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

S+3E of Bulk Power Systems for Carbon Neutral Society

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1. Introduction

Assessment of challenges and measures related to stable energy supply.

4th Forum (Dec. 2021)

Study of multiple scenarios and impact of measures for expanding renewable energy and increased electricity demand.

1. **Importance of stable power supply:**
   Ensuring stable power supply such as nuclear power, which balances the expansion of renewable energy and reduction of thermal power generation.
2. **Placement of energy storage sites for stable supply:**
   Large-scale energy storage for offshore wind power and utilization of EVs for distributed PV.
3. **Society where consumers choose decarbonization:**
   Visualization of CO_2 emissions, social modeling of increasingly complex supply chains, and digital analysis for smart decarbonization.

This report

Revision of energy scenarios in light of international situation, extraction of new issues, and verification of measures.

1. **Changes in energy scenarios as fuel prices soar.**
2. **Challenges and measures of bulk power system to prepare for rapid expansion of renewable energy introduction.**

CN: Carbon Neutrality

1. Introduction: Points of this report

(1) Is there a scenario where carbon neutrality is possible despite rising fuel prices? How is it different from scenarios to date?

(2) What challenges do bulk power systems face in transition to carbon neutrality? Are there solutions?

We simulated scenarios with assumptions about the future.

2-1. Consideration of changes in energy systems based on rising fuel prices

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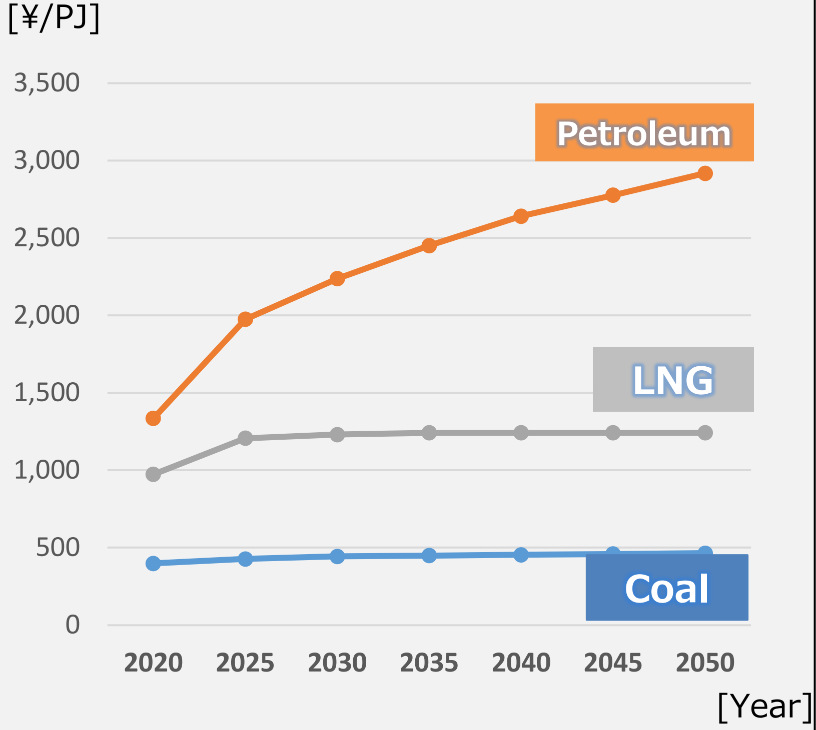
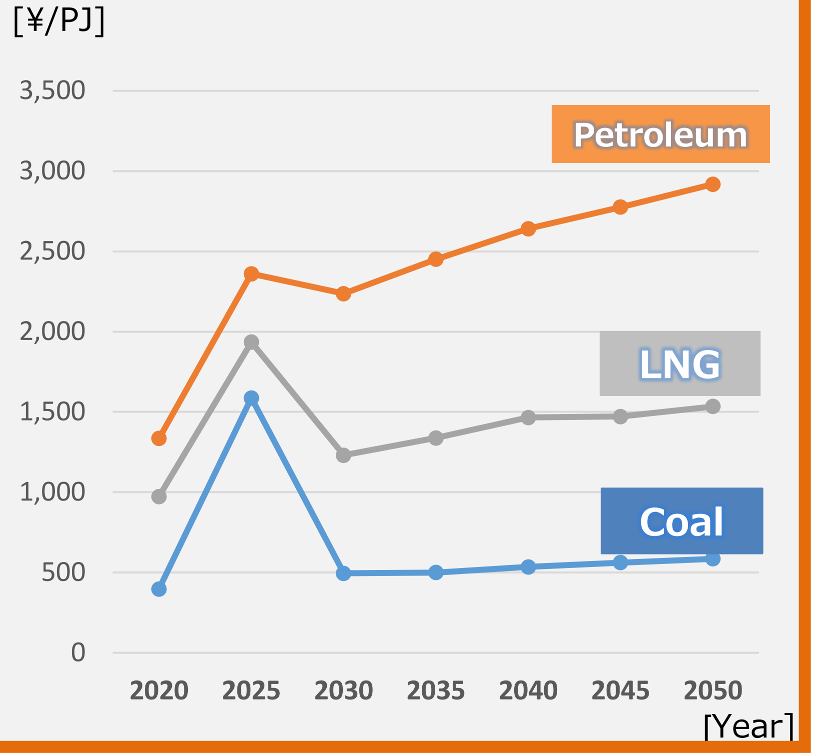
Examination of CN transition process in light of fuel price hikes.

Case 0: Assumptions based on U.S. EIA*1 calculations (Annual Energy Outlook 2022, Long Term Outlook*2)
Case 1: Current fuel prices fall by 2030 and return to long-term trend*3

Case 0: Long-term outlook before the invasion of Ukraine
(H-TokyoU Lab 4th Forum Report)



Case 1: Fuel price hikes are transitory



◆Inquiry conditions

Simulation tool:
Fujii-Komiyama Lab., University of Tokyo: Cost optimization calculation of transitions to 2050, minimizing total system costs while maintaining energy supply and demand, based on 8,760 hours per year (technology selection model)

Amt of CO_2 reduction:
46% reduction by 2030, CN by 2050

Fuel price trend
Case 1 adopted

*1 EIA: Energy Information Administration (information bureau of U.S. Department of Energy)
*2 EIA Outlook 2022: https://www.eia.gov/outlooks/aeo/
*3 Based on current fuel prices in 2025 and U.S. EIA estimates for 2030 and beyond.

2-2. Inquiry conditions for time of achieving CN by 2050 (studied in the previous forum)

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Optimization results for different energy and demand mixes by changing CCS, hydrogen imports, etc.

	(1) 100% RE	(2) Thermal power with CCS limit	(3) Use of nuclear power	(4) Hydrogen procurement
Nuclear plant life (years)	Stopped	60	←	←
Nuclear plant cap. upper limit (GW)	0	24	50 (SMR)	←
Thermal power with CCS upper limit (ton)	200 mil.	100 mil.	200 mil.	←
Hydrogen import upper limit (ton)	20 mil.	←	←	No upper limit
Hydrogen price (¥/Nm^3)*1	20	←	←	←
FCV price (compared to current)	0.68	←	←	0.20
EV price (compared to current)	0.68	←	←	←
Solar power upper limit (GW)	None	←	←	←
Onshore wind power upper limit (GW)	40	←	←	←
Offshore wind power upper limit (GW)	90	←	←	←
Solar power construction cost (10k yen/kW)	15	←	←	←
Onshore wind turbine construction cost (10k yen/kW)	21	←	←	←
Offshore wind turbine construction cost (10k yen/kW)	51	←	←	←
CCS cost (¥/tonCO$_2$)	7450	←	←	←
DAC cost (¥/tonCO$_2$)	10,340	←	←	←
LiB battery cost (¥/Wh)	10	←	←	←
	RE only (e.g. PV and wind power)	Limited CCS for thermal power	Additional SMRs after 2040	Import of hydrogen from overseas

CN: Carbon Neutrality, CCS: Carbon dioxide Capture and Storage, DAC: Direct Air Capture, EV: Electric Vehicle, FCV: Fuel Cell Vehicle, SMR: Small Modular Reactor, LiB: Lithium-ion Battery

2-3. Energy scenarios based on fuel price hikes: Case 0→Case 1: Case of transitory fuel price hikes

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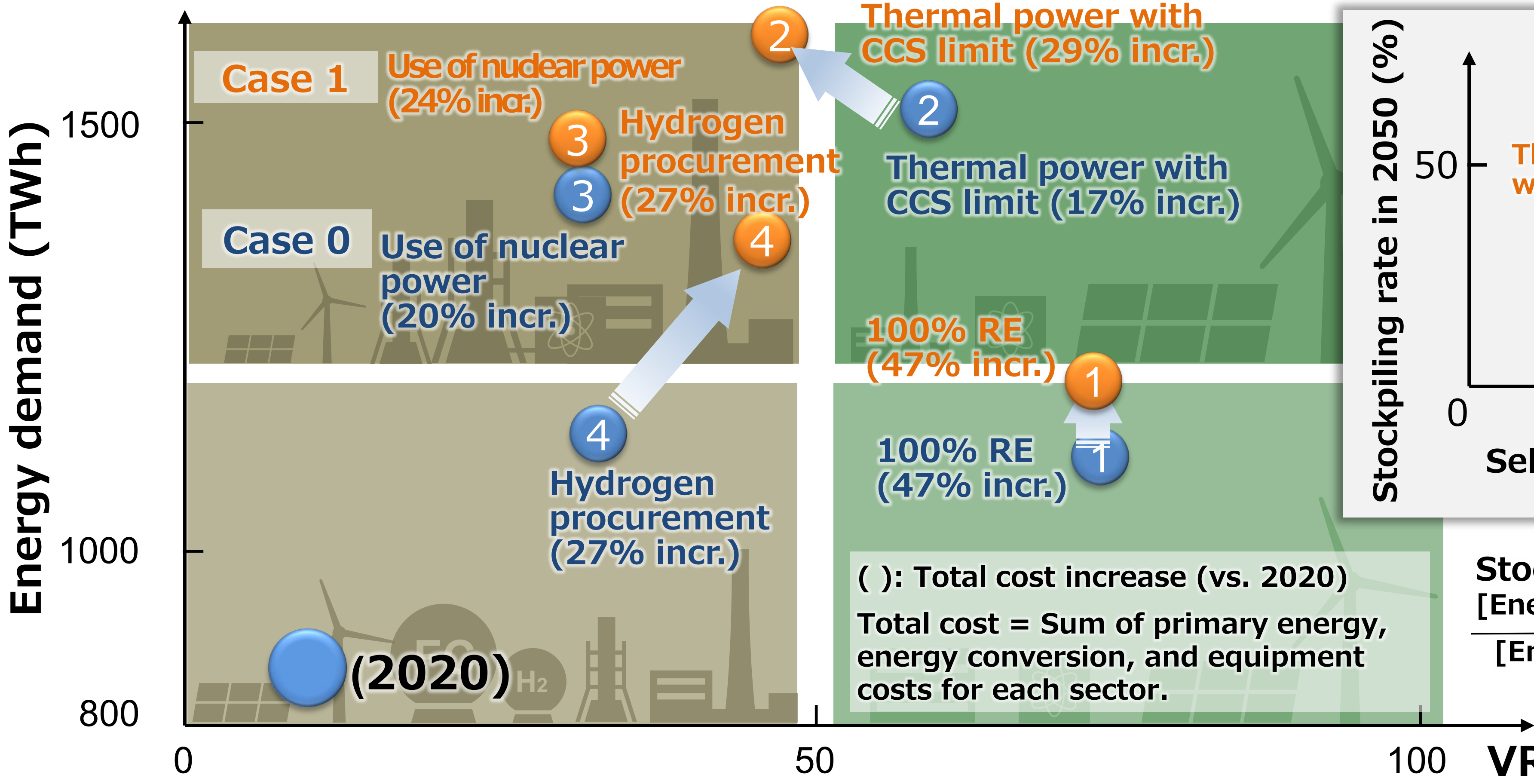
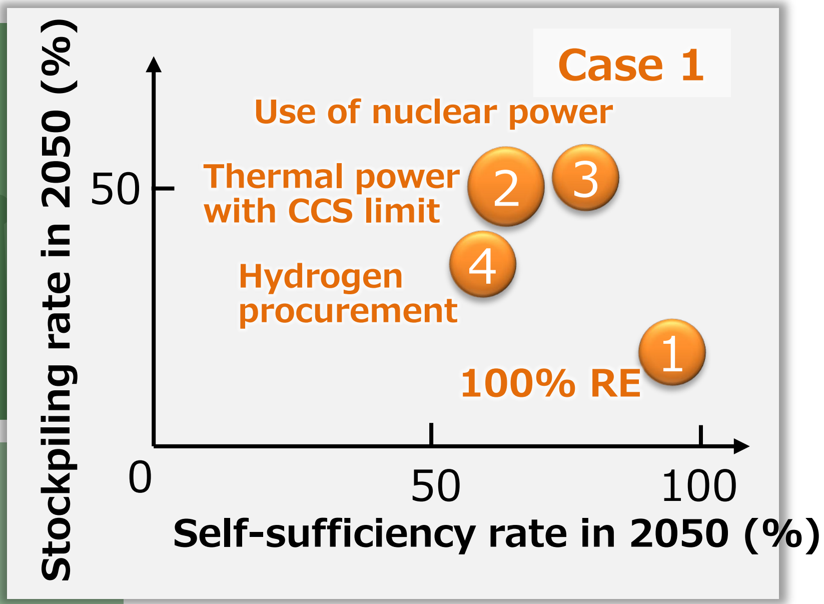
There are solutions to achieve CN even with fuel price hikes.
Demand of power increases, use of hydrogen fuel progresses, and total energy costs increase by 20-50% compared with 2020.





Stockpiling rate = [Energy generation from storable fuels] / [Energy generation from all sources]

From balancing total cost increase, self-sufficiency rate, and stockpiling rate, Case (3) "Utilization of nuclear power" will be used as the base case from the next page onward.

CCS: Carbon dioxide Capture and Storage, FCV: Fuel Cell Vehicle, VRE: Variable Renewable Energy, EV: Electric Vehicle

2-4. Case 1: Calculation results for case of transitory fuel price hikes (power supply capacity)

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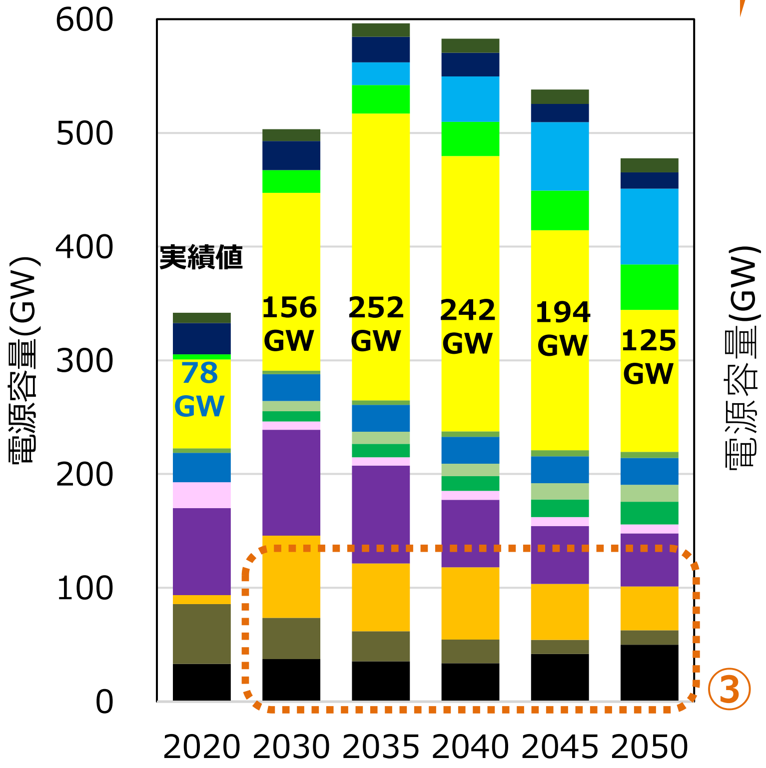
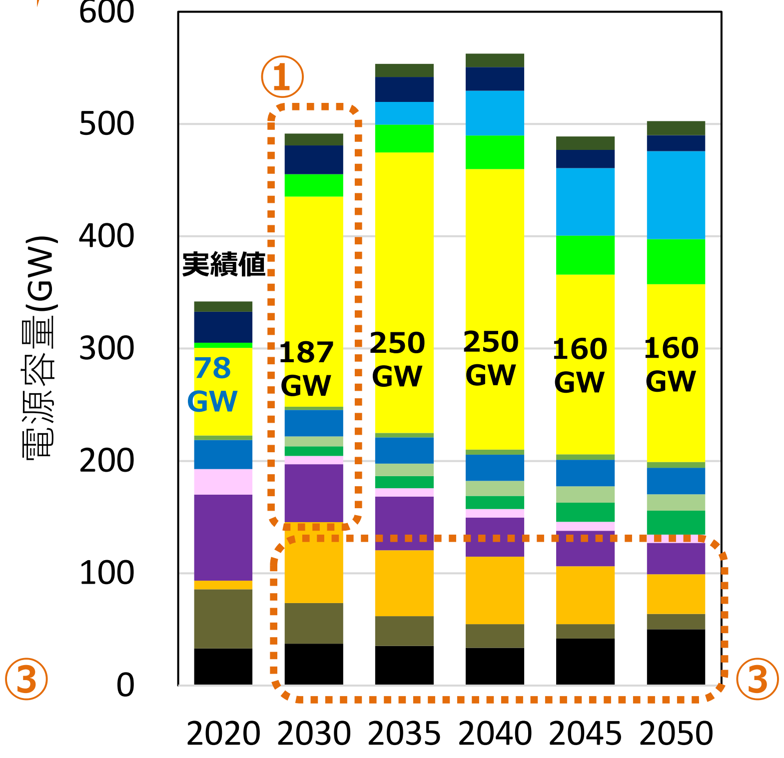
Solar power doubles by 2030, use of high-efficiency heat such as cogeneration, and restart of nuclear power plants to achieve CN.

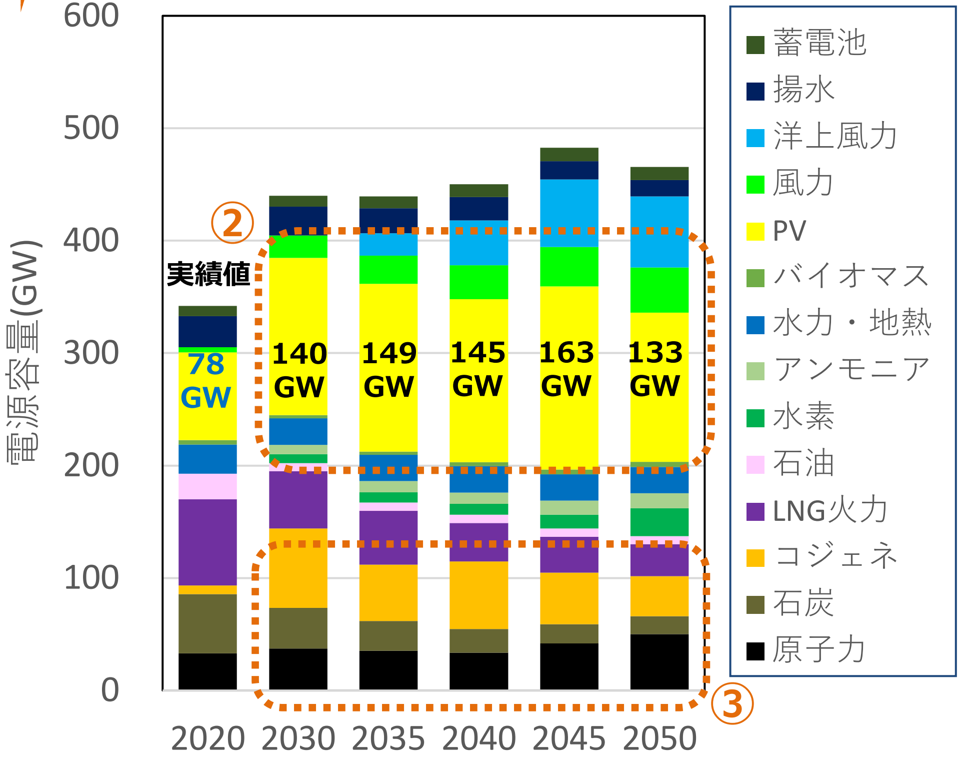
Case 0: Long-term outlook before invasion of Ukraine (4th Forum Report)



Case 1: Fuel price hikes are transitory (reflecting fuel price hikes)



Case 1’: Fuel price hike + correction by forecast (Reduction of PV waste from Case1’)



(1) Due to fuel price hikes, necessary to increase RE and reduce fossil fuel power generation by 2030.
(2) Possible to have correction scenario to avoid “PV installation → disposal in a short period of time” (Case 1’).
(3) Heat utilization by cogeneration, etc. and utilization of nuclear power are critical.

2-5. CN transition process taking into account uncertainty
Nuclear power use scenario: Use of hydrogen

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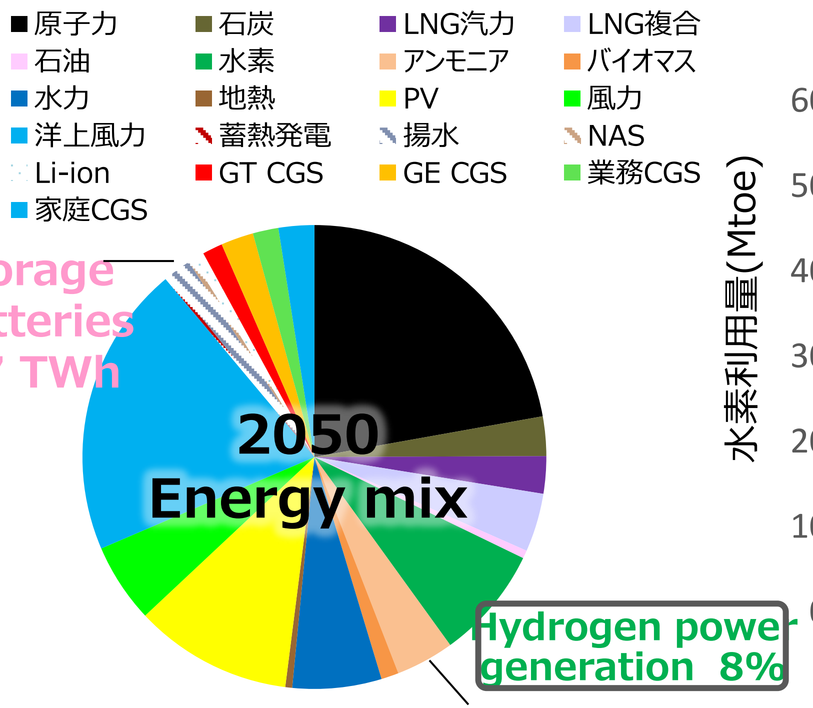
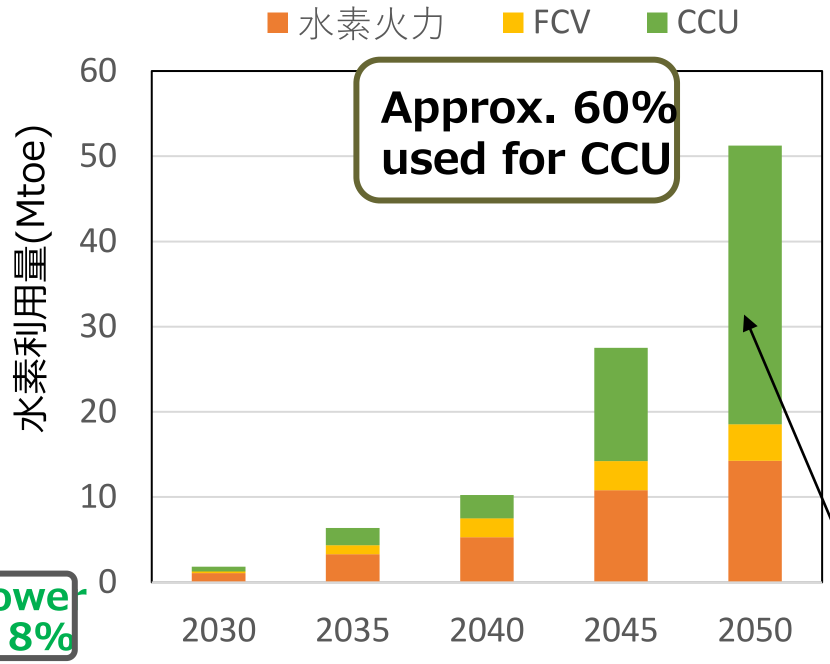
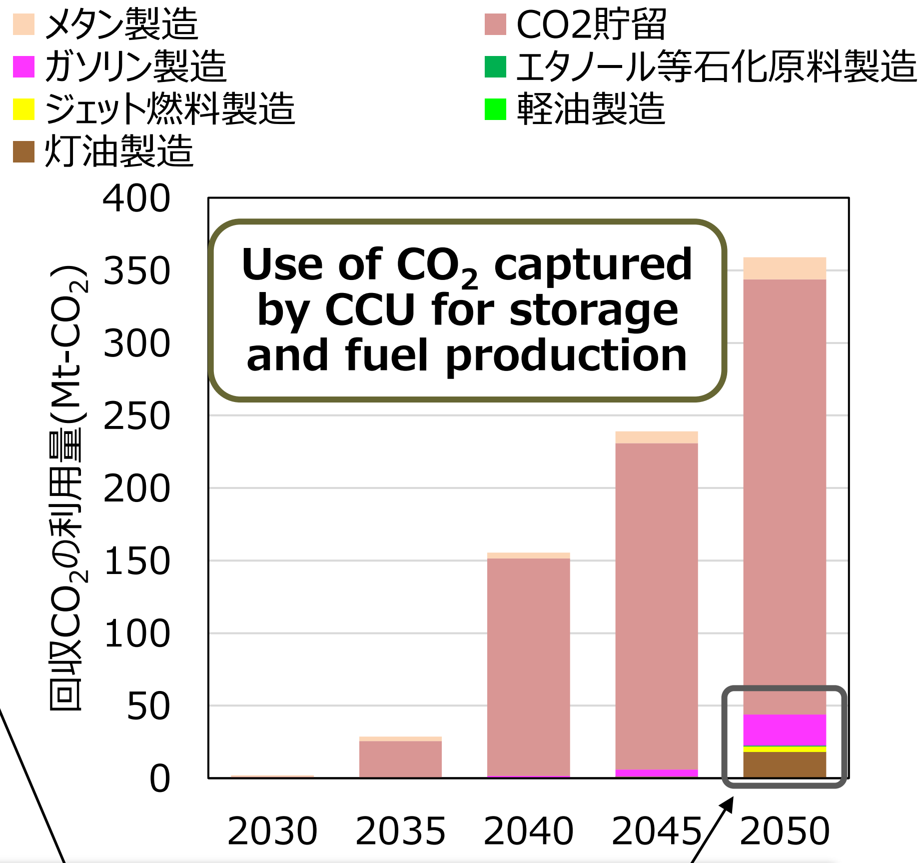
Contribution to resilience and security with hydrogen to produce new fuels from CO_2 in addition to power generation; introduction of 17 TWh of storage batteries; and ensuring stable power supply with nuclear power, etc.

Case1: Case of transitory fuel price hikes







Production of gasoline, kerosene, and other fuels from CO_2 and hydrogen

CCS: Carbon dioxide Capture and Storage, CCU: Carbon Capture and Utilization, FCV: Fuel Cell Vehicle

2-6. Changes in energy scenarios and insights gained

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1. **Changes in energy scenarios as fuel prices soar**
   - (a) Need to secure decarbonized power supplies at early stage (accelerate introduction of RE and use nuclear power, etc.).
   - (b) Diversification of hydrogen use: In addition to power generation, necessary to use hydrogen as a synthetic fuel.
   - (c) Efficient use of heat is necessary.

2. **Energy resilience, security**
   - (d) Resilience: Necessary to have medium- to long-term energy storage and stockpiling, e.g. 17 TWh of storage batteries.
   - (e) Security: Increase in energy self-sufficiency and having systems of international procurement and cooperation are critical.

Next, issues and measures for bulk power systems that support distribution of power are presented below.

3-1. Grid measures to prepare for rapid expansion of RE

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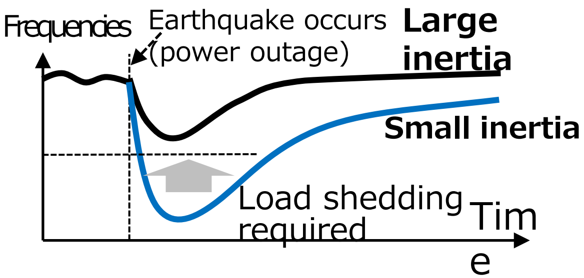
(2) What challenges do bulk power systems face in transition to carbon neutrality? Are there solutions?

1. Frequency degradation	2. Frequency fluctuations	3. Grid stability degradation

Challenges

1. Frequency degradation

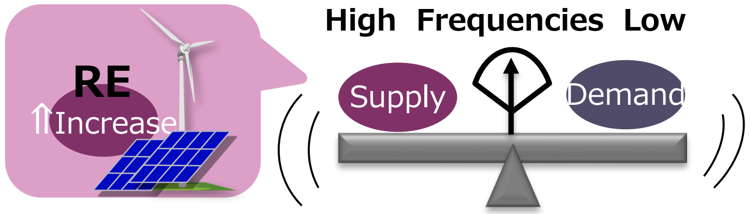
Frequencies degrade sharply when power supply stops during earthquake → Concerns about power supply disconnections and spread of outage areas



Inertia falls because of decrease in rotations for thermal power generation, etc.

2. Frequency fluctuations

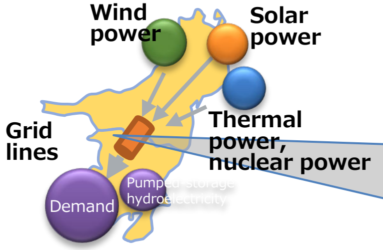
Concerns about frequency fluctuations due to supply-demand imbalance caused by rapid changes in RE output



Output fluctuation ⇒ Supply-demand imbalance ⇒ Frequency fluctuation

3. Grid stability degradation

Limited capacity to transmit unevenly distributed RE to energy demand areas

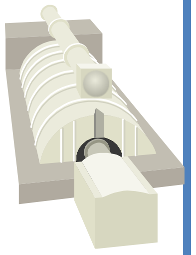


Limitations in power transmission due to grid stability and thermal capacity during lightning strikes

Solutions (proposed)

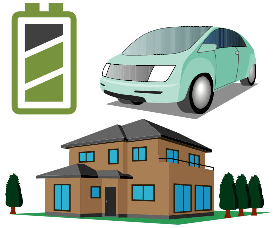
Increase in inertial

- “Low-power, multiple-unit” operation of thermal power units (new fuel, CCS); use of nuclear power units
- Deployment of “pseudo inertia control” and “synchronous regulator” for RE inverters

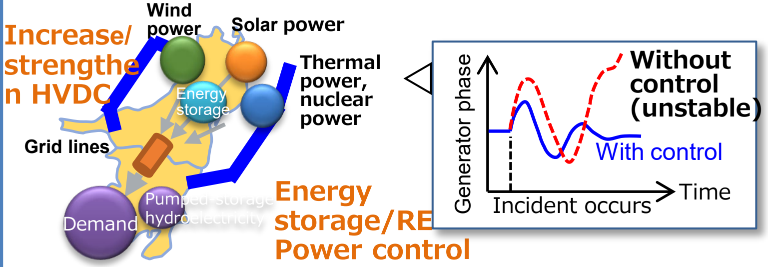


Ensure adjustment capacity

- Storage batteries and EV charging/discharging
- Control of electricity consumption (demand response)



Strengthening grid stability with HVDC and improvement of power control of distributed resources



3-2. Grid measures to prepare for rapid expansion of RE: (1) Frequency degradation

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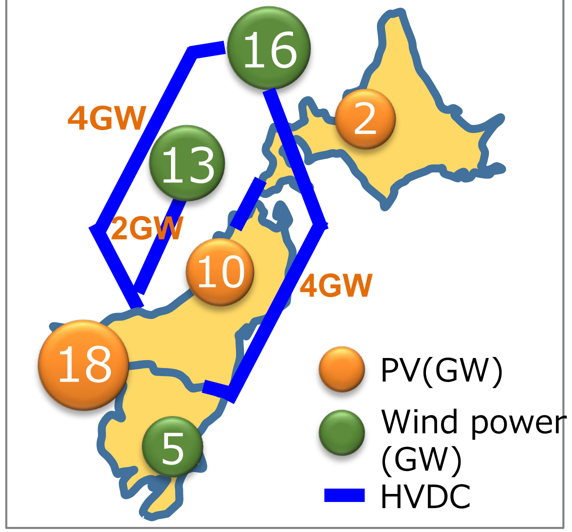
Challenge: Inertia decreases during times when RE generation is great, and frequencies degrade greatly during power supply outage.
Recommendation: To increase inertia, it is necessary to secure the number of rotating generators (thermal power, nuclear power, etc.).

Inquiry conditions

demand conditions from O・Grid:
Analysis of grid with modeling based on publicly available. information from power companies, etc.
・Assumption of generation and CCTO Master Plan power supply imbalance scenario (45 GW).
・Incident conditions: Simultaneous parallel offline of 7.1 GW of thermal power plants in Fukushima area.

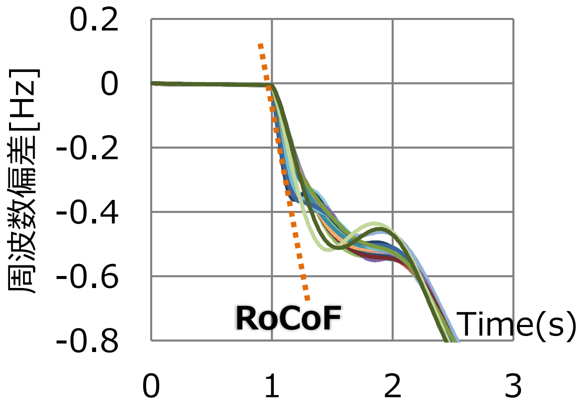
(~2030 – 40)

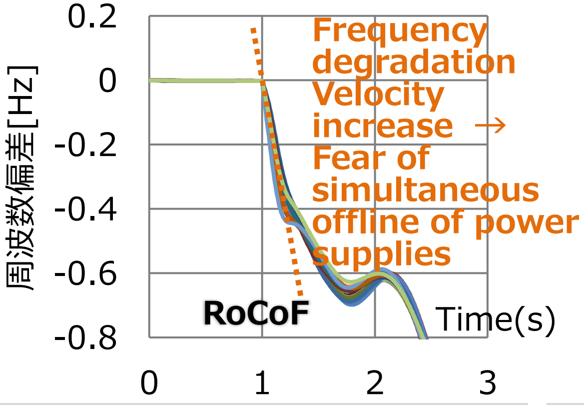


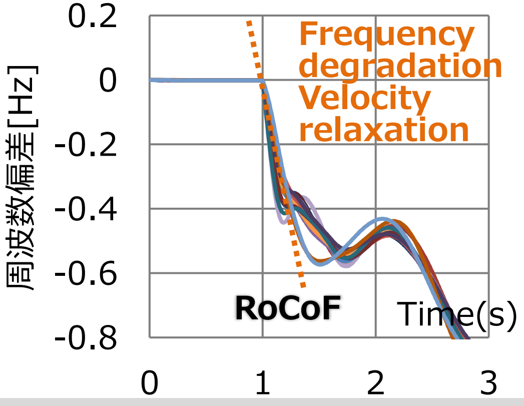
HVDC: High Voltage Direct Current

SNSP*1	**25% (nighttime, etc.)**	**75%** (Solar power gen. region)	**75%** (Solar power gen. region)
Inertia of grid	132 % (299 GWs)	100 % (227GWs)	**115 %** (261 GWs) (Increase number of rotators)

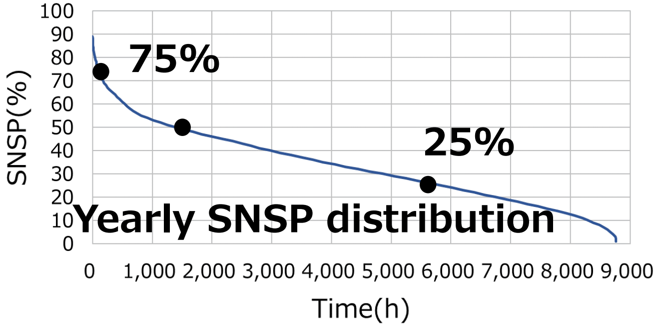
Generator frequencies (Tohoku)







RoCoF*2 (<2Hz)	**-1.5 Hz/s ○**	**-2.3 Hz/s ×**	**-1.96 Hz/s ○**



*1) SNSP: System Non-Synchronous Penetration
*2) RoCoF: Rate of Change of Frequency

Assuming severe conditions of scenario described above, simulations were conducted by choosing time periods from among 8760 hours per year. These time periods are times when it is difficult to maintain frequency (high SNSP) in the event of power outage.

Reference: "Master Plan (Interim)," Organization for Cross-regional Coordination of Transmission Operators, JAPAN (OCCTO)

3-3. Grid measures to prepare for rapid expansion of RE: (1) Frequency degradation

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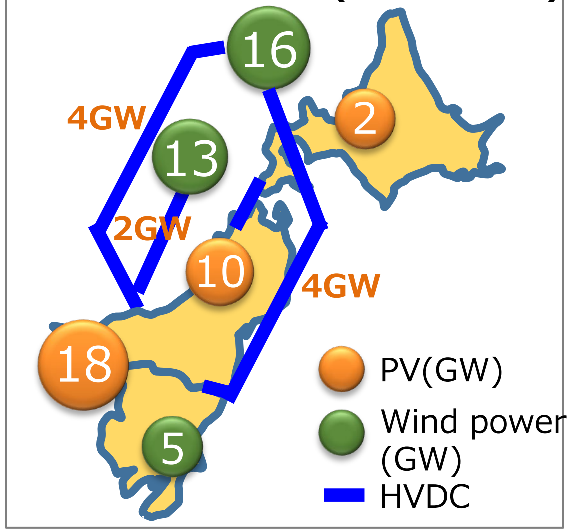
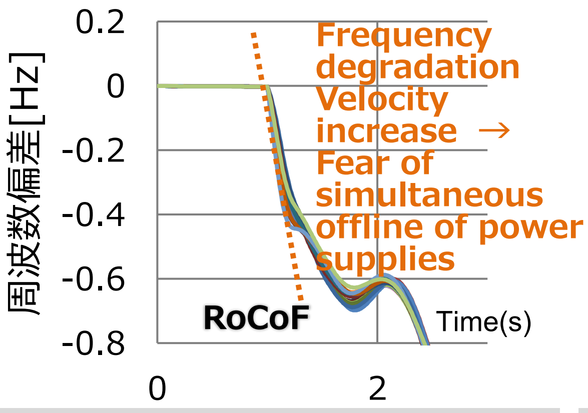
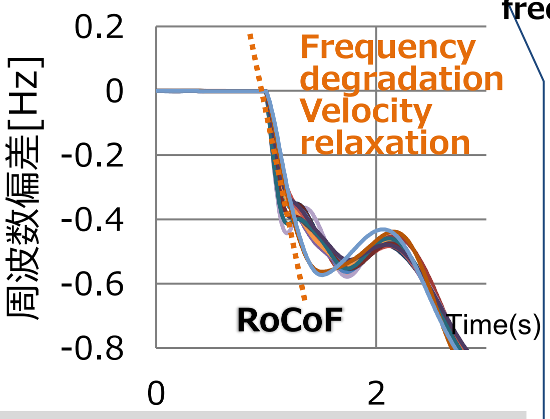
Challenge: Inertia decreases during times when RE generation is great, and frequencies degrade greatly during power supply outage.
Recommendation: Necessary to have inverter inertia control of RE and distributed resources to improve frequency degradation immediately after power outage.

Inquiry conditions

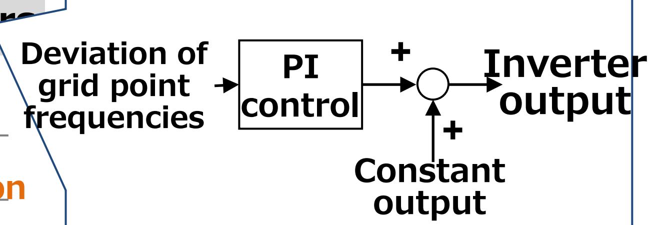
- Grid: Analysis of grid with modeling based on publicly available information from power companies, etc.
- Assumption of generation and demand conditions from OCCTO Master Plan power supply imbalance scenario (45 GW).
- Incident conditions: Simultaneous parallel offline of 7.1 GW of thermal power plants in Fukushima area.

(~2030 – 40)

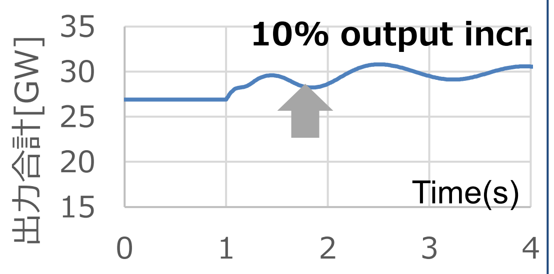


SNSP*1	75% (Solar power gen. region)	75% (Solar power gen. region)
Control	—	Inertial control of inverters
Generator frequencies (Tohoku)		
RoCoF*2 (<2Hz)	-2.3 Hz/s ×	-1.95 Hz/s O

Components of inverter control



Output of distributed resources (total)



◆Development challenges: Determination of inverter control method and parameters, control of increased RE output when output is suppressed.

SNSP: the System Non-Synchronous Penetration, HVDC: High Voltage Direct Current

Reference: "Master Plan (Interim)," Organization for Cross-regional Coordination of Transmission Operators, JAPAN (OCCTO)

3-4. Grid measures to prepare for rapid expansion of RE: (2) Frequency fluctuations

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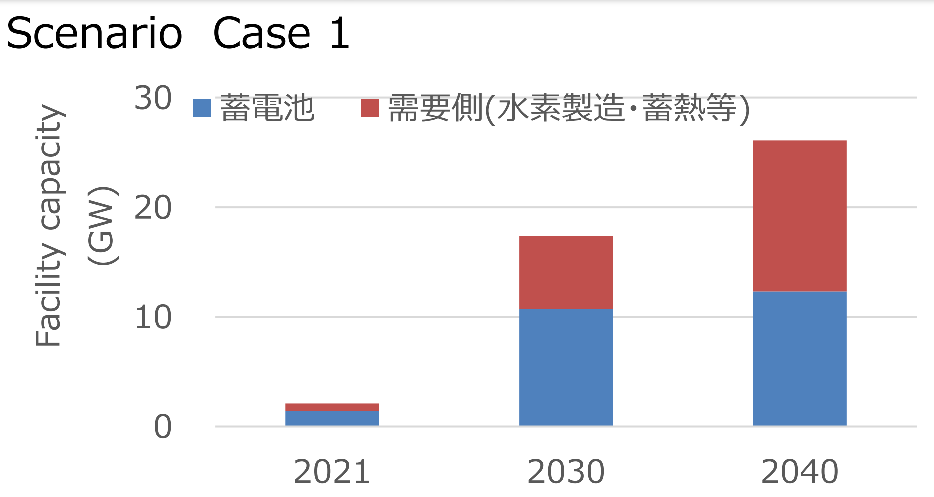
Challenge: Frequency fluctuations due to supply-demand imbalance caused by fluctuations in RE output, output suppression, and grid congestion during peak RE generation.
Recommendation: Necessary to ensure adjustment capacity while resolving grid congestion by utilizing distributed resources and guiding the placement of demand.

Example of calculation of necessary energy storage capacity



* Not incl. pumped-storage hydroelectricity
(Market size 4 trillion yen*1)

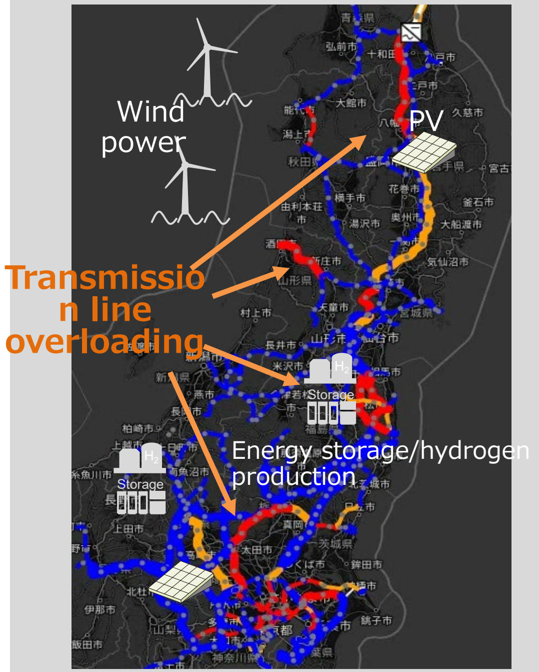
Points of optimization placement measures

- EV charging/discharging is effective measure against fluctuations in distributed PV.
- Guide demand with data centers, hydrogen production, etc., near generators.

Placement not considered

Uneven distribution of energy storage and hydrogen

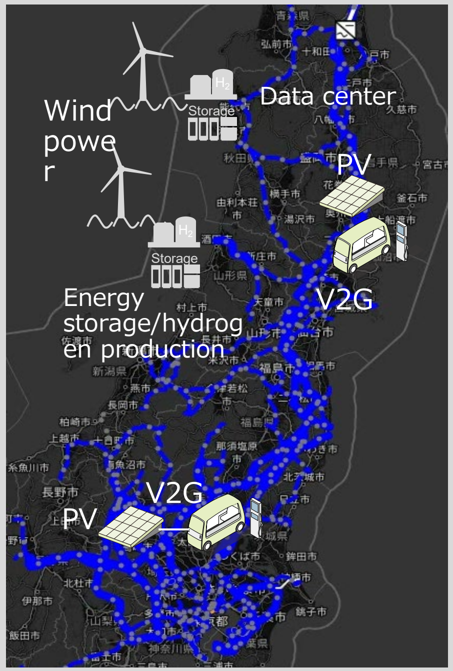
Transmission becomes congested and grid unstable



Optimization of placement

Installed near RE

Transmission line congestion elimination/stabilization



Working out of adjustment capacity in local communities will be presented in the next detailed report.

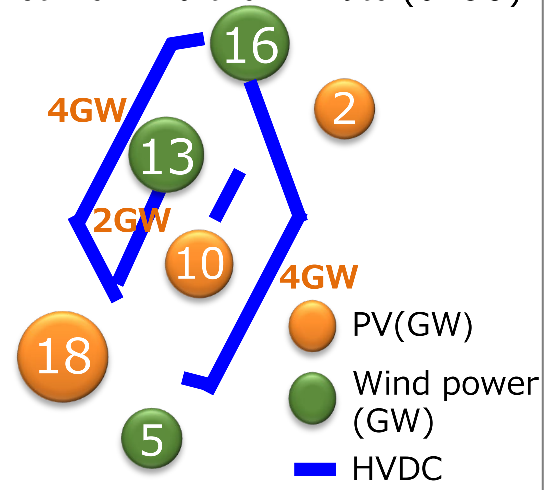
*1) Calculated based on a facility charge/discharge time of 4 hours and rate of 40 yen/Wh
WF: Wind Farm, PV: Photovoltaic, V2G: Vehicle to Grid, PV: Photovoltaic, HVDC: High Voltage Direct Current

3-5. Grid measures to prepare for rapid expansion of RE: (3) Degradation of grid stability

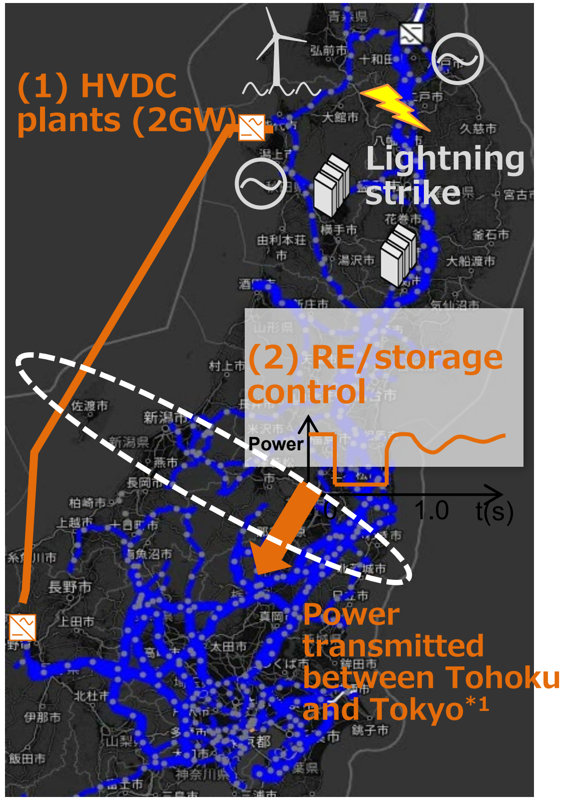
Challenge: Limited capacity to distribute uneven RE to energy demand areas.
Recommendation: Necessary to expand wide-area power transmission through increased transmission and grid stabilization.

Inquiry conditions

- Grid: Analysis of grid with modeling based on publicly available information from power companies, etc.
- Assumption of generation and demand conditions from OCCTO Master Plan power supply imbalance scenario (45 GW)
- Incident conditions: Ground fault on two lines due to lightning strike in northern Iwate (6LGO)

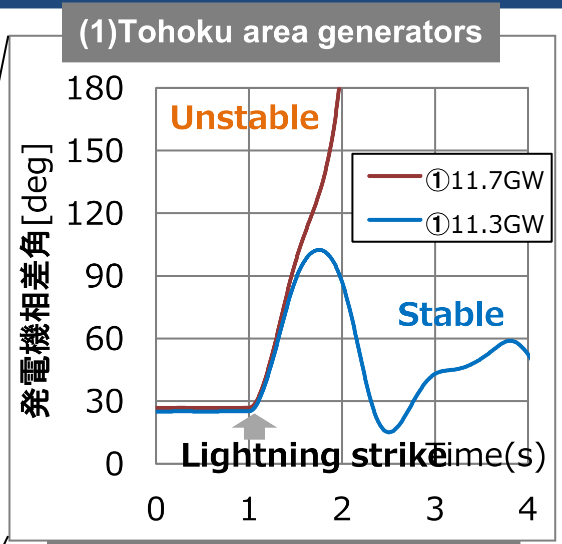


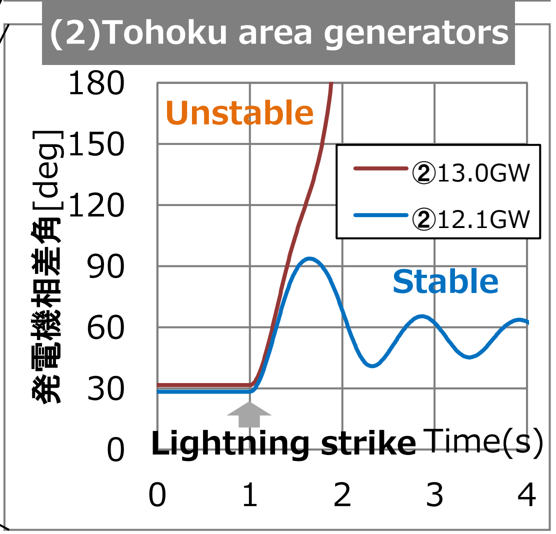
Cross-section of heavy flow current in Tohoku RE region and Kanto demand region



*1: With exception of 10GW (4+4+2GW) HVDC power sent from offshore wind power

#	Measure	Power transmitted between Tohoku and Tokyo
(a)	Base conditions (reinforcement of AC systems)	9.3 GW
(b)	Install HVDC 2GW	11.3 GW
(c)	Stabilization control of RE/storage	12.1 GW





HVDC: High Voltage Direct Current, 6LGO: 2 lines×3 phase ground contact fault

Reference: "Master Plan (Interim)," Organization for Cross-regional Coordination of Transmission Operators, JAPAN (OCCTO)

4. Conclusion

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1. Changes in energy scenarios as fuel prices soar

(a) Need to secure decarbonized power supplies at early stage (accelerate introduction of RE and use nuclear power, etc.).

(b) Diversification of hydrogen use: In addition to power generation, necessary to use hydrogen as a synthetic fuel.

(c) Efficient use of heat is necessary.

(d) Resilience: Necessary to have medium- to long-term energy storage and stockpiling, such as 17 TWh of storage batteries.

(e) Security: Critical are increasing energy self-sufficiency and having systems of international procurement and cooperation.

2. Challenges and measures in bulk power system to prepare for rapid expansion of renewable energy introduction

(1) Response to inertia reduction: Necessary to secure quantity of rotators and have inertial control of inverter-connected distributed resources.

(2) Ensuring adjustment capacity: Necessary to utilize local resources and have controls to prevent grid congestion.

(3) Ensuring grid stability: In addition to strengthening transmission, necessary to stabilize grid through regional energy storage and EV control.

EV: Electric Vehicle

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A1. Supply and demand simulation model by Fujii-Komiyama lab (University of Tokyo)

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- **Adopted a proven model as a tool for depicting the energy system when CN is achieved by 2050.**
- **Cost optimization calculations were performed for the energy supply-demand structure under constraints such as -46% by 2030 and CN by 2050.**

Overview of Fujii-Komiyama Lab's model: Energy technology selection model (dynamic cost minimization model).

- **Cost optimization calculations can be performed for the energy supply-demand structure based on CO_2 emission constraints** for the entire energy system in Japan.
  - Entire energy system (primary energy, conversion sector, final consumption sector [industry, household, business, passenger, freight]) is evaluated.
  - **Detailed analysis of the electricity sector** (time resolution -> 1 hour, 8,760 hours per year -> detailed consideration of RE output variability)
- **Analysis is performed by accumulating individual technologies on energy supply side** (primary/secondary energy) and **demand side** (steel, cement, chemicals, consumer, transportation, etc.). This allows **consistent analysis of the energy supply-demand structure during CN realization and its transitions (transition process)**.
- **A variety of technological elements including innovative technologies are considered**: next-generation cars (EVs, FCVs), energy storage (Li-ion, NAS batteries, thermal storage), CCUS (direct air capture, methanation, FT synthesis), energy carriers (hydrogen, ammonia, methanol, syngas, synthetic petroleum), power generation tech (hydrogen, ammonia, offshore wind power, fuel cells, thermal power storage), energy saving tech (heat pumps), etc.

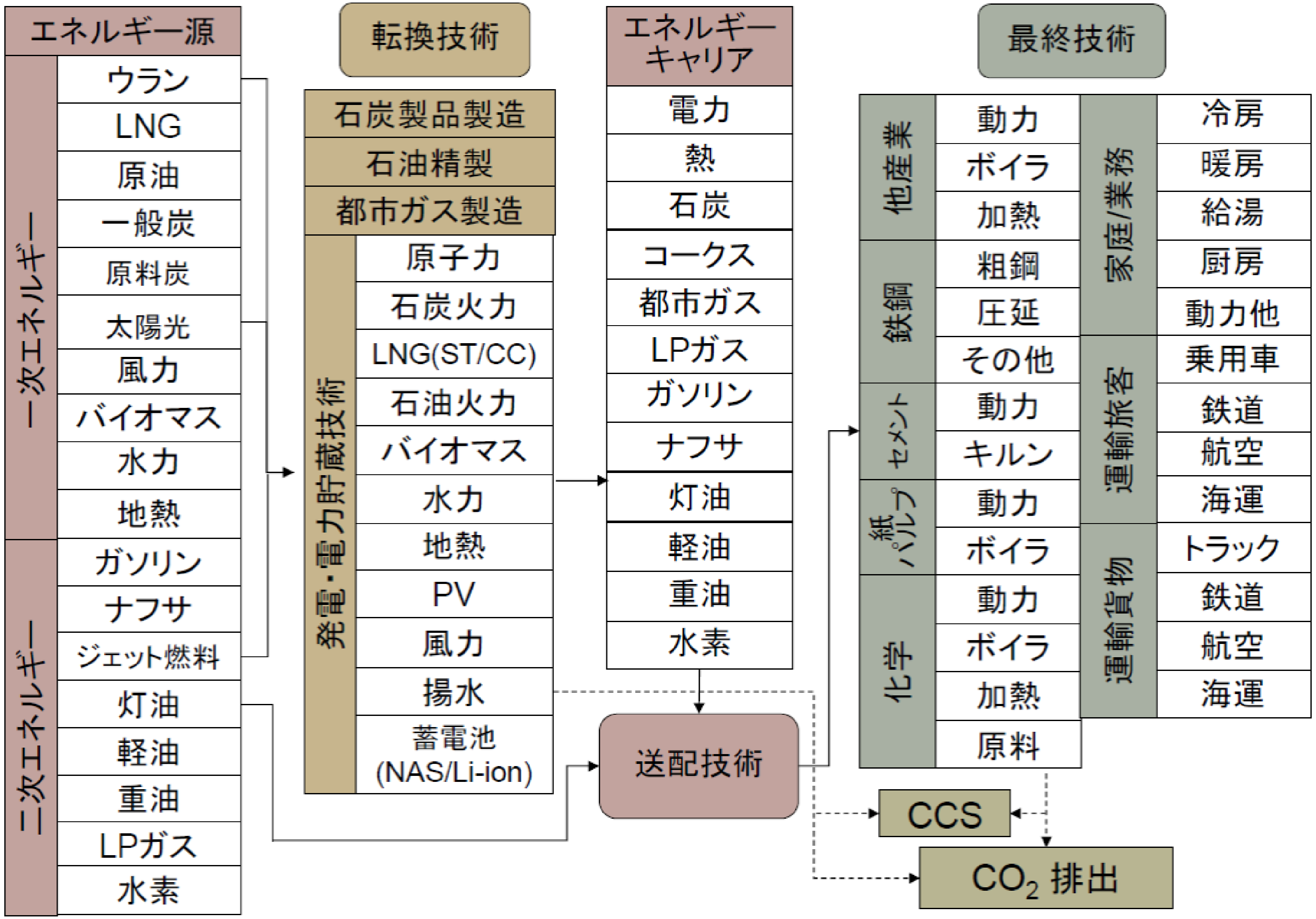
□ (Reference) <Results of Fujii-Komiyama lab's model

GAUC (Global Alliance of Universities on Climate Change) event (2021), ICEE (The International Conference on Electrical Engineering) panel session (2021), session of Japan Society of Mechanical Engineers (2021), report by Atomic Energy Society of Japan (2020), and other domestic and international academic sessions.

(References) Kawakami Y, Komiyama R, Fujii Y, IFAC-Papers Online 51(28)598-603 (2018); Kawakami, Komiyama, Fujii, IEEJ Transactions B, 138(5), 382-391 (2018)

CCUS: Carbon dioxide Capture, Utilization and Storage, FCV: Fuel Cell Vehicle, EV: Electric Vehicle, FT: Fischer-Tropsch, CN: Carbon Neutrality, LiB: Lithium-ion Battery

Overview of energy system covered by the Fujii-Komiyama lab’s model



- Model covers entire energy system from energy production (import) to conversion, transmission, distribution, and consumption in final demand sector.
- Model is constructed as optimization model that minimizes total system cost for targeted period.

CCUS: Carbon dioxide Capture, Utilization and Storage

A3. Simulation conditions: Consideration of technological innovations

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- **Assumption: All major decarbonization tech (RE, nuclear, hydrogen, CO_2 capture) are deployed.**
- **Cost-optimized simulations for 2050 CN and transitions.**

CO_2 emissions (reduction targets)	2030: Compared to 2013 -46 % 2050: Net zero (-100 %)

Power generation/tech deployment conditions (2050)

Solar power (PV): New installations and no upper limit on capacity
JPEA's target is 300 GW in 2050 (*1)

Wind power: New construction with target of 40 GW for onshore and 90 GW for offshore turbines .
Targets proposed by JWEA to government (*2)

Nuclear power: New installations with upper limit of 50 GW
・Restart of existing plants / extension of operational life (from 40 to 60 years) (excluding plants to be decommissioned).
・Completion and start of three new plants (currently halted construction).
・New construction of SMRs, etc.

Hydrogen power: Import volume: 20 million t / Import price: 20 yen/Nm3
Target values in "Green Growth Strategy Through Achieving Carbon Neutrality in 2050" (*3)

Conditions for CO_2 capture tech deployment
Introduction of CO_2 capture tech to reach emission reduction targets
CCS (Carbon Capture, Utilization & Storage)
DAC (Direct Air Capture of CO_2)

(*1) JPEA (8 Mar. 2021 materials) https://www.meti.go.jp/shingikai/enecho/denryoku_gas/saisei_kano/pdf/026_05_00.pdf
(*2) JWPA (24 Mar. 2021 materials) https://www.enecho.meti.go.jp/committee/council/basic_policy_subcommittee/039/039_008.pdf
(*3) "Green Growth Strategy Through Achieving Carbon Neutrality in 2050" https://www.meti.go.jp/policy/energy_environment/global_warming/ggs/pdf/green_honbun.pdf

CN: Carbon Neutrality, SMR: Small Modular Reactor, PV: Photovoltaic

A4 Case 1: Calculation results for case of transient fuel price hikes (electricity generated)

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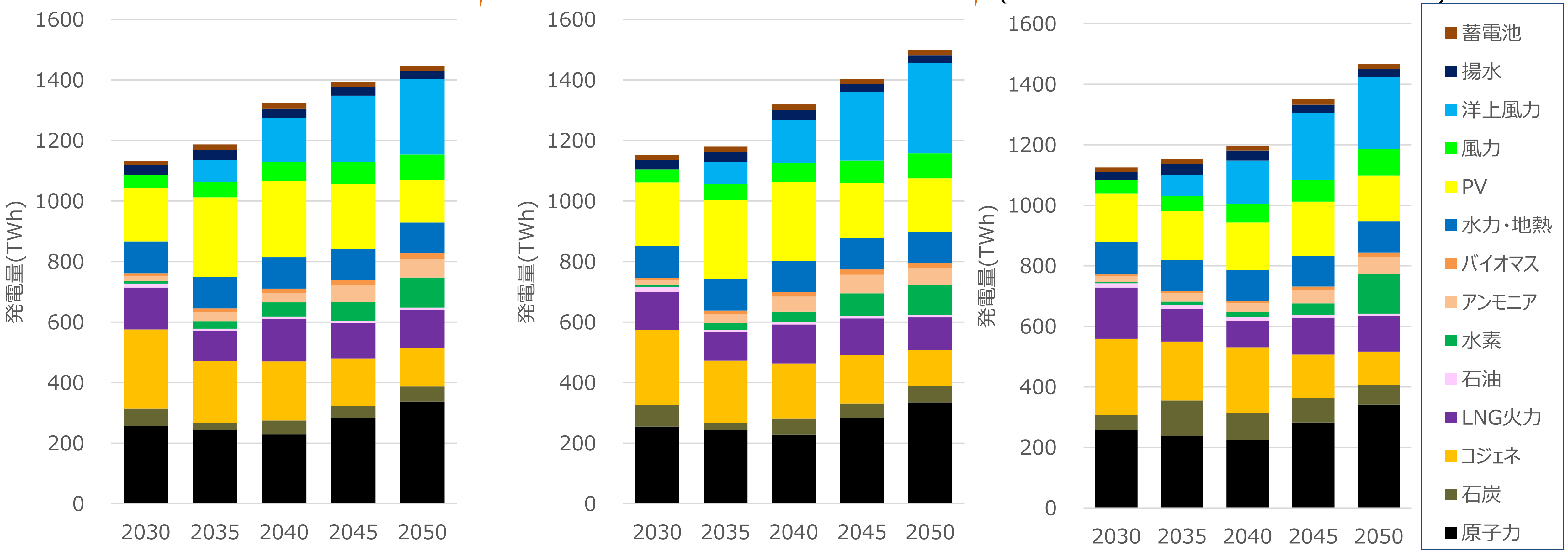
(3) Nuclear energy use case: Electricity generated

Case 0: Long-term outlook before invasion of Ukraine (4th Forum Report)

Case 1: Transient fuel price hikes (Reflecting sharp rise in fuel prices)

Case 1′: Fuel price hike + correction by forecast (Reduction of PV waste from Case1′)



A5. IEA's adjustment of amount of RE deployed and issues

HITACHI
Inspire the Next

Innovation is needed to solve issues in IEA's Phase 4 – 6 to achieve CN

Issue	Phase	% RE	Overview of phase	Candidate measures
	Phase 1	~5%	No significant impact of RE on power grid	・Real-time monitoring and control ・Expansion of transmission capacity
Micro corrections for systems	Phase 2	~10%	Slight impact of RE on operation of power grid	
Major change in trends	Phase 3	~20%	RE output determines grid operation	・Wide-area coordination of supply-and-demand operations ・Flexible power output control ・Power grid stabilization system
Flexible supply adjustment	Phase 4	~45%	Timing for 100% RE	・Restricting interconnections of asynchronous power ・Improved pumped-storage hydroelectricity ・High-speed frequency response ・Electricity storage systems
Long-term excess/deficiency of energy	Phase 5	~70%	Excess RE on daily basis (storage of electricity)	・Hydrogen/large-scale electricity storage (multiple days)
Power storage based on season	Phase 6	~100%	Excess RE on seasonal basis (hydrogen)	・Long-term storage of hydrogen and new fuels

Need for development/proliferation

* Created by H-TokyoU Lab as addendum based on [1] IEA, "Integrating variable renewables: Implications for energy resilience," Asian Clean Energy Forum 2017, [2] IEA, "Status of Power System Transformation 2019"

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