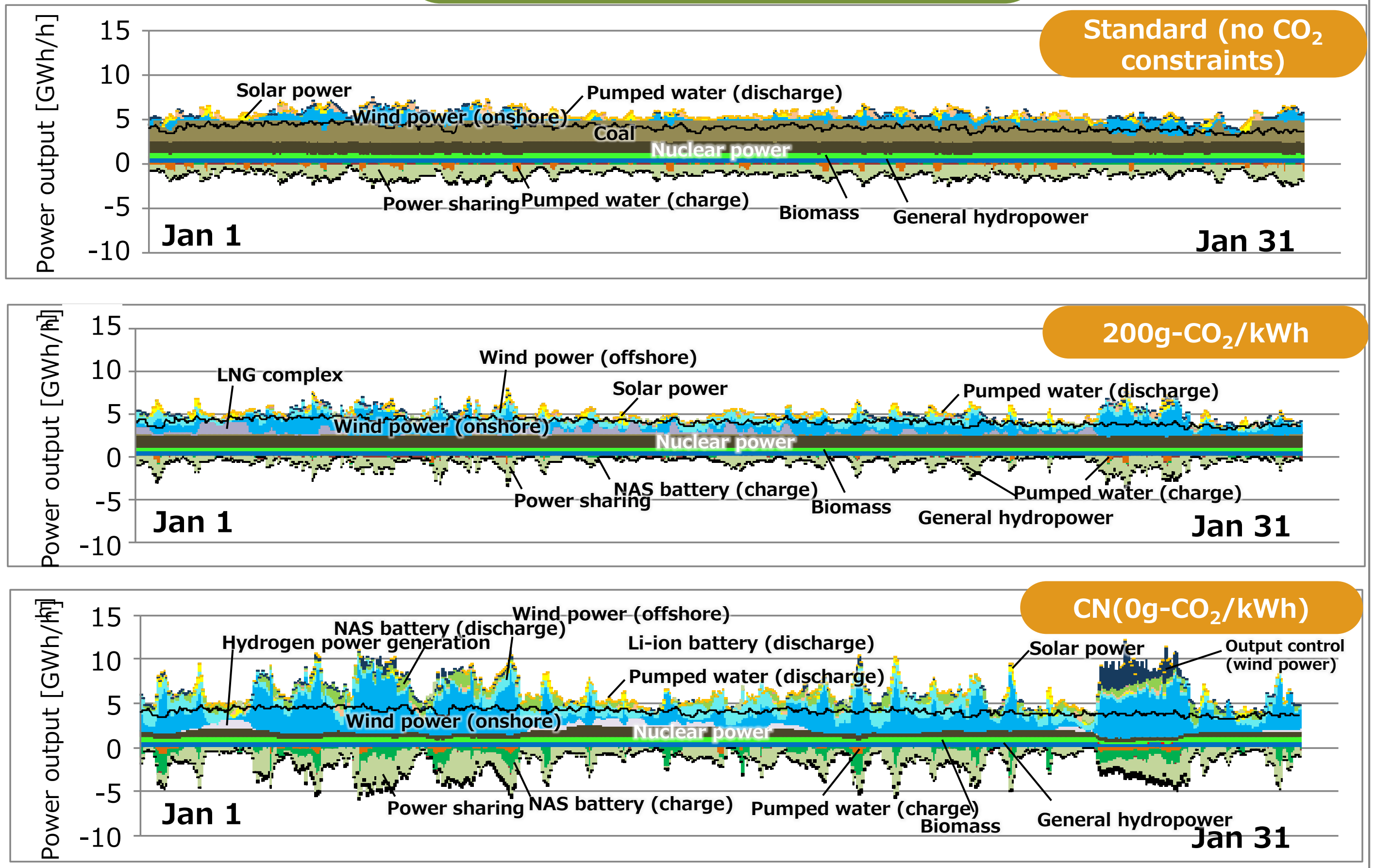
Enables derivation of period and quantity needed to strengthen the inertia force
Enables quantitative evaluation of effectiveness of inertia enhancement measures.

Pseudo-inertia control of renewable energy inverters, synchronous condensers, clean thermal power (hydrogen, CCS, etc.), nuclear power, pumped water hydropower, thermal storage power generation, etc.

SNSP (Hokkaido region)



Power supply/demand operations (Hokkaido Region)



SNSP: System Non-Synchronous Penetration

(Source) Prepared from analysis by Komiyama, Fujii, (Symposium Lecture) Power Supply and Demand Analysis in the Age of Carbon Neutrality, Institute of Electrical Engineers of Japan (2022)

Emerging Issue 1:
Need for Locational Electricity Pricing and Distributed Resource Coordination

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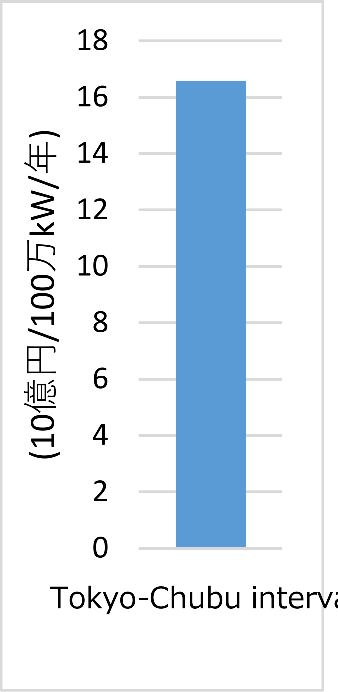
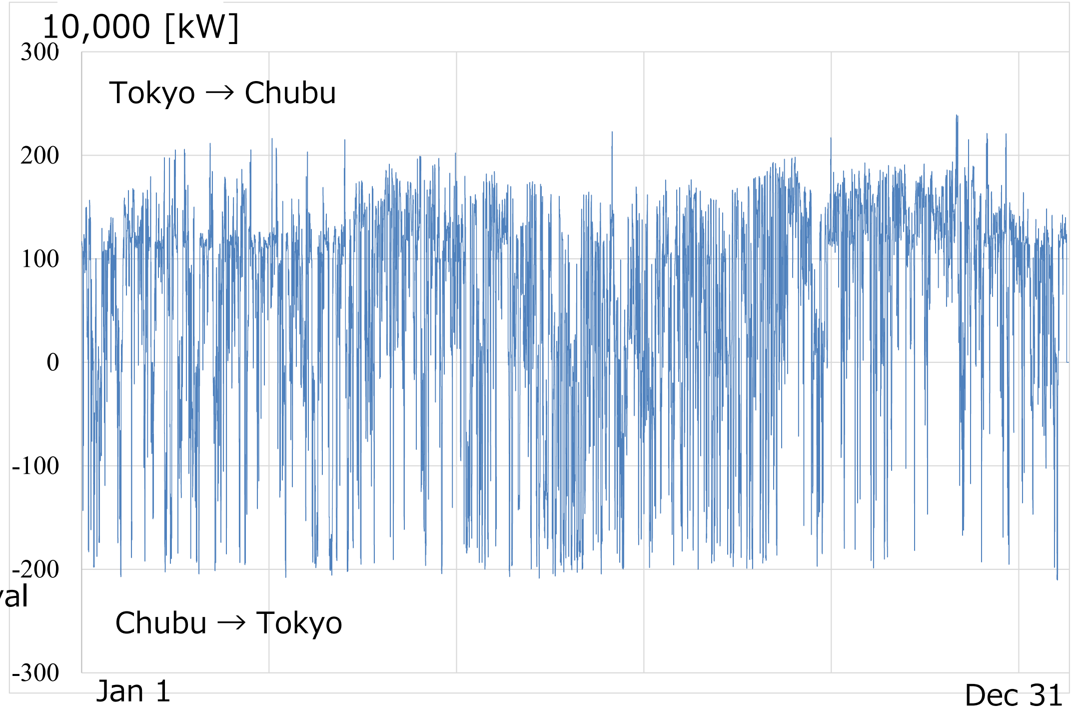
For the construction of an optimal power grid (effective utilization and enhancement of power line capacity) aimed at shift to renewable energy as main power source, it is effective to alleviate power transmission congestion through the locational electricity pricing (nodal pricing) mechanism.

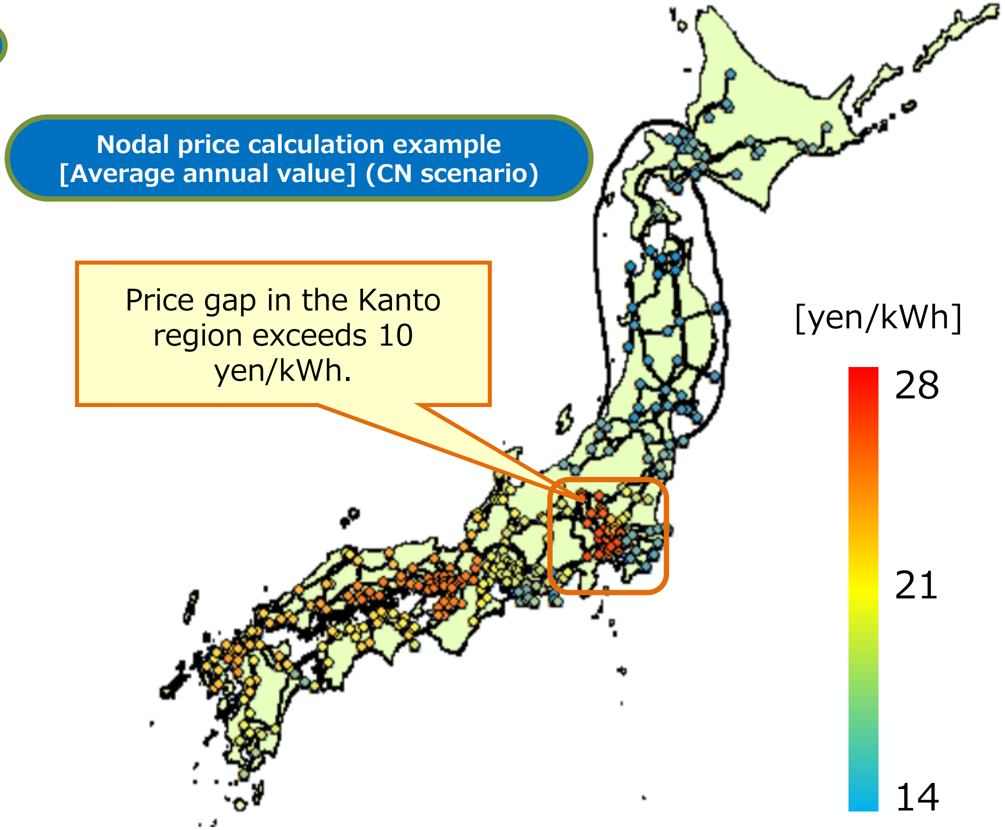
- Transmission line reinforcement: Important to evaluate cost-effectiveness of transmission line reinforcement costs, taking into account the cost of transmission line congestion mitigation measures (DR, storage batteries, etc.).
- Locational marginal price (nodal price [LMP]): Important indicator for determining transmission line investments, reflecting the supply/demand situation at each location (high-priced locations → relatively high cost-effectiveness of power supply expansion). Location guidance of renewable energy sources through nodal-price visualization is also an important issue in alleviating transmission line congestion.

Transmission line capacity shadow price, inter-regional transmission flow (e.g. Tokyo-Chubu)



*Weighted average of Sakuma FC, Higashi-Shimizu FC and Shin-Shinano FC





FC: Frequency Converter, LMP: Locational Marginal Price

(Source) Prepared from analysis by Komiyama, Fujii, (Symposium Lecture) Power Supply and Demand Analysis in the Age of Carbon Neutrality, Institute of Electrical Engineers of Japan (2022)

Emerging Issue 2:
Formulation of Measures to Improve the Flexibility of Electricity Demand

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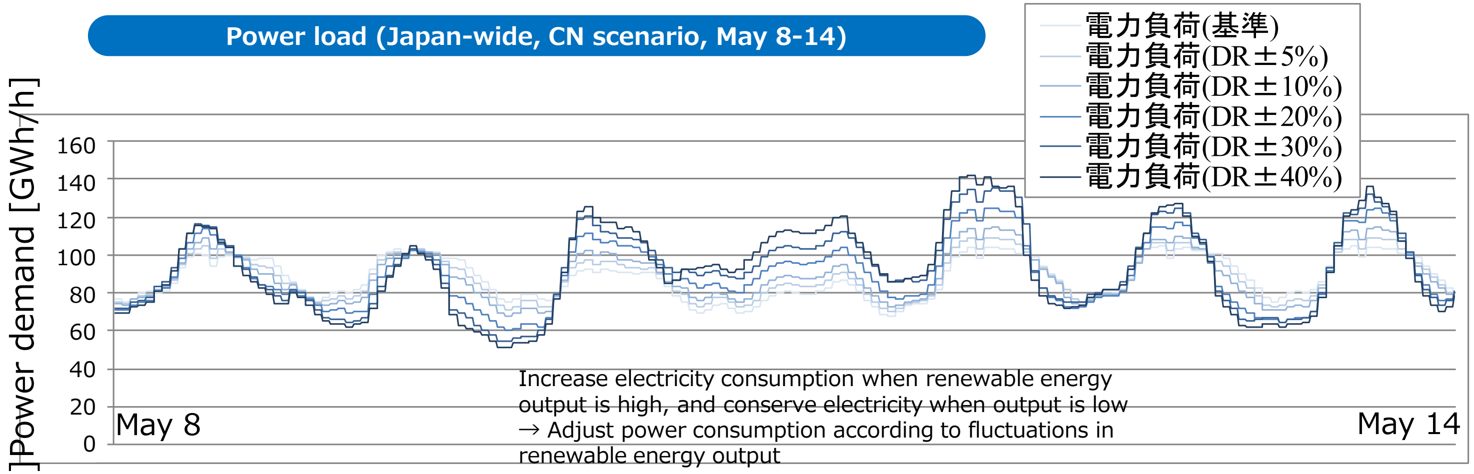
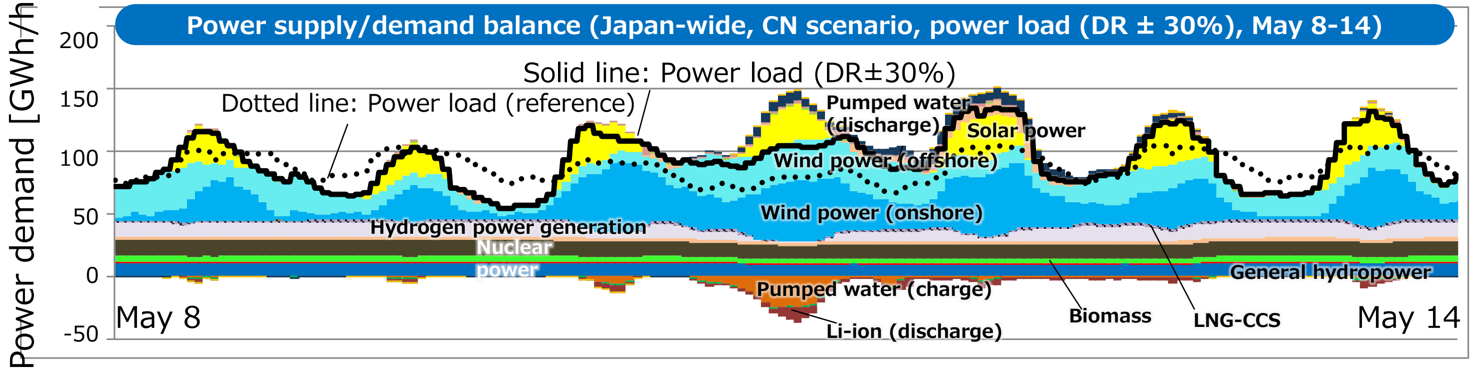
Improving the flexibility of electricity demand, such as through DR, is extremely effective for shifting to economically rational renewable energy as main power source. Efforts should be made to motivate demand coordination, secure a commitment base, and maximally leverage voluntary coordination.

- How should we increase the flexibility of power demand through end-use technologies (EV, heat pumps, BEMS, HEMS, etc.) and behavioral changes, and how should we commit demand-side technologies to supply and demand adjustment?

Power load (Japan-wide, CN scenario, May 8-14)



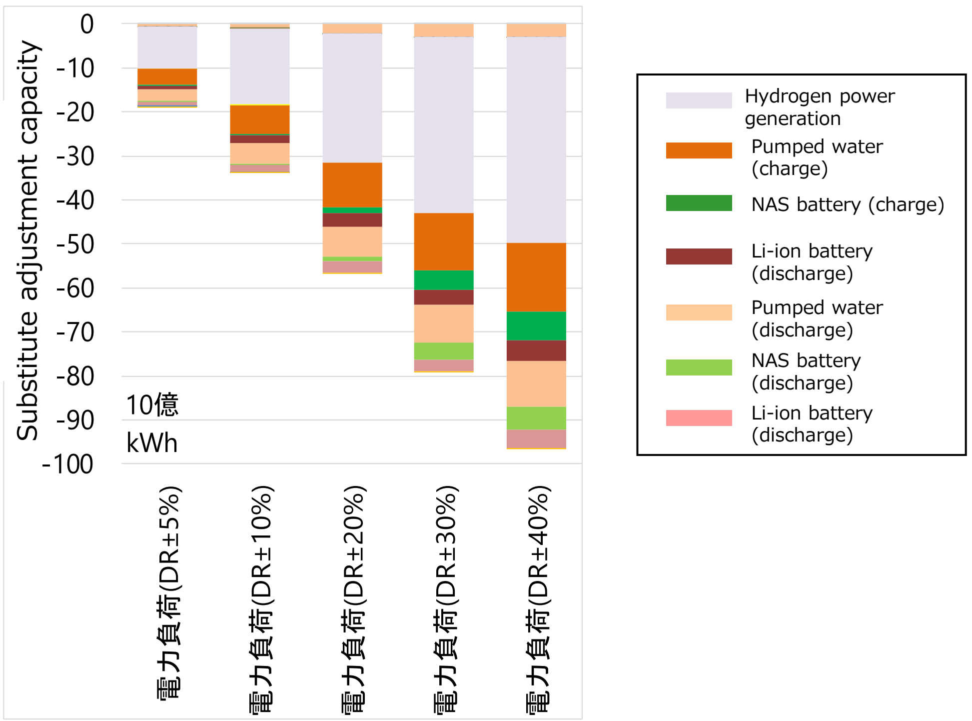
Power supply/demand balance (Japan-wide, CN scenario, power load (DR ± 30%), May 8-14)



(Note) DR upper and lower limits are imposed on the power load level of each node at each point in time, and the system cost is minimized on the assumption that the total annual power demand of each node is unchanged before and after DR to determine the optimal DR implementation amount for each node at each point in time.

Substitution amount for each resource through DR implementation

Enable reduction of required amount for each adjustment capacity by improving flexibility of power demand



BEMS: Building Energy Management System, HEMS: Home Energy Management System, DR: Demand Response

Emerging Issue 3:
Fusion of Hydrogen Technology and Power Control that Balances Storage and Energy Security

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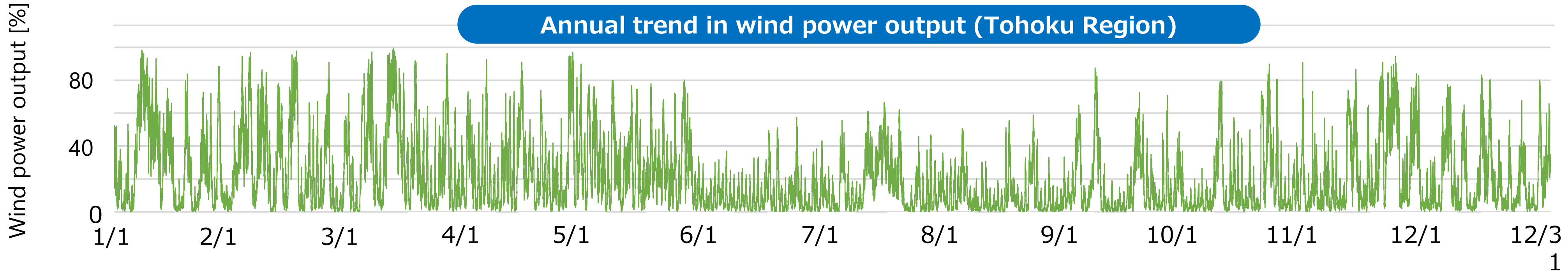
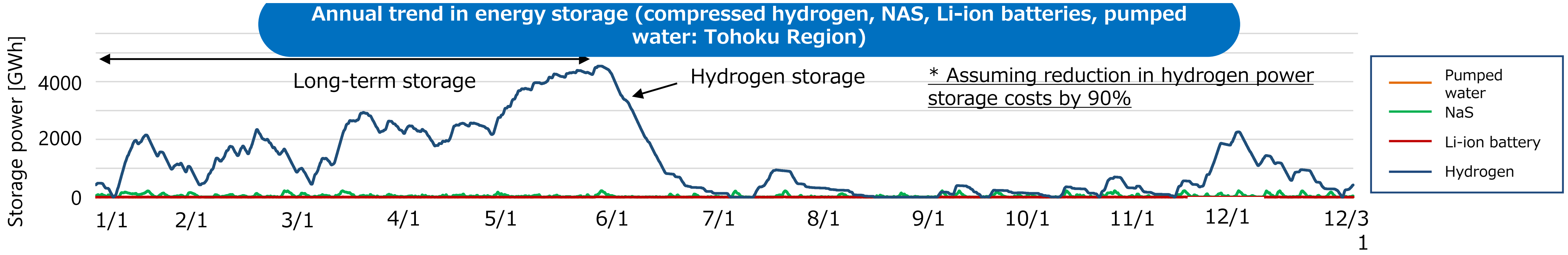
There is a need to properly grasp the duration and quantity of energy storage, and to operate optimal storage technologies and develop elemental technologies in accordance with the duration and quantity.

- Hydrogen storage is one of the technology options suitable for long-term storage (weekly, monthly, seasonal) with low storage loss.
  (However, since long-term hydrogen storage has high OPEX, storage by methanation, ammonia, MCH conversion, etc. may be more economical.)
- Long-term storage of battery power entails large losses, while batteries are better suited to frequent charging and discharging on a daily basis.
- However, seasonal storage of renewable energy requires a significant reduction in initial investment (there are few opportunities for charging/discharging, and limited profit opportunities).





MCH: Methylcyclohexane, OPEX: Operating Expense

(Source) Prepared from Komiyama, R., Fujii, Y, *Energy*, 81, pp.537–555 (2015)

Conclusions

Issues and recommendations for decarbonization of electricity systems derived from large-scale numerical simulation model of power supply and demand.

Decarbonization of electricity systems requires ① visualizing multifaceted and quantitative issues using numerical simulation models, and ② evaluating the measures. Evaluation using large-scale numerical simulation model backed by digital technology is imperative.

■ **Main functions of the model**

- Power source analysis: Under transmission and resource constraints, derive the power supply configuration with the lowest social cost and the amount of power generated to achieve the target CO_2 emissions.
- High temporal resolution: Sectional analysis at 8,760 [hours/year] for supply/demand analysis for power, energy storage, and demand by incorporating hourly, daily, and seasonal fluctuations.
- Quantification of power generation costs: Visualization of changes in power costs over time, including power generation, storage, and transmission losses, as well as cost changes according to the transmission network reinforcement plan.
- Evaluation of renewable energy ratio over time: Enables derivation of period and quantity needed to strengthen the inertia force Enables quantitative evaluation of effectiveness of inertia enhancement measures.

■ **Issues that have emerged from model analysis**

- **Need for locational electricity pricing and distributed resource coordination**
  Building an optimal transmission network aimed at shift to a renewable energy as main power source entails alleviating transmission congestion through the nodal price mechanism.
- **Formulation of measures to improve flexibility of electricity demand**
  Improving the flexibility of electricity demand, such as through DR, is extremely effective for shifting to economically rational renewable energy as main power source. Efforts should be made to motivate demand coordination, secure a commitment base, and maximally leverage voluntary coordination.
- **Fusion of hydrogen technology and power control that balances storage and energy security**
  There is a need to properly grasp the duration and quantity of energy storage, and to operate optimal storage technologies and develop elemental technologies in accordance with the duration and quantity.

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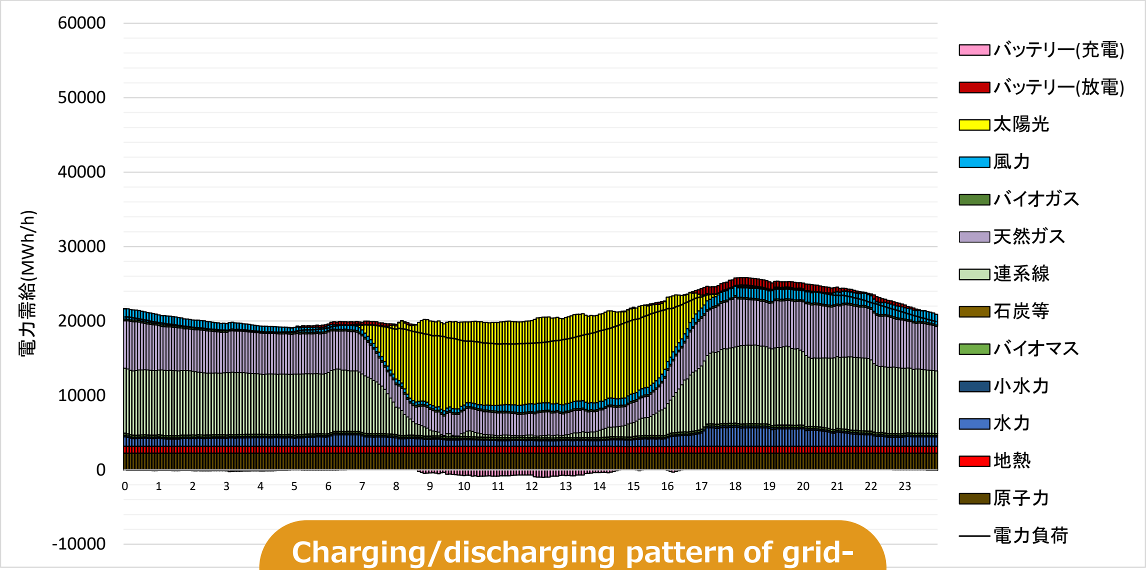
(Appendix) Role of Power Storage

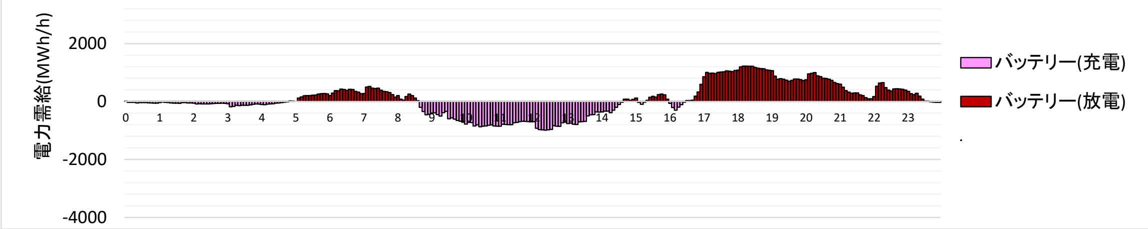
Expectations for the use of power storage towards a stable supply of electricity and large-scale introduction of renewable energy.

- Against the backdrop of lower costs and the spread of electric vehicles, interest in the utilization of grid-use storage batteries is growing.
- In California, grid-use storage batteries are being used to alleviate fluctuations in renewable energy output and during supply shortages.

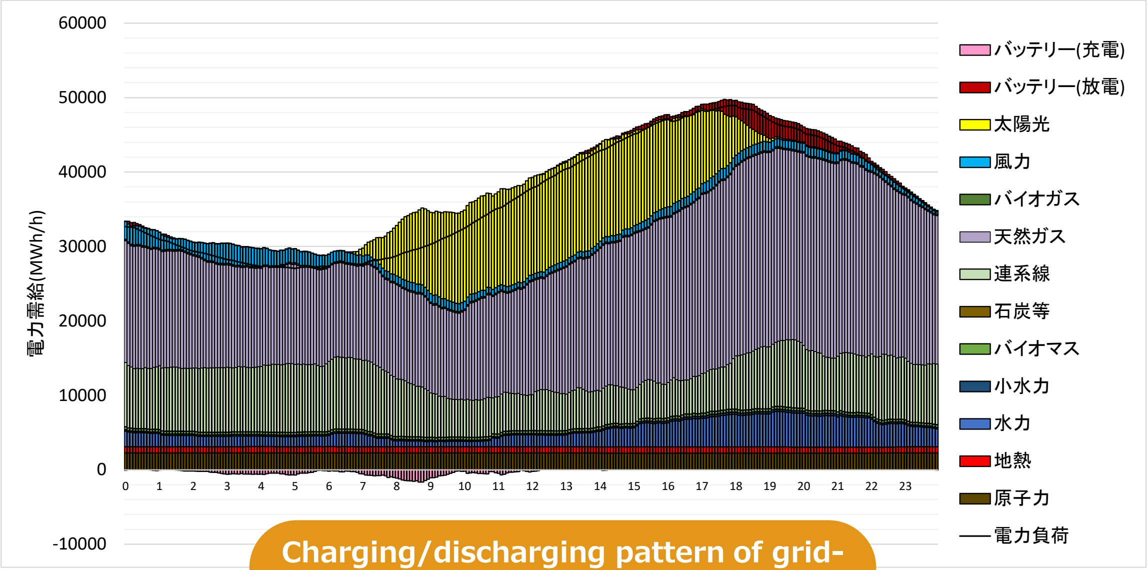
Power supply/demand balance (California, Feb 4, 2022 [Sun])



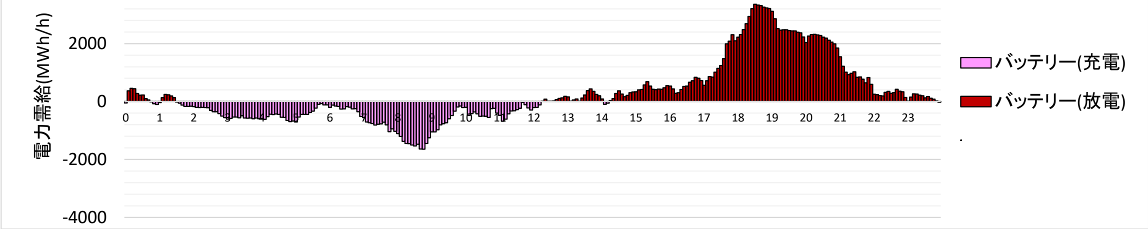
Charging/discharging pattern of grid-use storage batteries



Power supply/demand balance (California, Sep 5, 2022 [Mon])



Charging/discharging pattern of grid-use storage batteries



(Source) Prepared from publicly available data on California Independent System Operator website

(Appendix) Role of Power Storage

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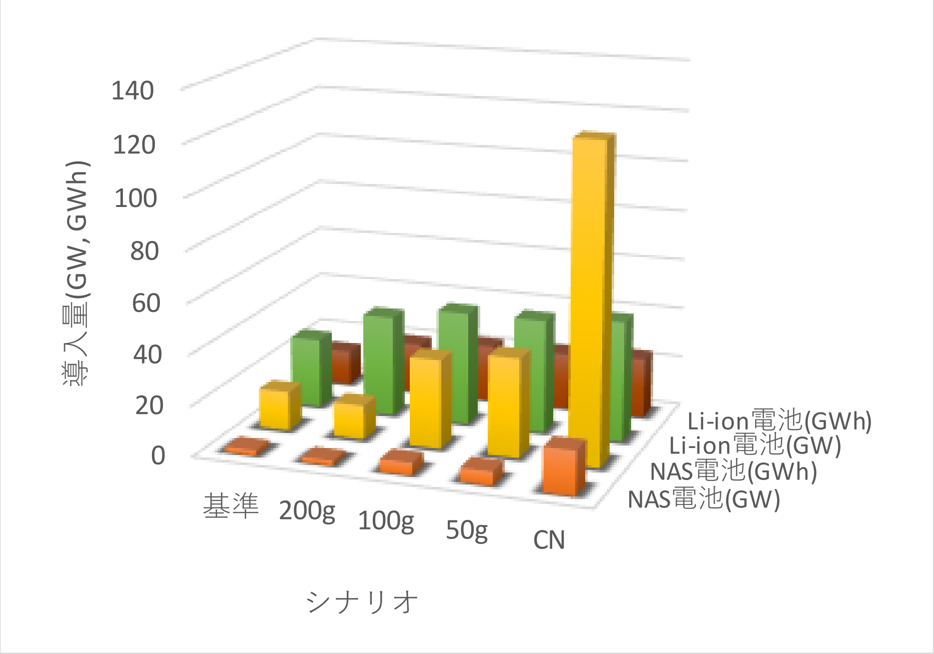
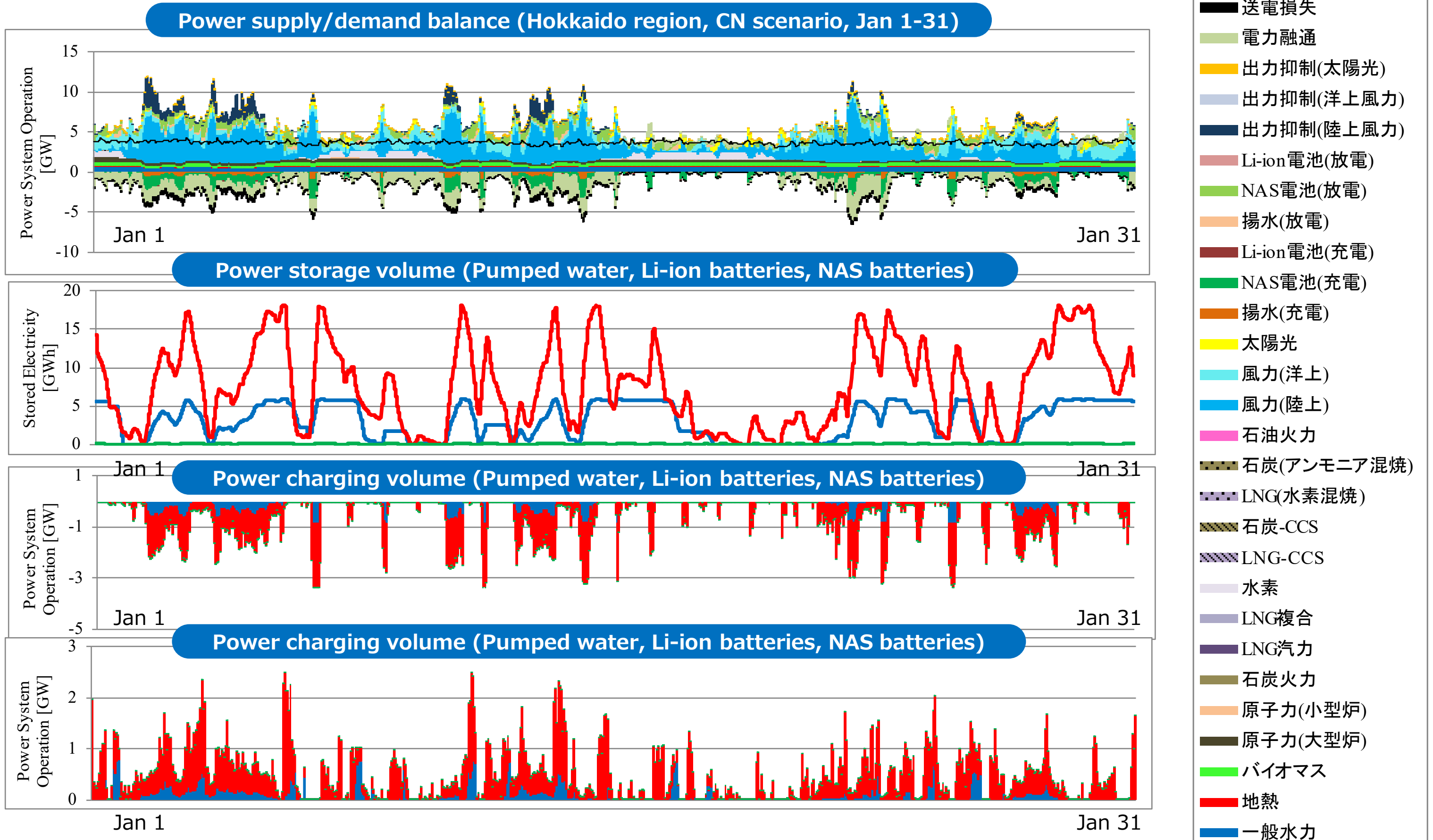
Introduction of grid-use storage batteries and use of pumped water hydropower contribute to decarbonization and expansion of introduction of renewable energy.

- During large-scale introduction of renewable energy, sufficient power storage is maintained in preparation for a windless period, and electricity is discharged when there is no wind.
- It is suggested that it is best to operate power storage technology based on forecast of future supply/demand situation.

Optimal introduction volume of grid-use storage batteries (Li-ion batteries, NAS batteries) (different scenarios)





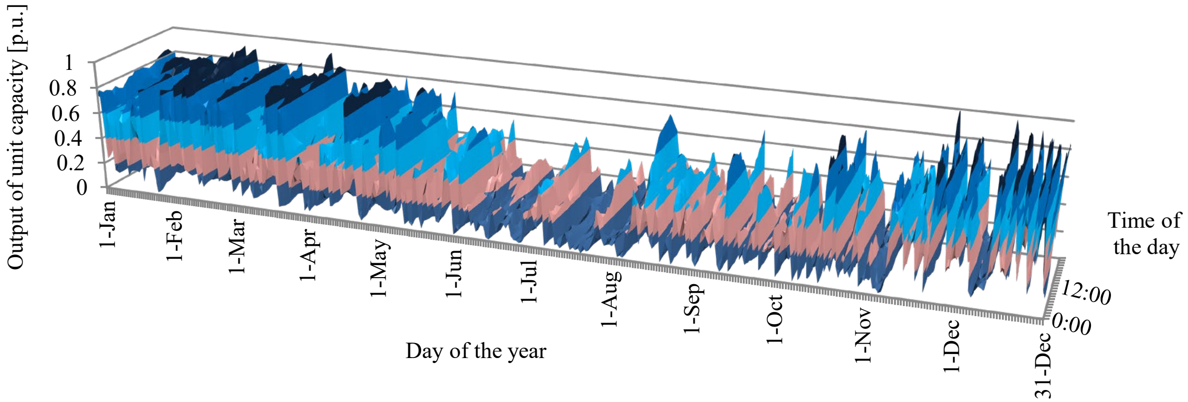
(Source) Prepared from analysis by Komiyama, Fujii, (Symposium Lecture) Power Supply and Demand Analysis in the Age of Carbon Neutrality, Institute of Electrical Engineers of Japan (2022)

(Appendix) Renewable Energy Output Fluctuations

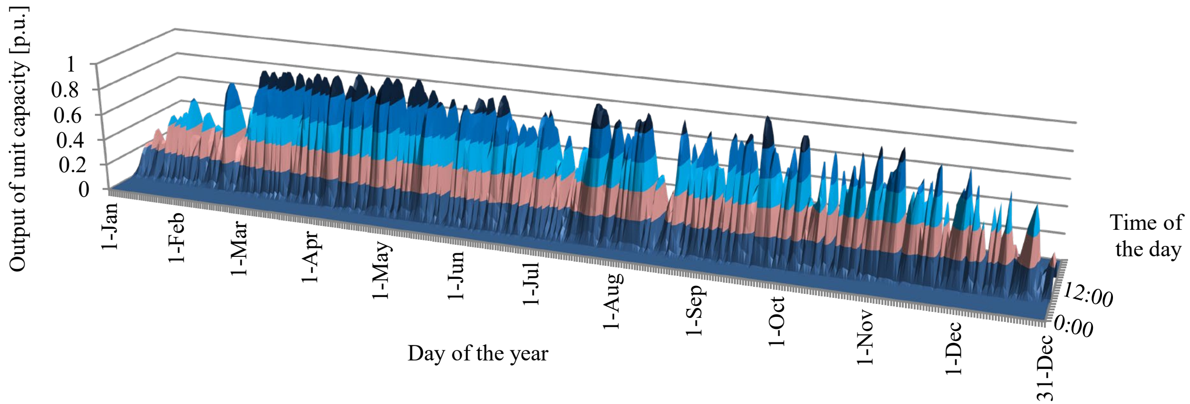
Large-scale introduction of renewable energy also requires taking comprehensive measures against fluctuations in renewable energy output (by minute, hour, day, and season).

- Wind and solar power output fluctuates in short cycles (by minute, hour, and day,) as well as in long cycles (by season).
- Wind power generation: Relative decrease in output around summer; solar power generation: relative decrease in output around winter.
- Seasonal fluctuations must be addressed to effectively utilize renewable electricity upon large-scale introduction of natural variable power sources.
- Challenge: Long-term energy storage is required, and opportunities for charging/discharging are limited -> not easy to recover investment.

Wind power output (Jan. 1 to Dec. 31, 2021, Tohoku Region)



Solar power output (Jan. 1 to Dec. 31, 2021, Tohoku region)



(Source) Prepared based on actual supply and demand in the Tohoku Electric Power Network area