# Power Supply and Demand for Decarbonized Society:

# Trade-offs between Increase in Storage Batteries and Strengthening Grid Capacities to enhance Renewable Energy Use in Japan

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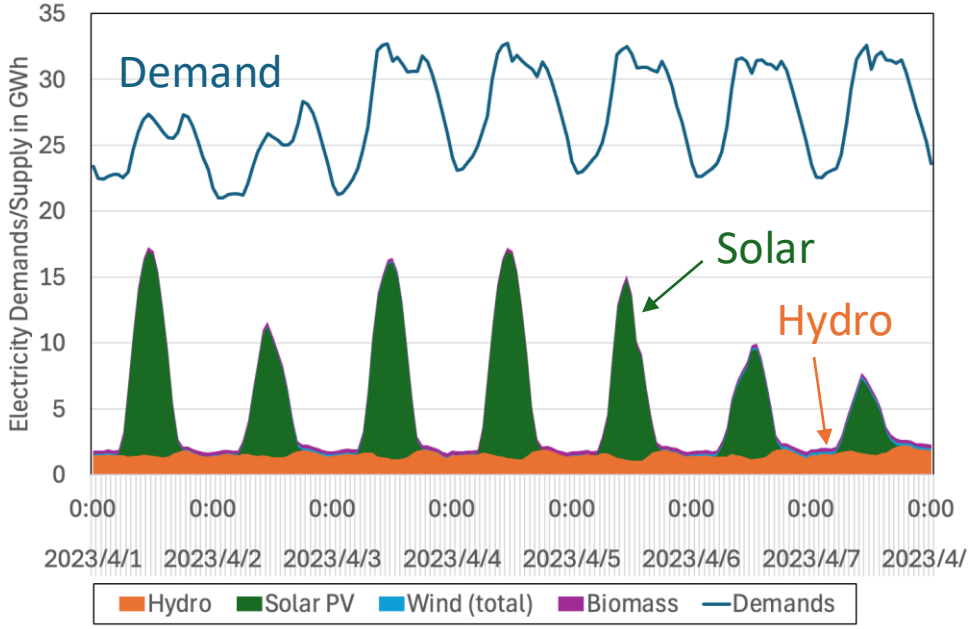
This presentation includes research outcomes by Environment Research and Technology Development Fund (ERTDF, JPMEERF20201002, JPMEERF20201003, JPMEERF20221002 and JPMEERF20231002) of Environmental Restoration and Conservation Agency and Ministry of the Environment, Japan, and Decarbonized and Sustainable Society Research Program of NIES.

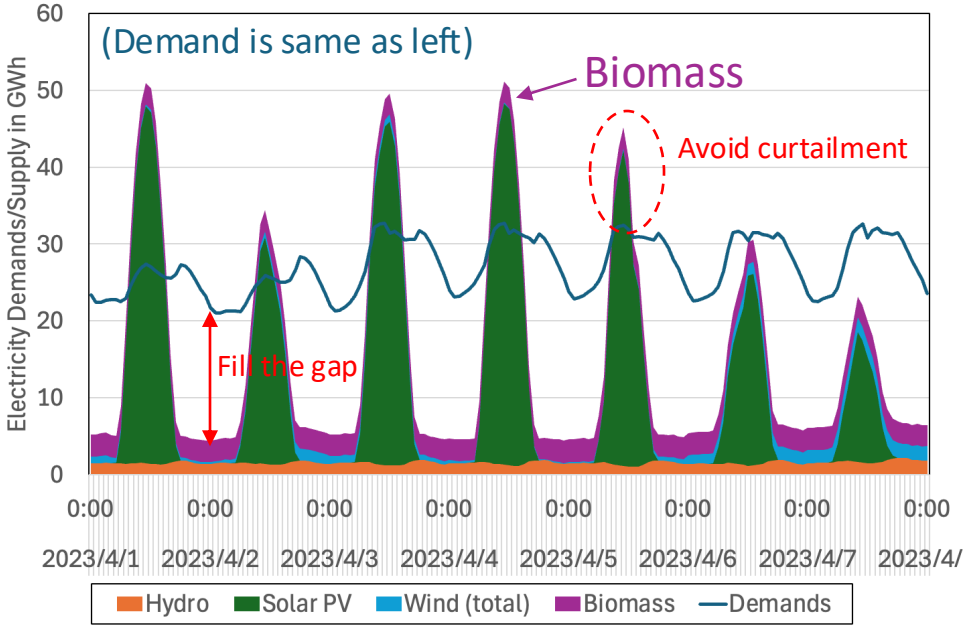
# Motivation: How to Match Electricity Demands and Renewable Supply on an hourly basis?

- Renewable outputs may not match hourly demand pattern.
- How to fill the gap, or to avoid curtailment?

Actual Demand and Renewable Supplies in TEPCO Area



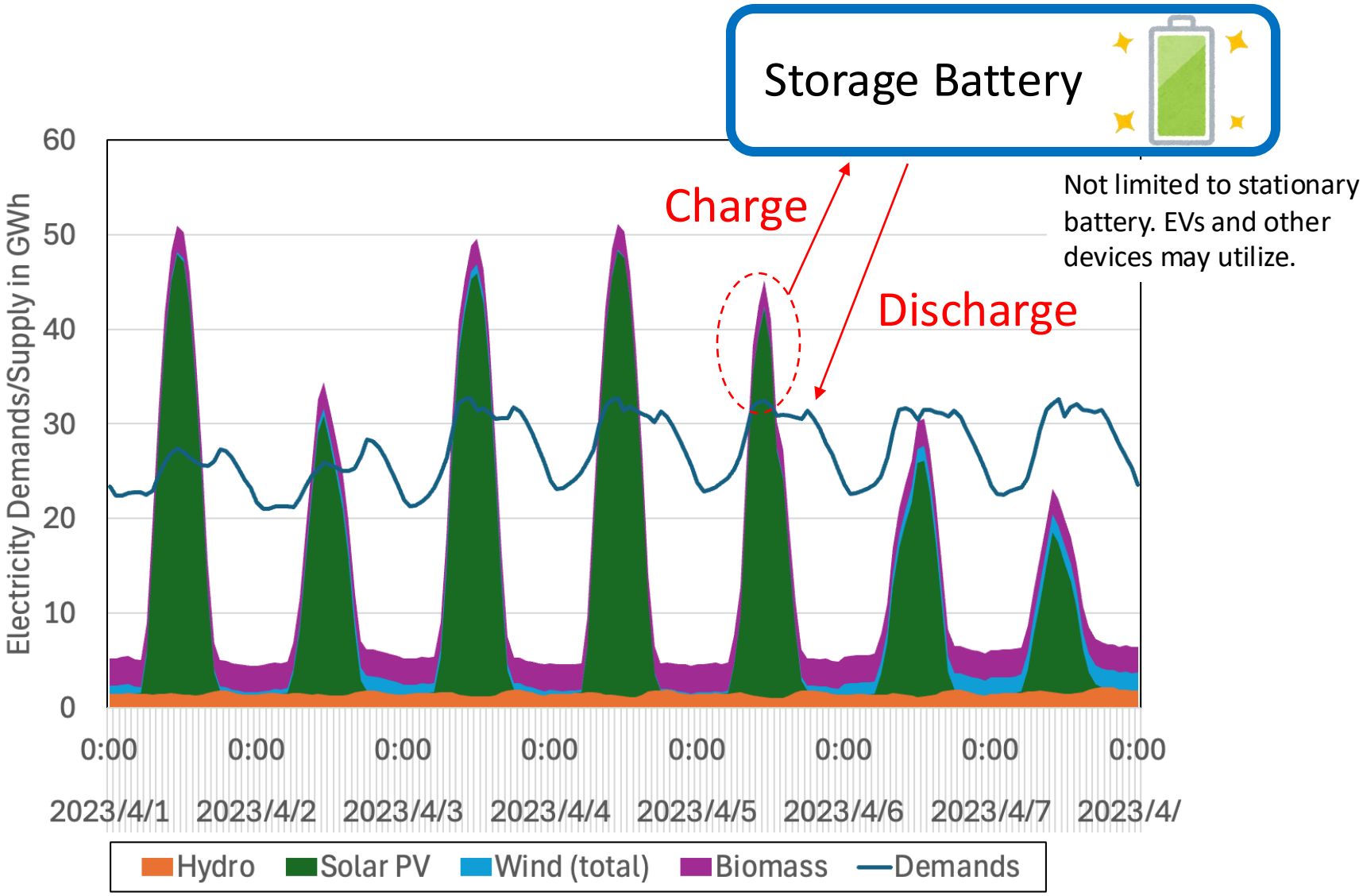

**IF**: Solar PV increases 3-fold, Wind and Biomass will be 10-fold




Data range: 0:00 April 1 to 0:00 April 8, 2023

Source of the Data: Demand-Supply Data in TEPCO area https://www.tepco.co.jp/forecast/html/area_jukyu_p-j.html

# Measures to keep balance (1): Use of Storage Battery




Modified based on Demand-Supply Data in TEPCO area https://www.tepco.co.jp/forecast/html/area_jukyu_p-j.html

# Spatial distributions of Renewables in Japan

Solar PV potentials in MW

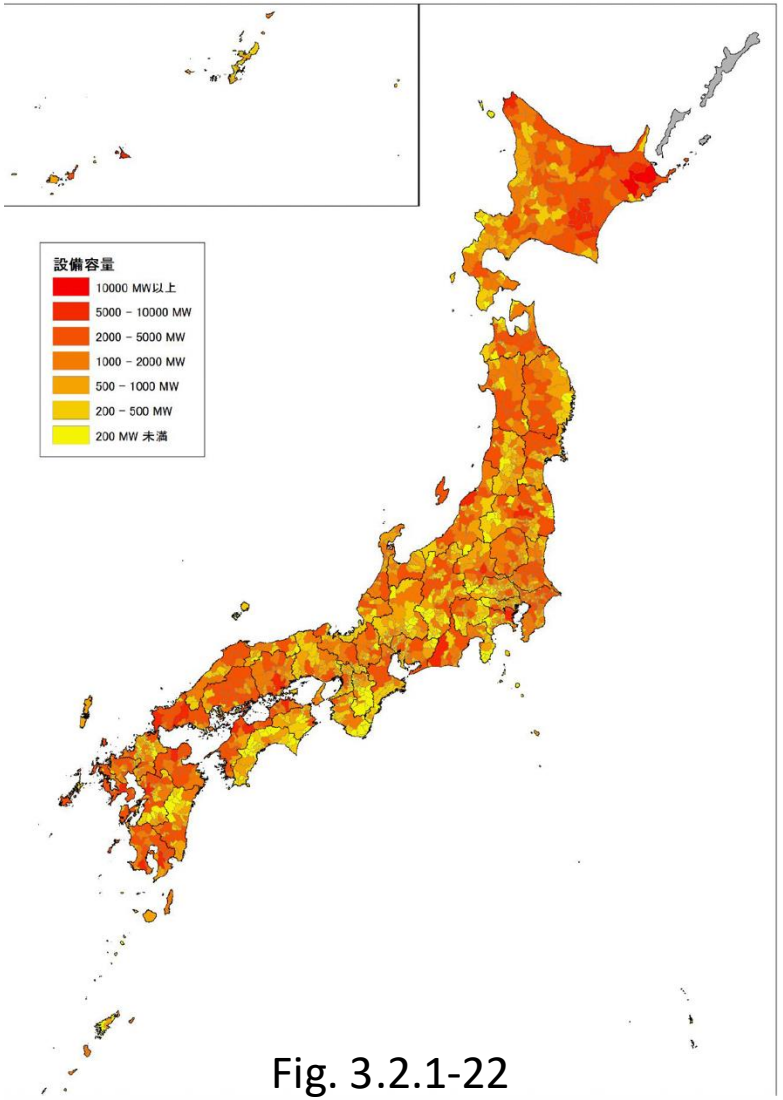
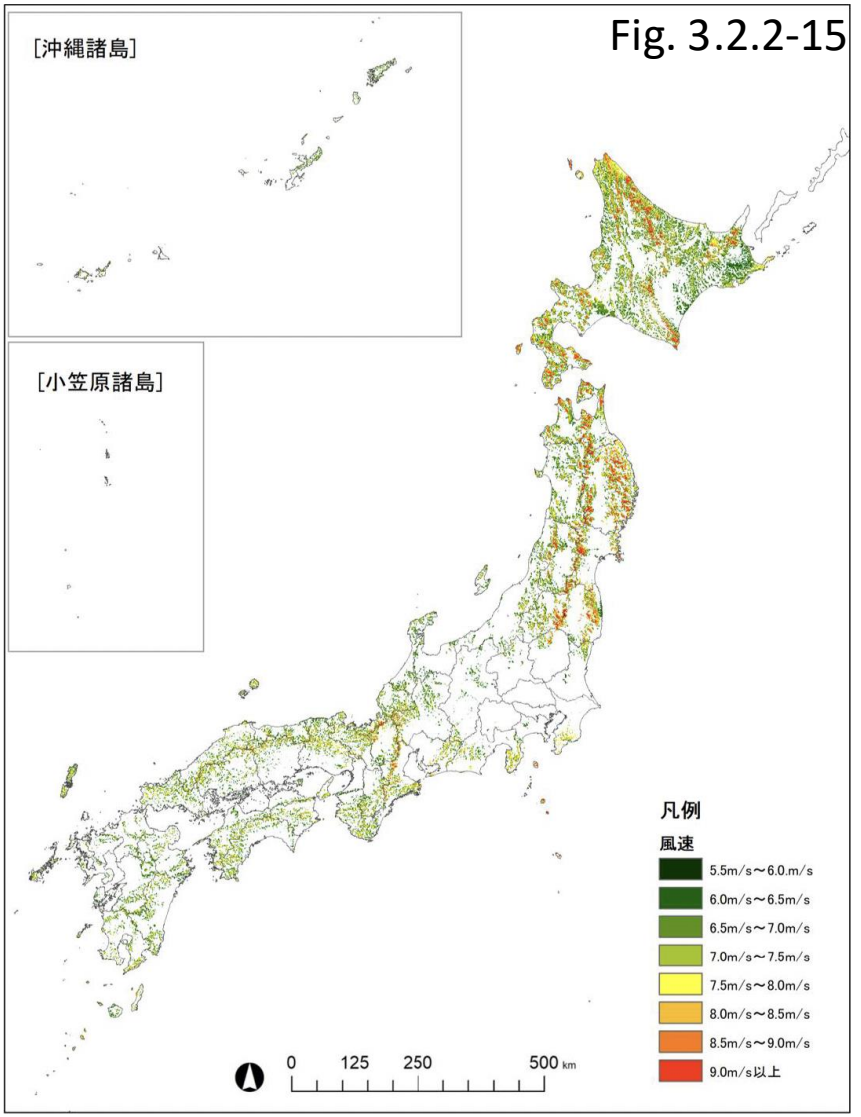



Fig. 3.2.1-22

Onshore Wind potentials in average m/s

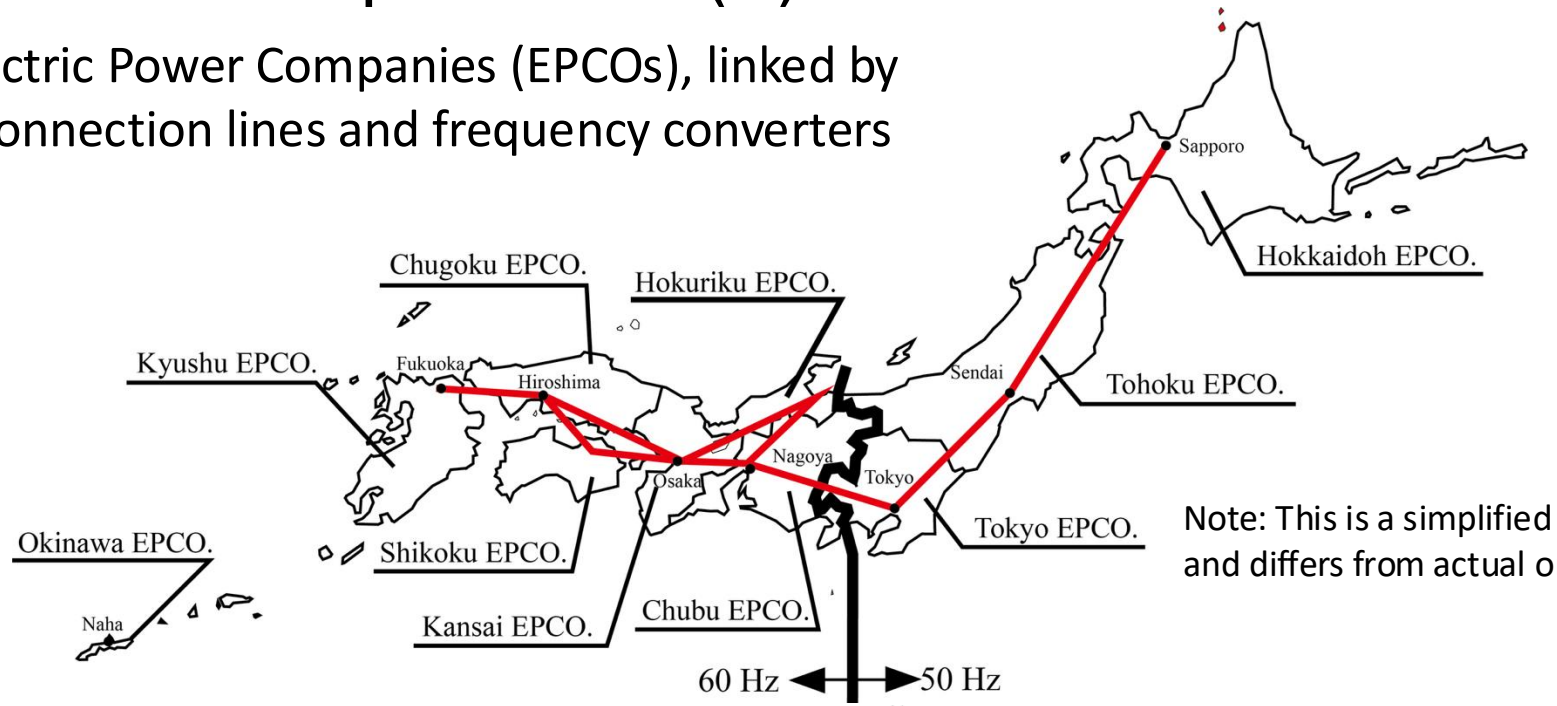
Fig. 3.2.2-15



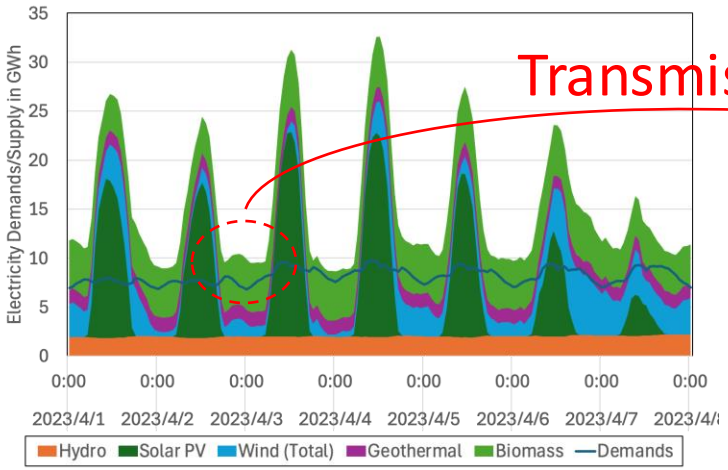

Source: Ministry of the Environment, Japan: Renewable Energy Potential System (REPOS)
https://repos.env.go.jp/web/data/reportdetail/r03

# Measures to keep balance (2): Transfer to/from other area

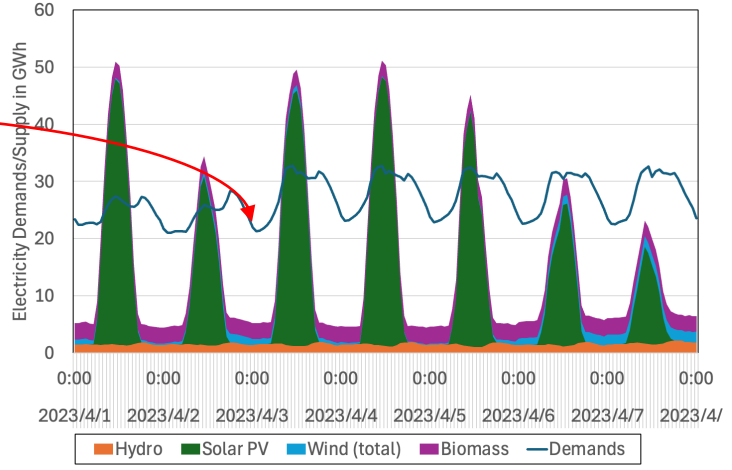
10 Electric Power Companies (EPCOs), linked by interconnection lines and frequency converters




Note: This is a simplified network, and differs from actual one.




Transmission




Modified based on Demand-Supply Data in Tohoku area https://setsuden.nw.tohoku-epco.co.jp/download.html and TEPCO area https://www.tepco.co.jp/forecast/html/area_jukyu_p-j.html

# Objectives of this study

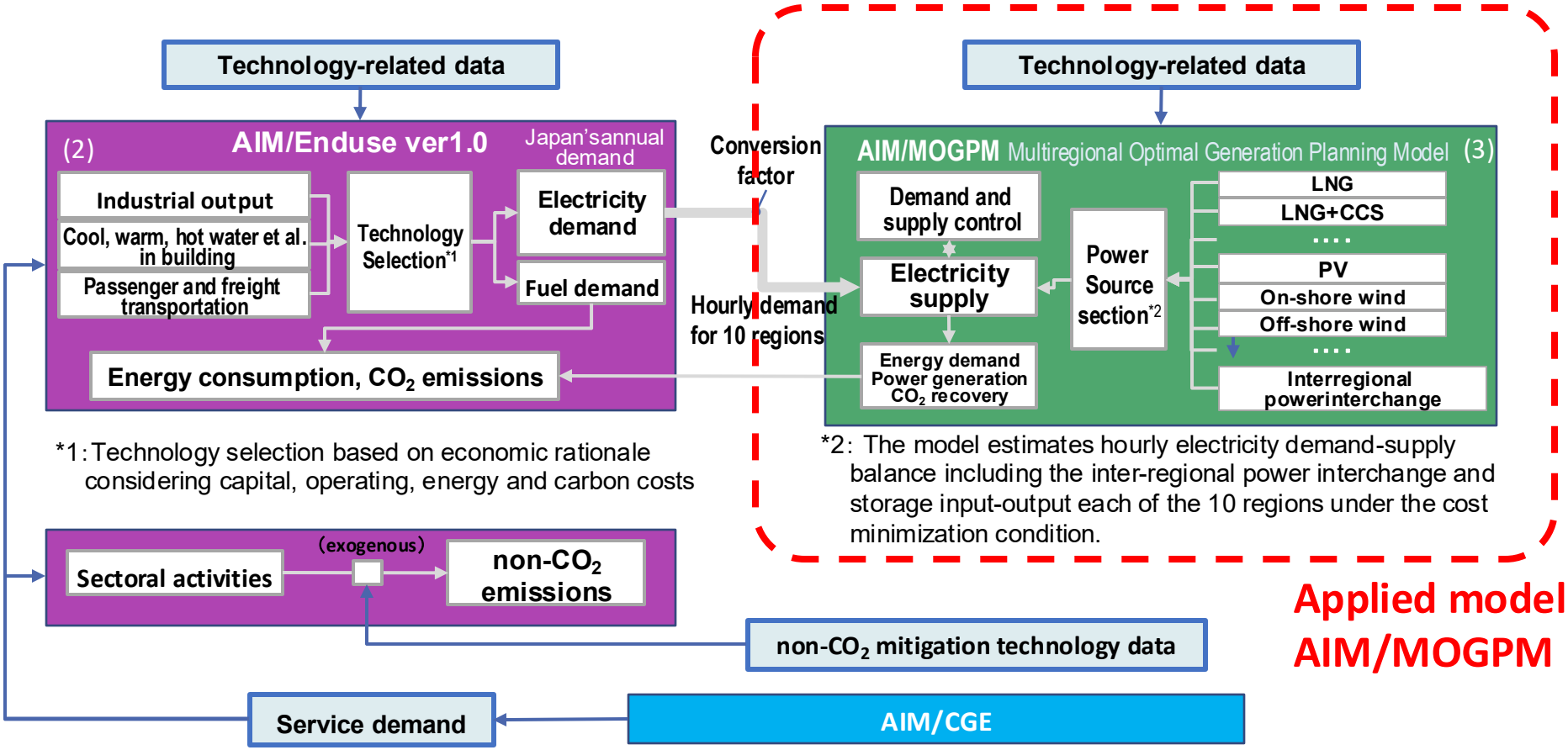
- Investigating trade-offs between increase in storage batteries and strengthening grid capacities to enhance renewable energy use in Japan's electricity sector.

[Key assumption]

- Macro-frame settings, CO2 emission pathways, electricity demands, limits of renewables and other major conditions are come from AIM's Japan net-zero GHG analysis.

# Models for Japan net-zero GHG analysis

- An applied general equilibrium model is used to establish a macro-frame for the future, given the economic growth rate and population assumptions (1). Next, future energy demand is estimated using an energy demand model (2). The annual electricity demand estimated in (2) is expanded to hourly demand by region, and the generation facility configuration and supply configuration are estimated using a cost-optimized power supply model that can take into account coincidence constraints and inter-regional interconnection line constraints (3). The results are fed back into the energy demand model to calculate Japan's overall energy supply and demand and $CO_2$ emissions.



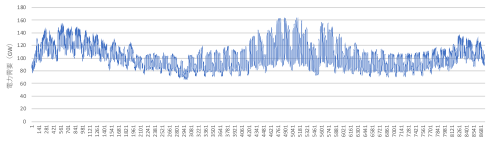
# Overview of AIM's Power Plant Model (AIM/MOGPM)

- The model designs long-term electricity generation (**capacity expansion**) and **grid planning** as well as **system configuration and their dispatches** with renewables while maintaining supply and demand on an hourly basis.

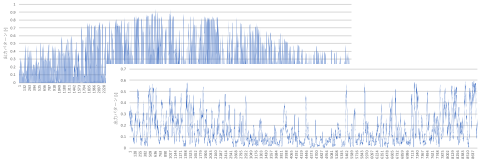
- **Key features** of the model:
  1) **Hourly-basis**: the model finds hourly operation of power plants as well as storages (batteries).
  2) **Grid network (Location)**: The model analyzes required capacity and investment plan of grid network to encourage use of renewables.

**Key inputs of the AIM/MOGPM**

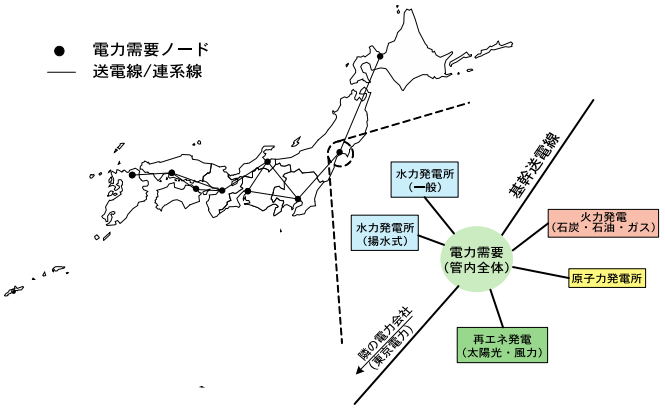
Hourly Demands



Hourly Outputs of Renewables



Grid Network / Power Plant Location



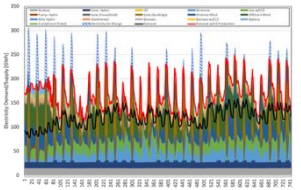

Other Parameters

Efficiency, Ownuse, Capital and O&M costs, Fuel costs etc.

Cost Min.

**Outputs**

- Hourly demand-supply Balance



- Annual generation
- Capacities of power plants
- Capacities of grids and configuration of network
- GHG emissions
- Costs for power plants and generations

Refs of the model: Gao and Ashina (2022) https://doi.org/10.1016/j.jclepro.2021.129828 / Shiraki et al. (2015) https://doi.org/10.1016/j.jclepro.2015.09.079

# Selected Scenarios

・Following cases for Innovative Technology Scenario and Social Transformation Scenario were assumed for the share of renewable energy generation in power generation and the share of domestic production of new fuels.

| | | Technology Progress | | Innovative Technology | | Social Transformation | | |
|---|---|---|---|---|---|---|---|---|
| | | Scenario I | Scenario I-a | Scenario II | Scenario III | Scenario III-a | Scenario III-b | Scenario III-c |
| Contributuin to policies | NDC | ○ | ○ | ○ | ○ | ○ | | |
| | Energy Master Plan | ○ | | | ○ | | ○ | ○ |
| Outline | | | Innovative technologies after 2040 | Low RE Low CCUS | Low RE Low CCUS | Early implementation | Low RE High CCUS | High RE Low CCUS |
| Innovative technoloigies | | | △ | | | ○ | | |
| Social transformation | | | | | | ○ | | |
| Electrification | | Continuing NDC | Acceleration after 2040 | | Acceleration after 2030 | | | |
| Progress of energy saving technologies | | Low | High after 2040 | | | High | | |
| Upper limits of renewable energies (GW) | PV | 160/209 | 160/209 | 160/209 | 160/209 | 185/209 | 160/209 | 201/384 |
| | Wind | 15/45 | 15/45 | 15/45 | 15/45 | 25/45 | 15/45 | 45/179 |
| New fuels ($H_2$, synfuel & $NH_3$) | Upper limit to fuel demand | 0%/0% | 0%/100% | 25%/100% | 25%/100% | 25%/100% | 25%/100% | 25%/100% |
| | self-sufficient ratio | — | 10% | 10% | 10% | 10% | 10% | 30% |
| Nuclear power | | | | | 140TWh | | | |
| GHG emission in 2050 | | 70% reduction to 2013 level | | | GHG net-zero | | | |
| GHG emission pathway | | | Convex upward | Linear | Linear | Convex downward | Linear | Linear |
| CO2 price (1000 JPY/$tCO_2$) | | 0 | 10/40 | 10/40 | 10/40 | 20/40 | 10/40 | 10/40 |
| Upper limit of $CO_2$ storage | | 0 | 6/120 | 27/120 | 27/120 | 82/120 | 27/200 | 27/120 |

"*/*" show the values in 2040 and 2050, respectively.

# Analyzed cases

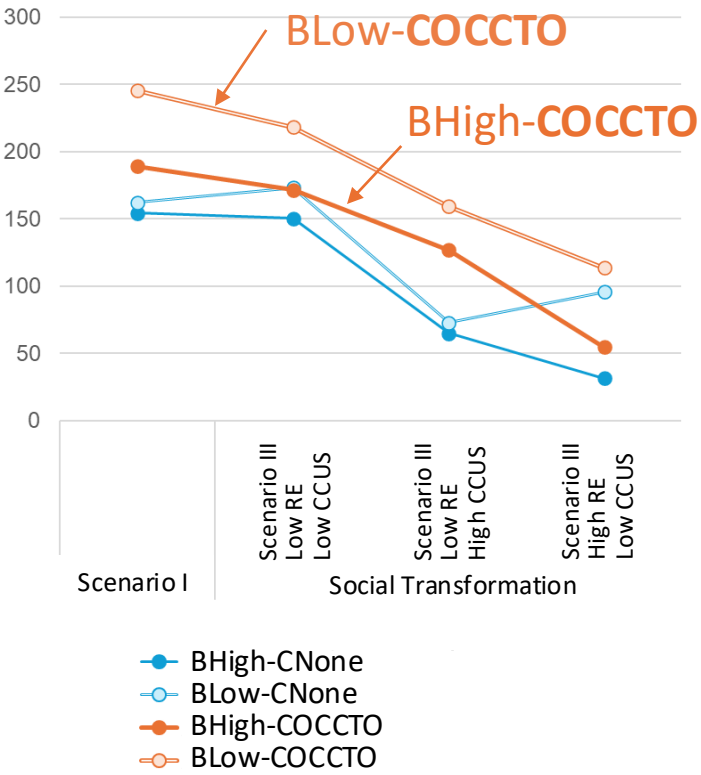
| | | Battery cost in 2050 | |
|---|---|---|---|
| | | Low ($120/kWh)*1 | High ($226/kWh) *2 |
| Upper limit of interconnection lines | | | |
| | None | BLow-CNone | BHigh-CNone |
| | Planned capacity in OCCTO's master plan*3 | BLow-COCCTO | BHigh-COCCTO |

*1: IEA World Energy Outlook 2024
*2: NREL USDOE Cost Projections for Utility-Scale Battery Storage: 2023 Update
*3: Organization for Cross-regional Coordination of Transmission Operators (OCCTO), Japan, "Master Plan for Wide-Area Interconnected Grid" (in Japanese), March 2023, https://www.occto.or.jp/kouikikeitou/chokihoushin/230329_choukihoushin_sakutei.html

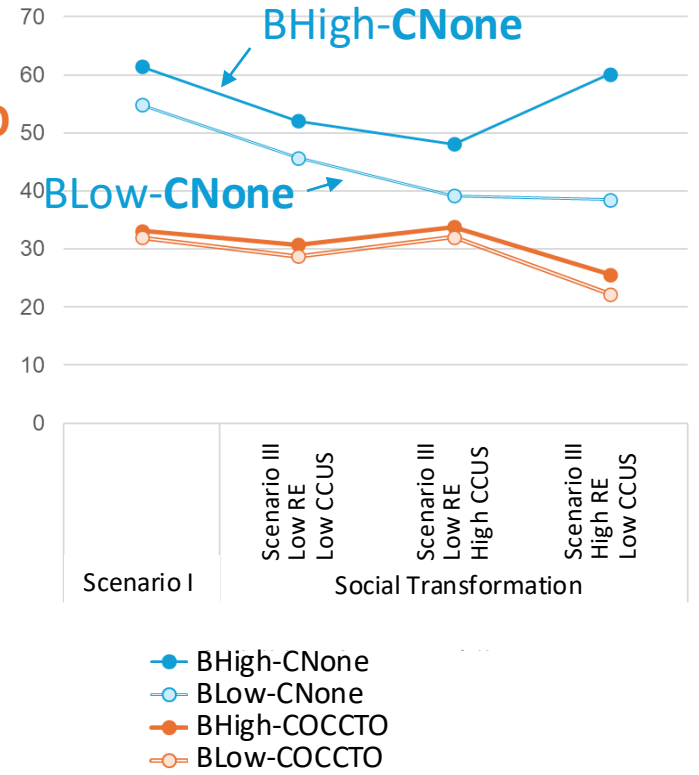
# Results in Capacities and Curtailment

- Trade-offs between storage battery and interconnection lines.
- Cheap battery would lead to suppress investments to interconnection lines.
- We will accept certain level of curtailment under large-scale penetrations of renewables.

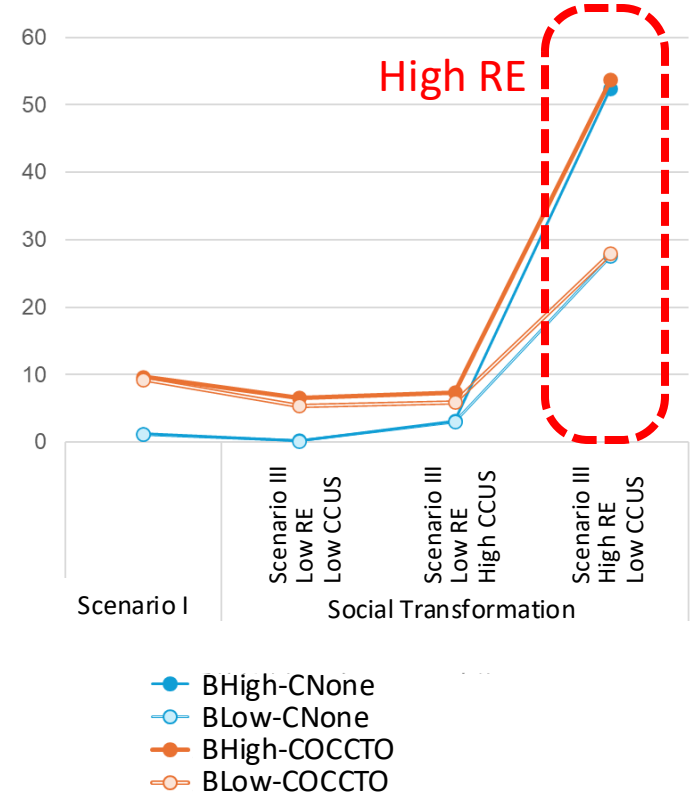
Additional Capacities in Storage batteries [GW in 2050]




Additional capacities in interconnection lines [GW by 2050]



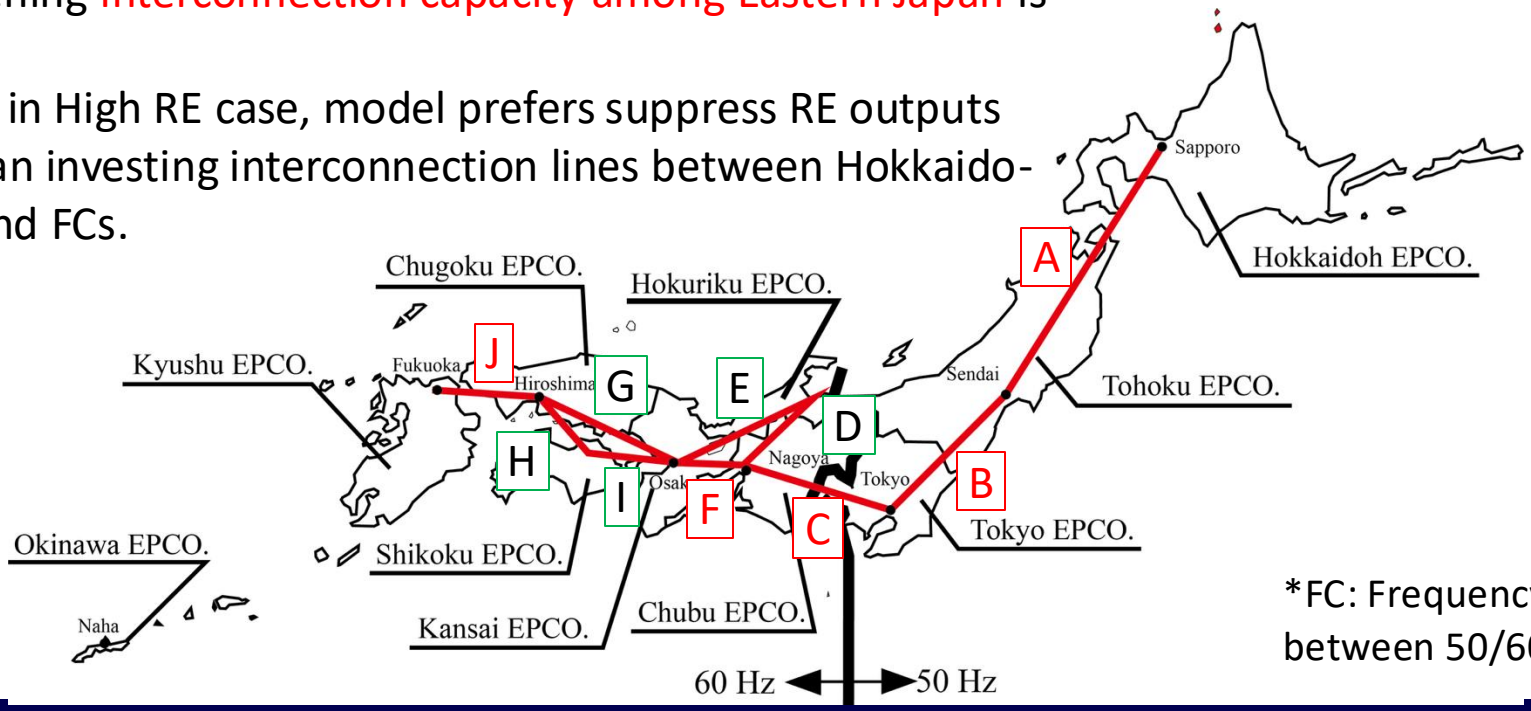

Curtailment [TWh in 2050]



# Results in Line Capacities: Comparison in CNone case

| (Additional Capacity by 2050 in GW) | Scenario I | | Scenario III Low RE High CCUS | | Scenario III High RE Low CCUS | |
|---|---|---|---|---|---|---|
| | BLow | BHigh | BLow | BHigh | BLow | BHigh |
| A: Hokkaido-Tohoku | 16.1 | 17.8 | 16.8 | 17.5 | 0.3 | 2.0 |
| B: Tokyo-Tohoku | 21.1 | 22.7 | 20.7 | 21.3 | 20.3 | 23.3 |
| C: Tokyo-Chubu (FC*) | 4.1 | 5.5 | 2.9 | 3.2 | 0.0 | 0.3 |
| F: Chubu-Kansai | 4.2 | 5.2 | 2.7 | 3.4 | 7.6 | 12.7 |
| J: Chugoku-Kyushu | 4.8 | 5.6 | 7.1 | 7.2 | 3.9 | 10.5 |

- Strengthening interconnection capacity among Eastern Japan is crucial.
- However, in High RE case, model prefers suppress RE outputs rather than investing interconnection lines between Hokkaido-Tohoku and FCs.

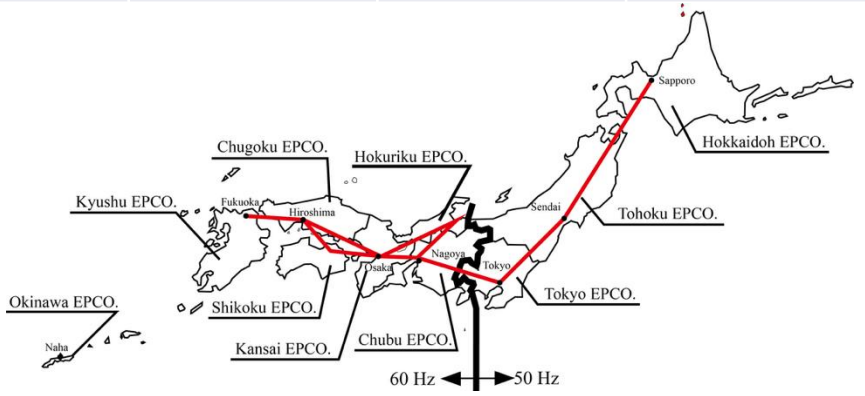



*FC: Frequency Converter between 50/60 Hz

# Results in Storages: Comparison in COCCTO case

| (Additional Capacity in 2050 in GW) | Scenario I | | Scenario III Low RE High CCUS | | Scenario III High RE Low CCUS | |
|---|---|---|---|---|---|---|
| | BLow | BHigh | BLow | BHigh | BLow | BHigh |
| Hokkaido | 81.5 | 48.4 | 70.8 | 44.3 | 2.3 | 0.7 |
| Tohoku | 17.1 | 16.6 | 14.6 | 11.7 | 18.6 | 6.1 |
| Tokyo | 50.0 | 39.7 | 20.7 | 19.2 | 29.9 | 18.4 |
| Hokuriku | 6.6 | 6.2 | 5.2 | 4.8 | 5.6 | 2.2 |
| Chubu | 17.6 | 16.4 | 8.3 | 6.4 | 10.3 | 5.2 |
| Kansai | 8.9 | 5.1 | 0.7 | 0.1 | 4.8 | 1.0 |
| Chugoku | 14.5 | 13.5 | 10.2 | 9.8 | 14.6 | 7.9 |
| Shikoku | 11.1 | 10.3 | 7.0 | 7.0 | 9.1 | 5.3 |
| Kyushu | 32.5 | 29.3 | 27.8 | 24.9 | 12.6 | 2.8 |
| Okinawa | 5.7 | 3.6 | 2.8 | 1.9 | 1.6 | 0.6 |

- Limiting capacity of interconnection line encourage installation of storages in large RE potential areas – such as Hokkaido and Kyushu.
- In High RE case, model prefers suppress RE outputs rather than investments to storage.



# Summary

- We've investigated trade-offs between increase in storage batteries and strengthening grid capacities to enhance renewable energy use in Japan's electricity sector by using AIM/MOGPM.

[Some findings]

- Results shows trade-offs between storage battery and interconnection lines. Cheap battery would lead to suppress investments to interconnection lines.
- We will accept certain level of curtailment under large-scale penetrations of renewables.

- Strengthening interconnection capacity among Eastern Japan is crucial. However, in High RE case, model prefers suppress RE outputs rather than investing interconnection lines especially between Hokkaido-Tohoku and FCs.

- Limiting capacity of interconnection line encourage installation of storages in large RE potential areas, such as Hokkaido and Kyushu.