6th AIEE Energy Symposium, Concurrent session 16. Circular economy and Smart Solutions, December 16, 2021

Installable Potential of Small Modular Reactors and Renewable Energy for Achieving Carbon Neutrality in Electric Power System

Ryoichi Komiyama
Department of Nuclear Engineering and Management,
The University of Tokyo

THE UNIVERSITY OF TOKYO

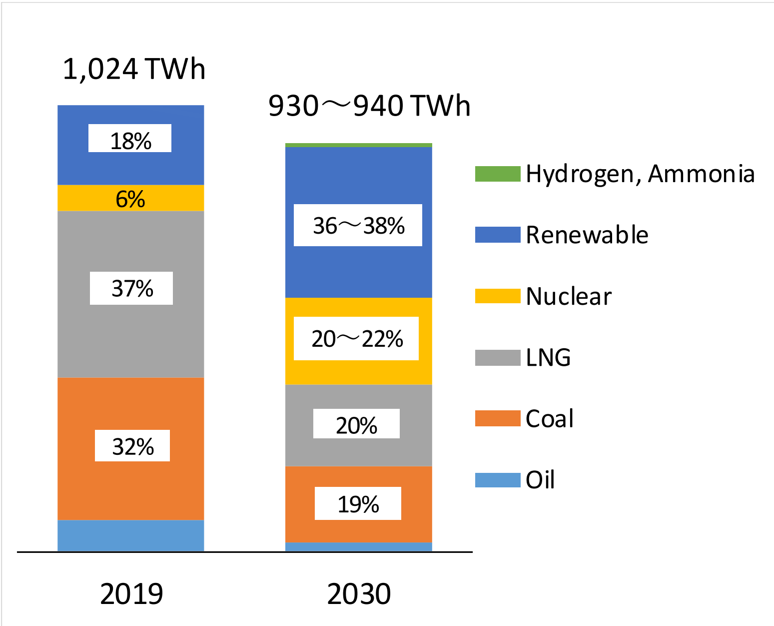
Outline

- Introduction
  - Energy Policy in Japan, Renewable Energy, Small Modular Reactor (SMR)
- Analysis by Optimal Power Generation Mix Model (OPGM)
  - Overview
  - Scenario
  - Results
- Conclusions

Target of Power Generation Mix of Japan in 2030

- Long-term energy outlook to 2030 of Japan was published in 2021 by Ministry of Economy, Trade and Industry Japan (METI).
- Important agenda consist in the maximization of the fraction of **renewable energy (36～38%)** and the utilization of **nuclear (20～22%)**.

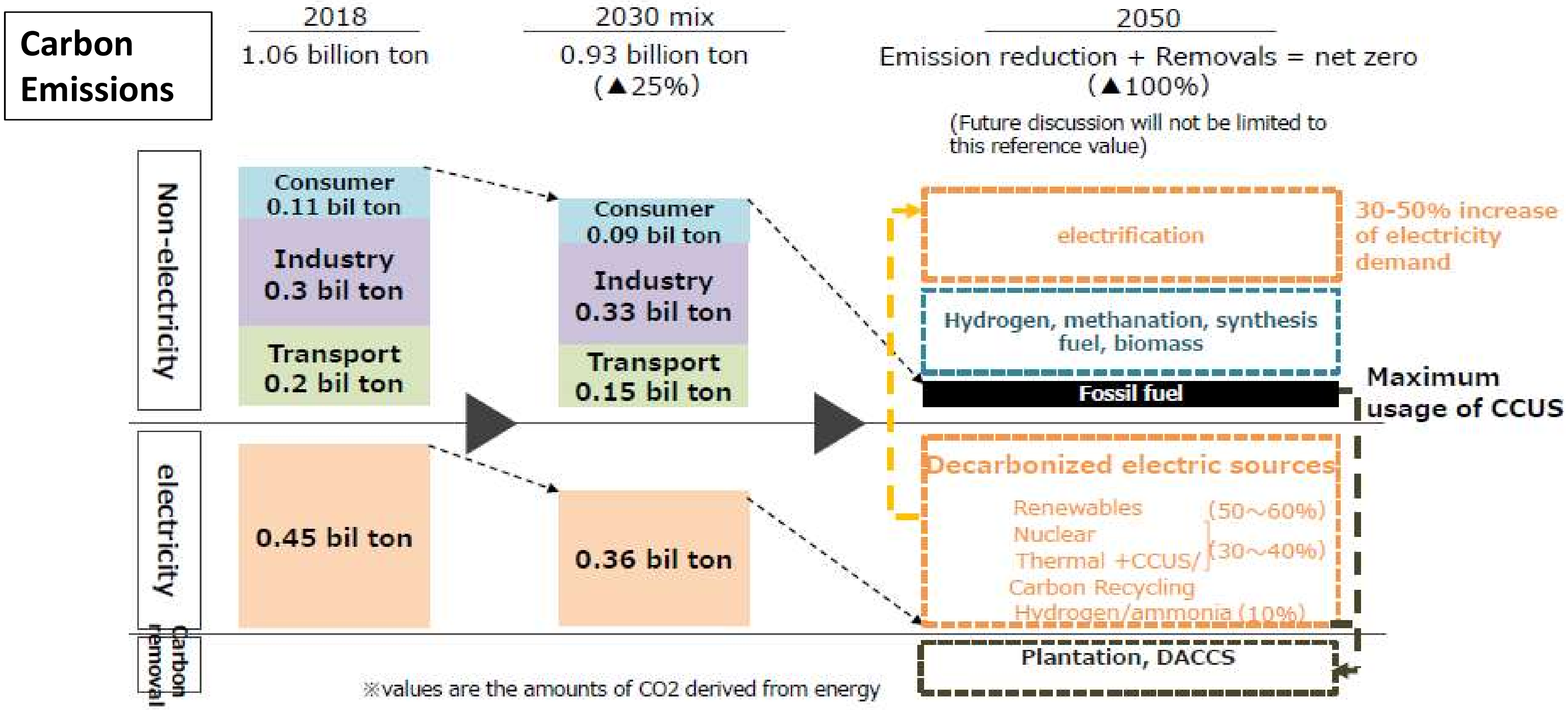
Outlook of Power Generation Mix in Japan



(Source) METI(Ministry of Economy, Trade and Industry)

Carbon Neutrality in Japan towards 2050 (Reference Images)(METI)

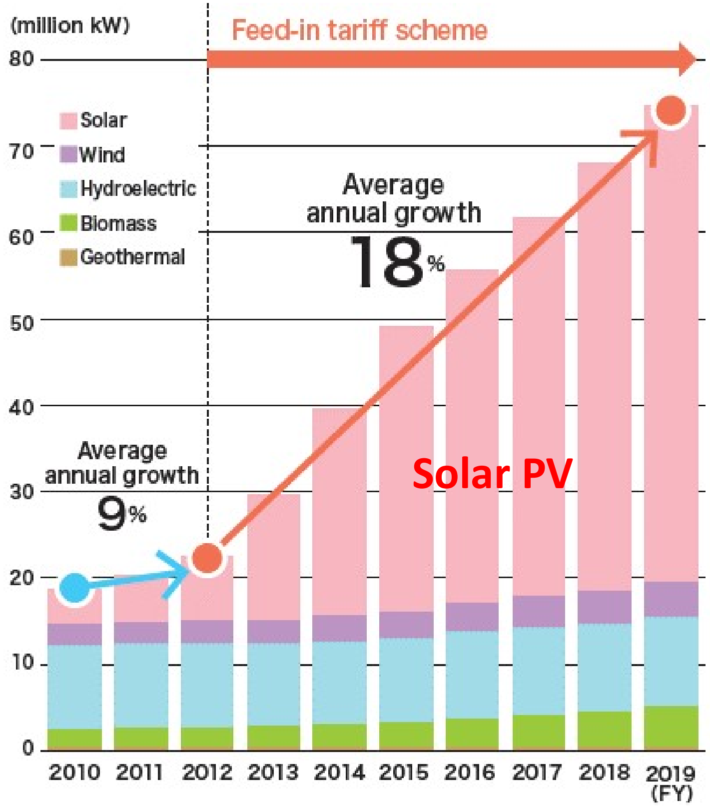
Electrification, Clean Fuels, CCUS (incl. Negative Emission Technology)

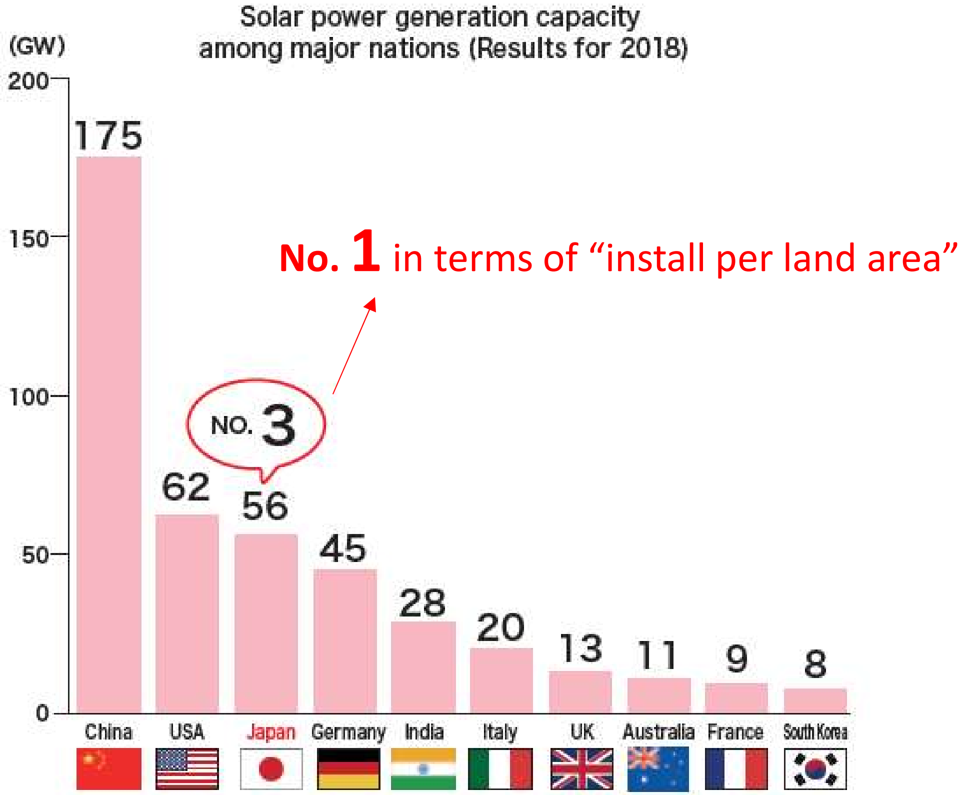


(Source) Ministry of Economy, Trade and Industry (METI): Overview of Japan's Green Growth Strategy Through Achieving Carbon Neutrality in 2050, Jan 2021

Rapid Growth of Renewable in Japan

Changes in the installed capacity of renewable energy
(excluding large-scale hydroelectric power)

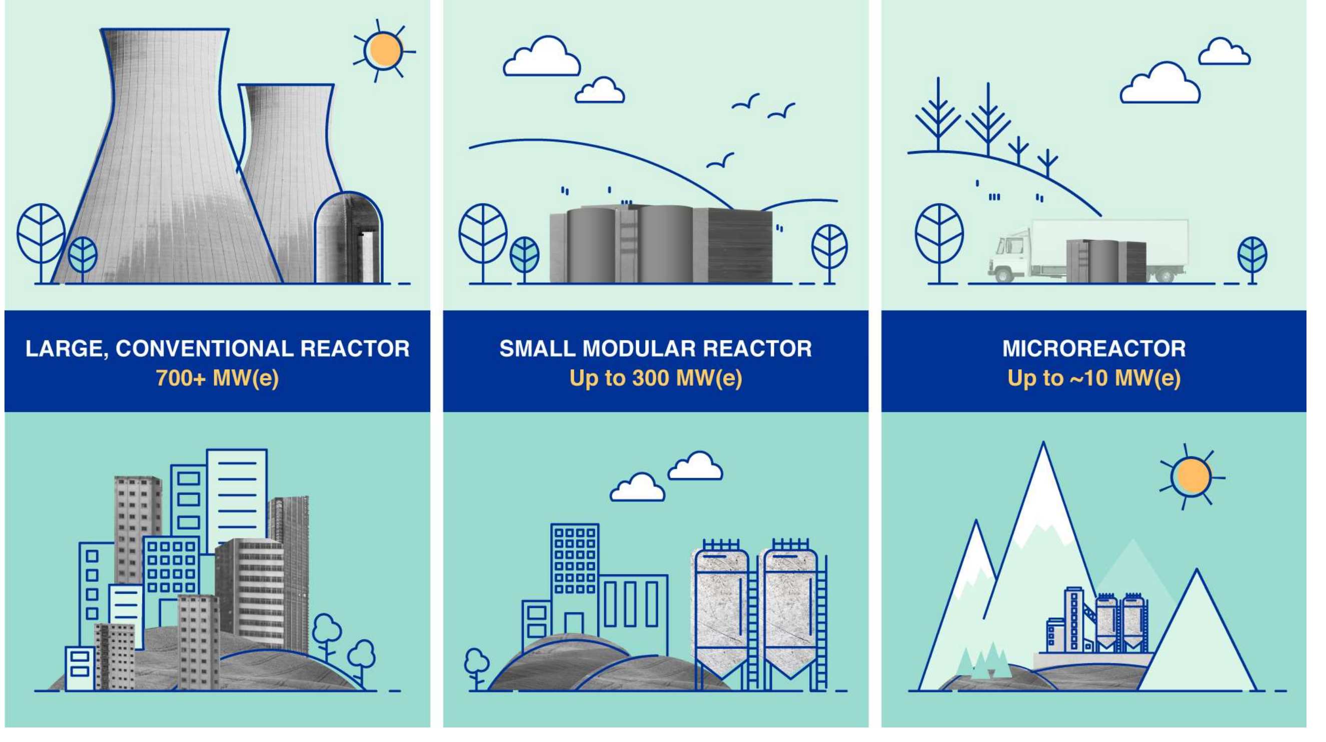




(Source) Ministry of Economy, Trade and Industry (METI)

Small Module Reactor: SMR

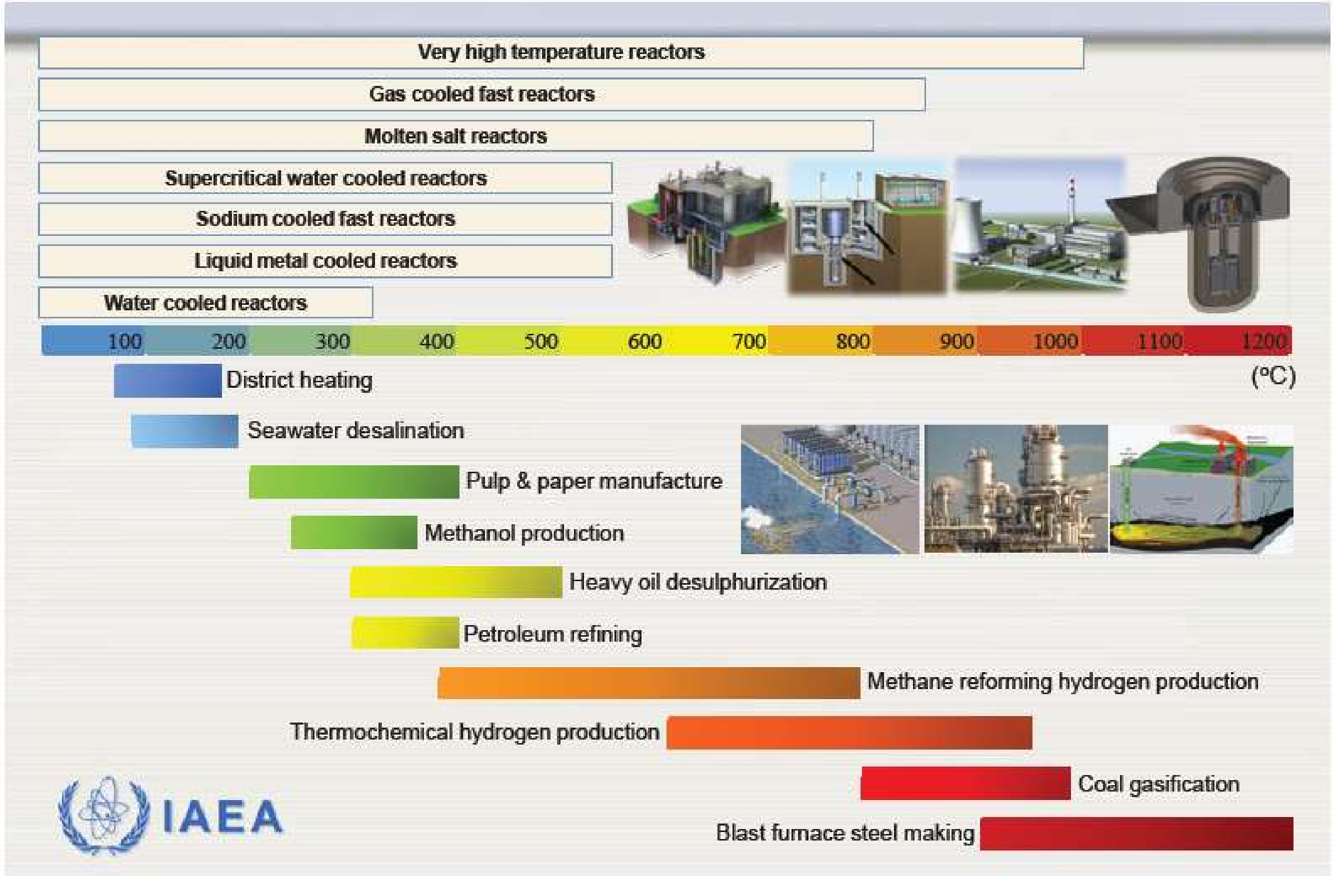
Small – physically a fraction of the size of a conventional nuclear power reactor.
Modular – making it possible for systems and components to be factory-assembled and transported as a unit to a location for installation.
Reactors – harnessing nuclear fission to generate heat to produce energy.



(Source) IAEA: What are Small Modular Reactors (SMRs)?, November, 2021
https://www.iaea.org/newscenter/news/what-are-small-modular-reactors-smrs

SMR Designs for Non-electrical Applications

Nuclear heating is expected for decarbonizing non-electrical sector



temperature

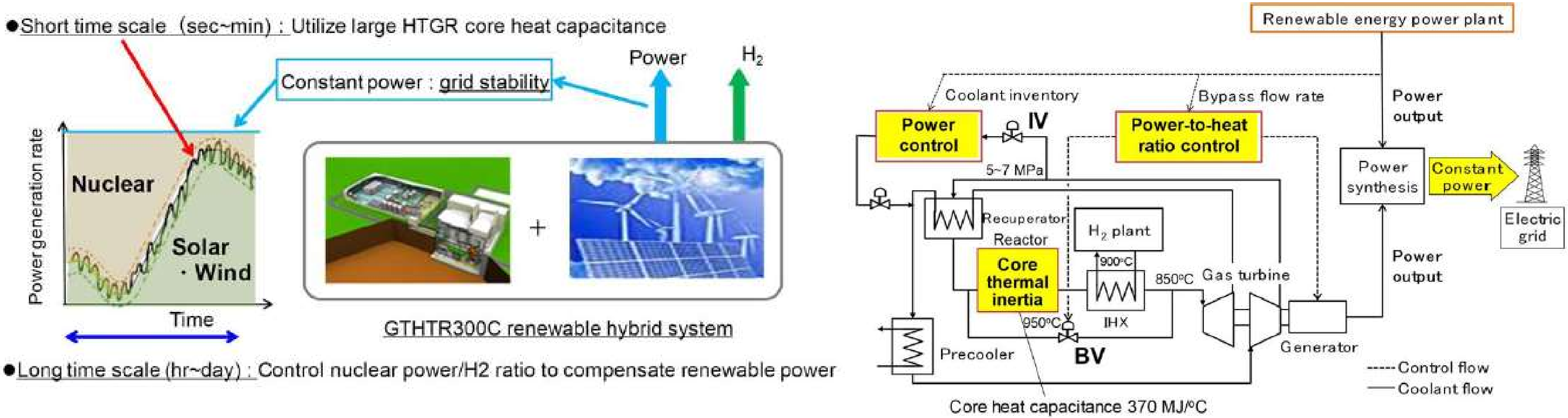
(Source) IAEA: IAEA Nuclear Energy Series No. NR-T-1.18 (2021)

High Temperature Gas-cooled Reactor (HTGR)

Enhanced Safety, Load Following Capability, Multipurpose Use of Nuclear Energy (Electricity, Heat, Hydrogen)

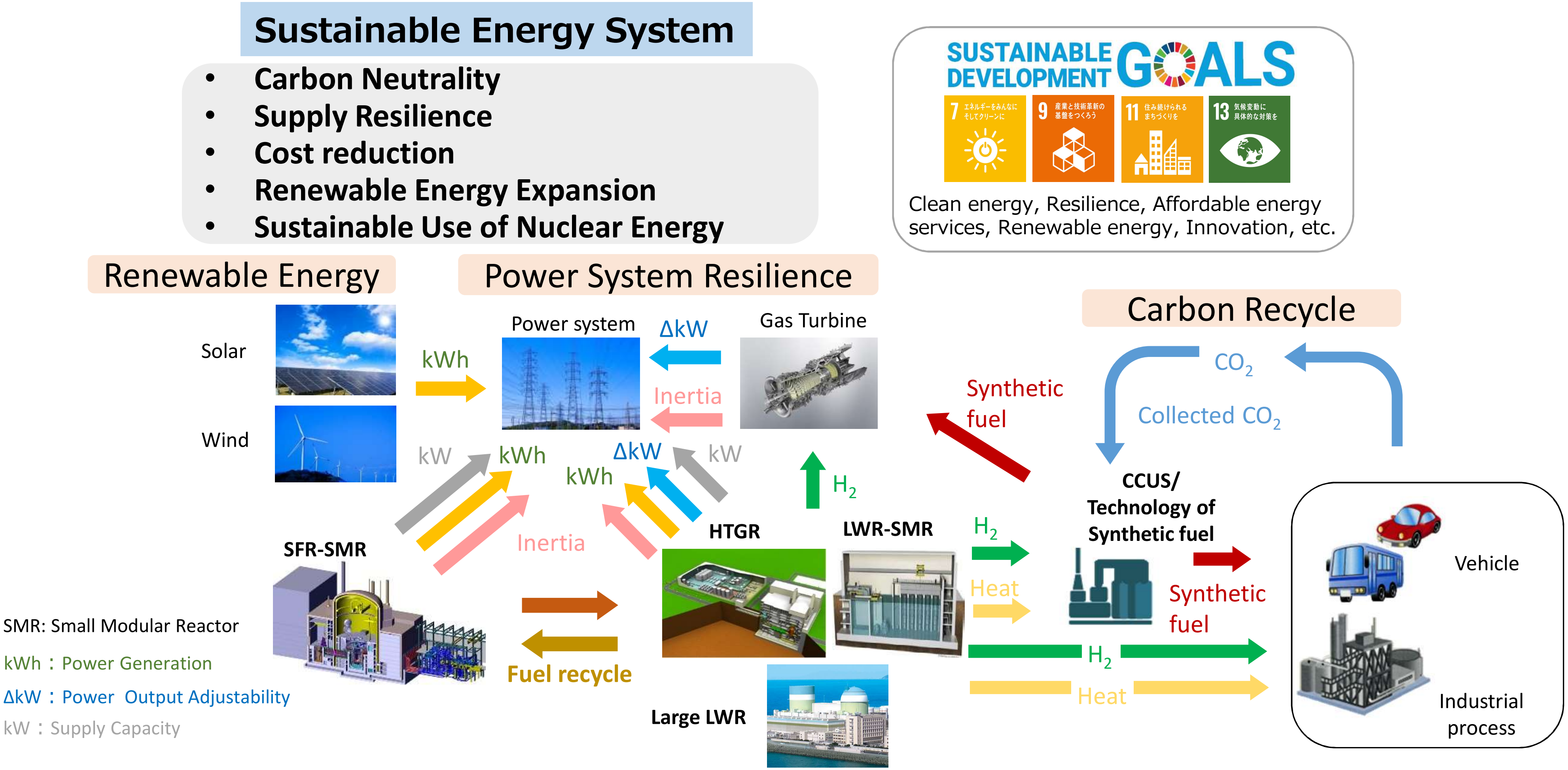
- Short-cycle Renewable Variability → HTGR output can be adjusted directly
- Long-cycle Renewable Variability → HTGR output can be adjusted by controlling H_2 production

HTGR Controllability under Renewable Energy Penetration



(Source) IAEA, Nuclear–Renewable Hybrid Energy Systems for Decarbonized Energy Production and Cogeneration, IAEA-TECDOC-1885, 2019

SMR-based Energy System for Decarbonization and Resilience



(Source) Ministry of Education, Culture, Sports, Science and Technology, Japan (MEXT) "Nuclear System Research and Development Project" The University of Tokyo, JAEA, Institute of Energy Economics, Japan(IEEJ), JGC, Mitsubishi Heavy Industries

Research Objective

Optimal integration of SMR into a power grid under carbon regulation
→ Identification of the best install capacity of SMR in the grid, so as to minimize power system cost and to decarbonize power supply

Optimal Power Generation Mix Model (OPGM)

- Geographical Resolution: 383 buses, 472 transmission lines
- Temporal Resolution: an hourly resolution through 8,760 hours

Optimal Power Generation Mix Model (OPGM) in Japan

Geographical Resolution: 383 nodes, 472 bulk power transmission lines (All of the buses and inter/intra-regional lines)

Temporal Resolution: 8,760 time slices / year, An hourly resolution for 1 year

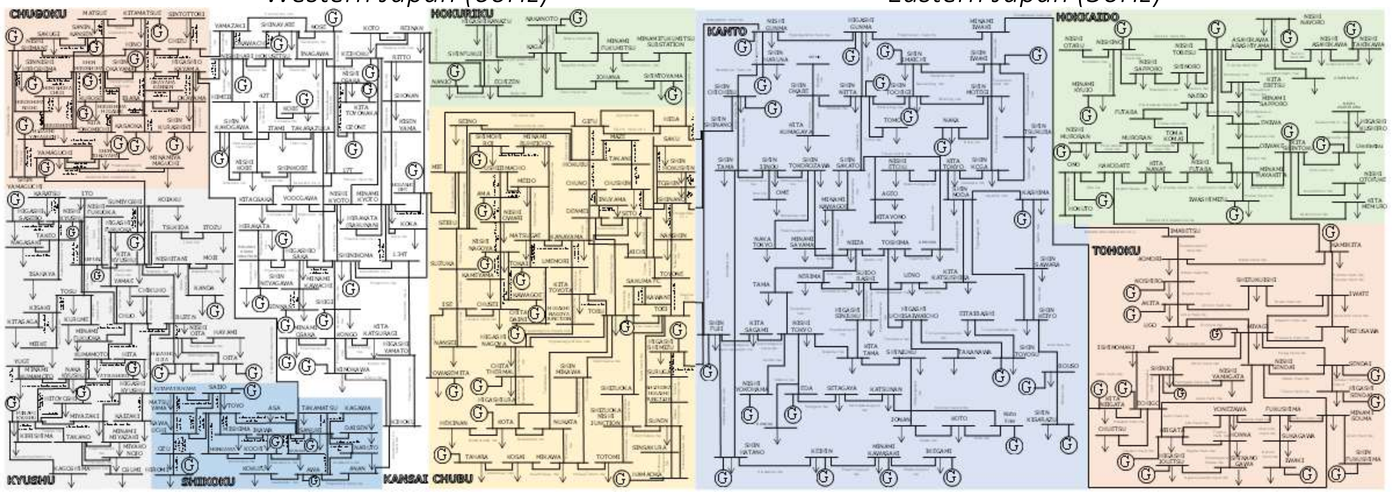
Technology (19 types): Hydro, Geothermal, Biomass, Marine, Nuclear(Large), Coal, LNG ST, LNG GCC, Oil, Nuclear(SMR), Hydrogen, LNG-CCS, Coal-CCS, Wind(onshore), Wind(offshore), PV, Pumped, NAS battery, Li-ion battery

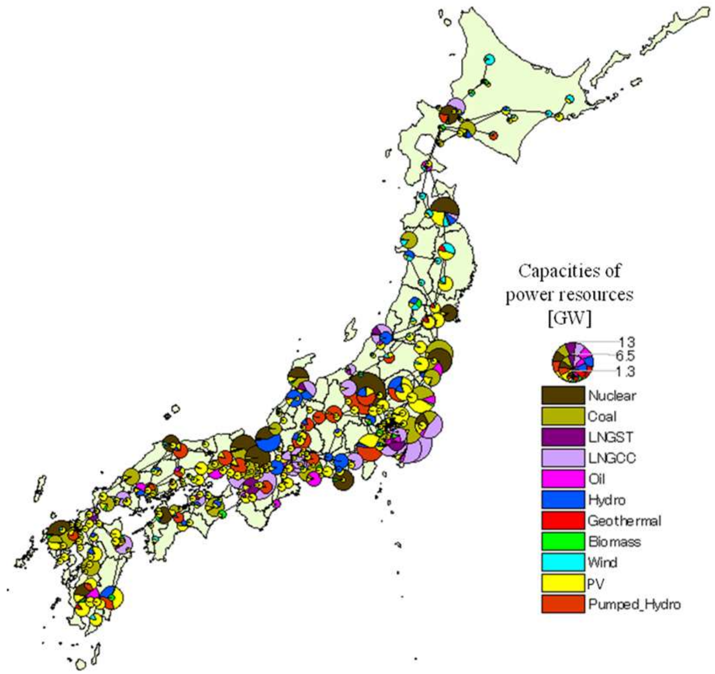
Method: LP model from scratch, Single-year cost min. (operating cost + battery install cost)

Scale of LP Model: Constraints: 62 millions, Endogenous variables: 44 millions

Bus system diagram in Japan (383 buses and 472 bulk power lines)

Western Japan (60Hz) *Eastern Japan (50Hz)*

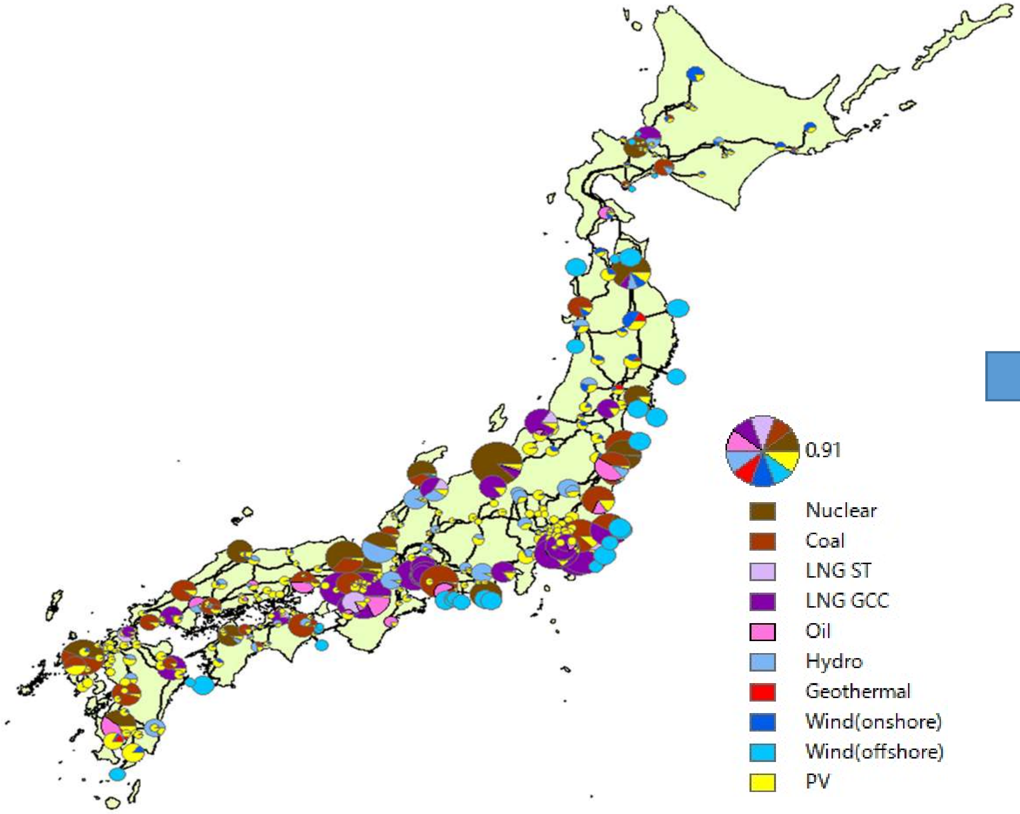


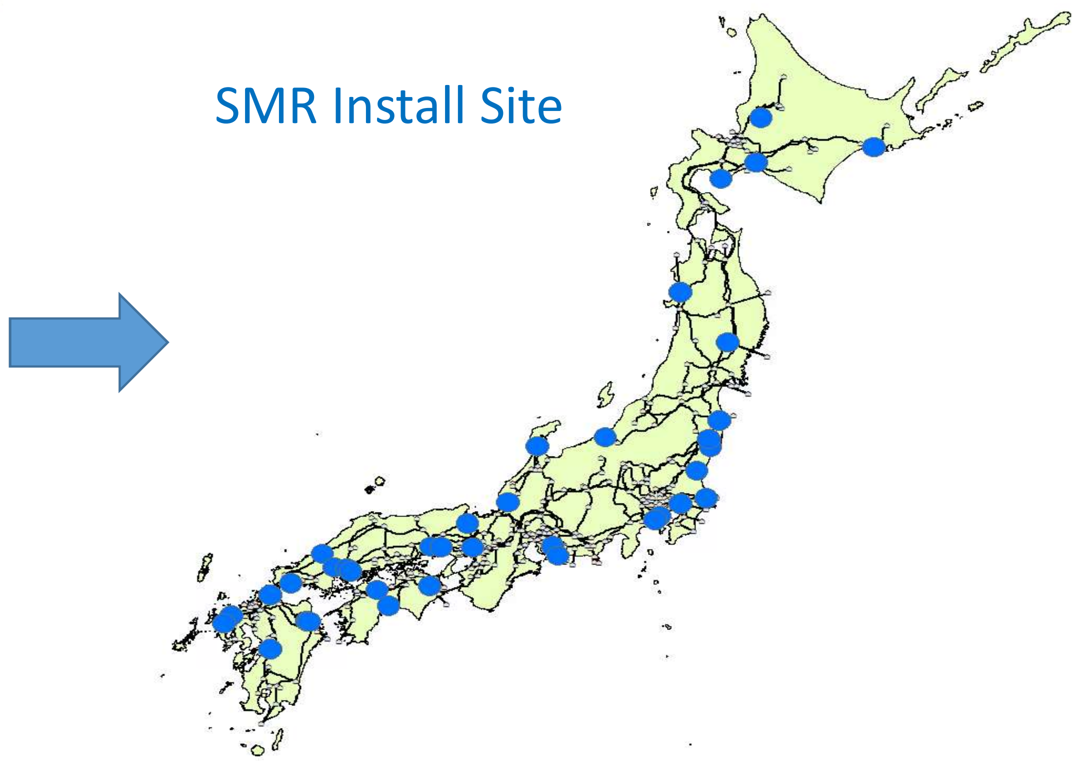


(Related Works)
Komiyama R, Fujii Y, *Energy Policy* ;66:73-89 (2014)
Komiyama R, Fujii Y, *Energy Policy* ;101:594-611 (2017)
Komiyama R, Fujii, Y, *Renewable Energy* ; 139: 1012-1028 (2019)

SMR Consideration in Japan

- SMR installation → Assuming SRM building in the site of coal-fired power plant
- Type of SMR → Light water reactor (LWR)





Assumption

■ Nuclear capacity

- Large reactor: total 23.7 GW (2050 fixed values, 60 years of operation)
- Small reactor(SMR): determined by optimization (max 29 GW [1 unit 50 MW])

■ Nuclear power generation (large + small)

- Limit 20% of total power generation in Japan (under 200 TWh)

■ SMR technical data

- Construction cost: 500,000 yen/kW (5,000 $/kW)
- Load following constraint: 44% increase per hour, 31% decrease per hour
- Minimum output: 30% of rated output

■ CO_2 emissions constraint

- CO_2 zero constraint (carbon neutral)

Scenario

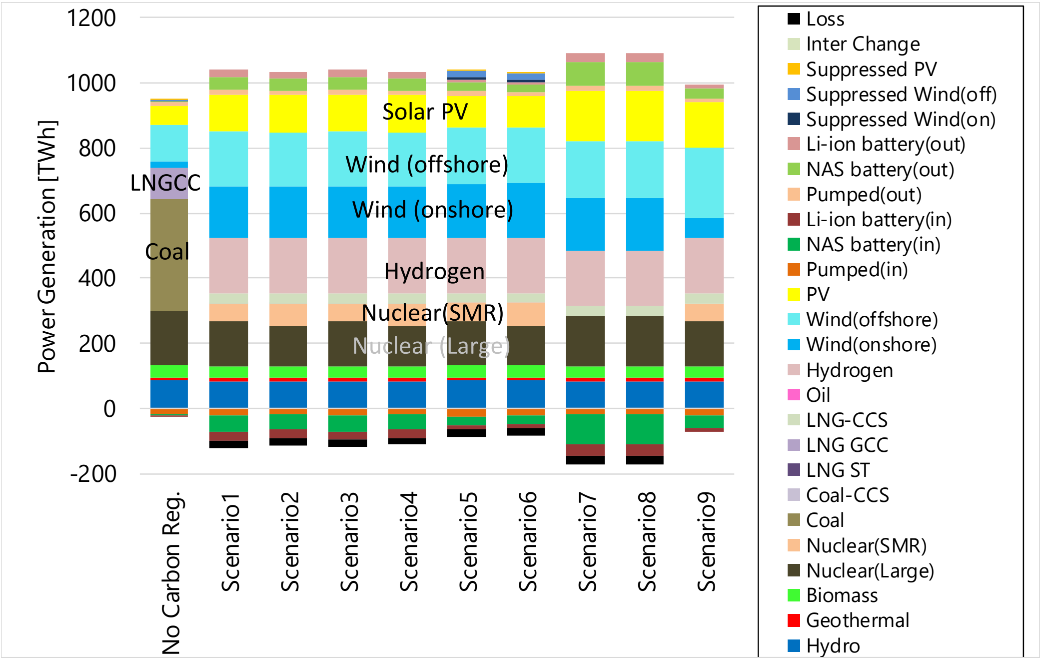
All Scenario → Carbon emissions from power sector = 0

<table>
<tr><th colspan="2"></th><th>SMR consideration</th><th>SMR cost</th><th>H2 cost</th><th>RE curtail</th><th>SMR flexiblity</th></tr>
<tr><td>Scenario 1</td><td>Base</td><td rowspan="6">○</td><td>base</td><td>base</td><td>No</td><td>base</td></tr>
<tr><td>Scenario 2</td><td>SMR cost down</td><td>down</td><td>base</td><td>No</td><td>base</td></tr>
<tr><td>Scenario 3</td><td>H2 cost down</td><td>base</td><td>down</td><td>No</td><td>base</td></tr>
<tr><td>Scenario 4</td><td>Scenario 2+3</td><td>down</td><td>down</td><td>No</td><td>base</td></tr>
<tr><td>Scenario 5</td><td>RE curtailment</td><td>base</td><td>base</td><td>Yes</td><td>base</td></tr>
<tr><td>Scenario 6</td><td>Scenario 2+5</td><td>down</td><td>base</td><td>Yes</td><td>base</td></tr>
<tr><td>Scenario 7</td><td>No SMR</td><td rowspan="2">×</td><td rowspan="2">–</td><td>base</td><td>No</td><td>base</td></tr>
<tr><td>Scenario 8</td><td>Scenario 3+7</td><td>down</td><td>No</td><td>base</td></tr>
<tr><td>Scenario 9</td><td>SMR flexibility down</td><td>○</td><td>base</td><td>base</td><td>No</td><td>down</td></tr>
</table>

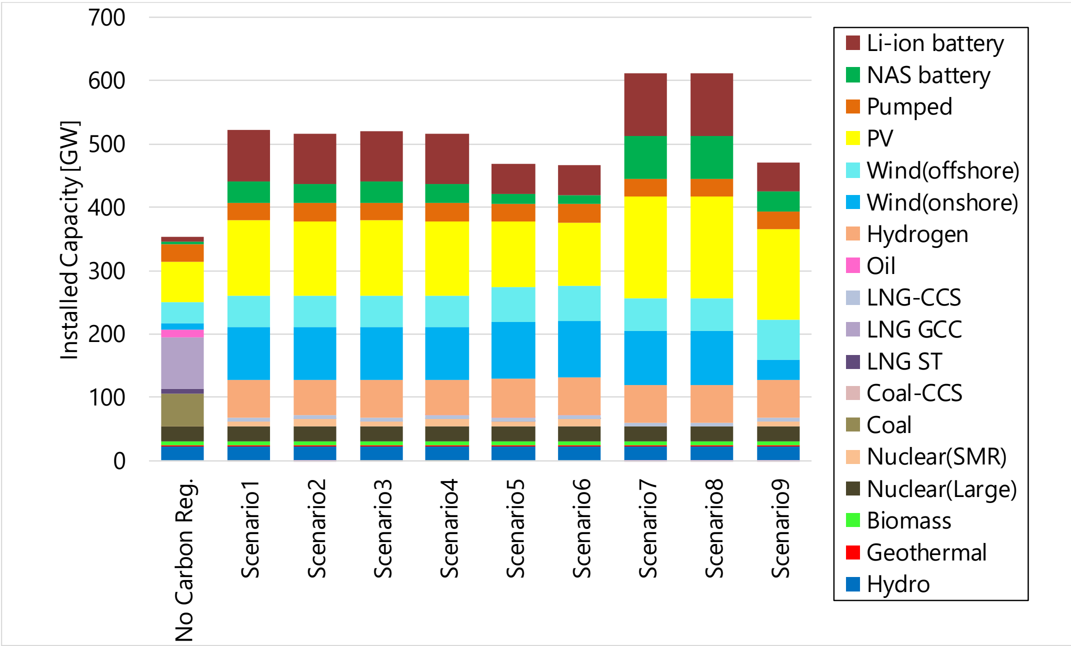
Power Generation Mix

- <u>SMR is deployed in all cases considering SMR</u> → SMR is economically rational option for decarbonization
- Expanded introduction of hydrogen power generation (assuming consumption of imported carbon-free hydrogen)

Power generation



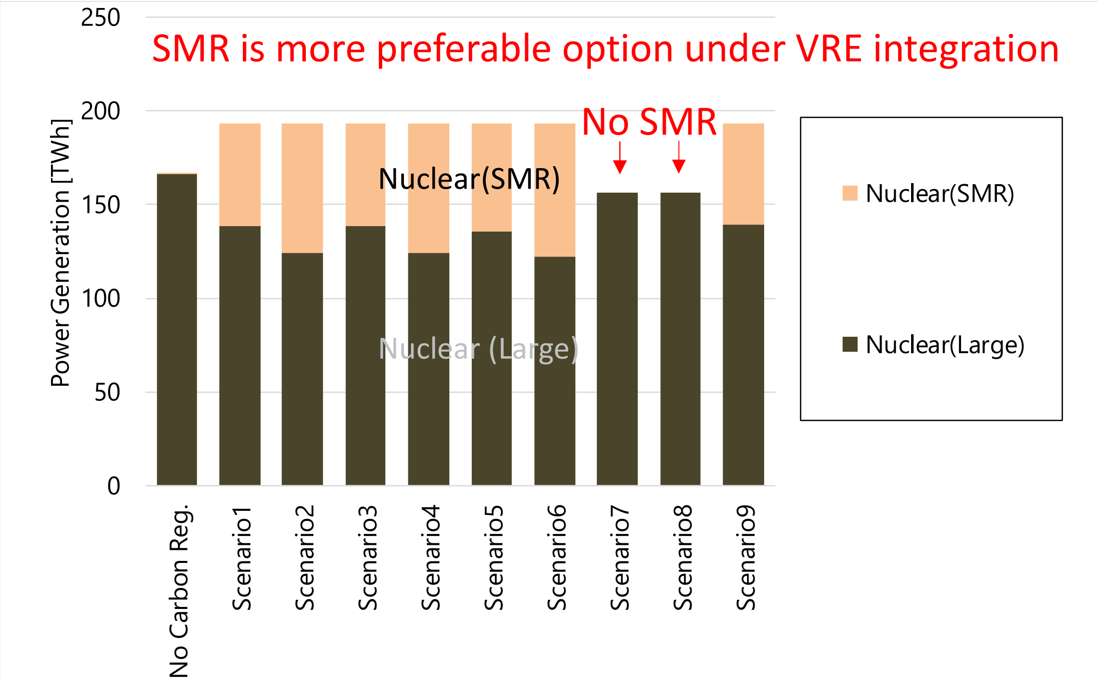
Capacity



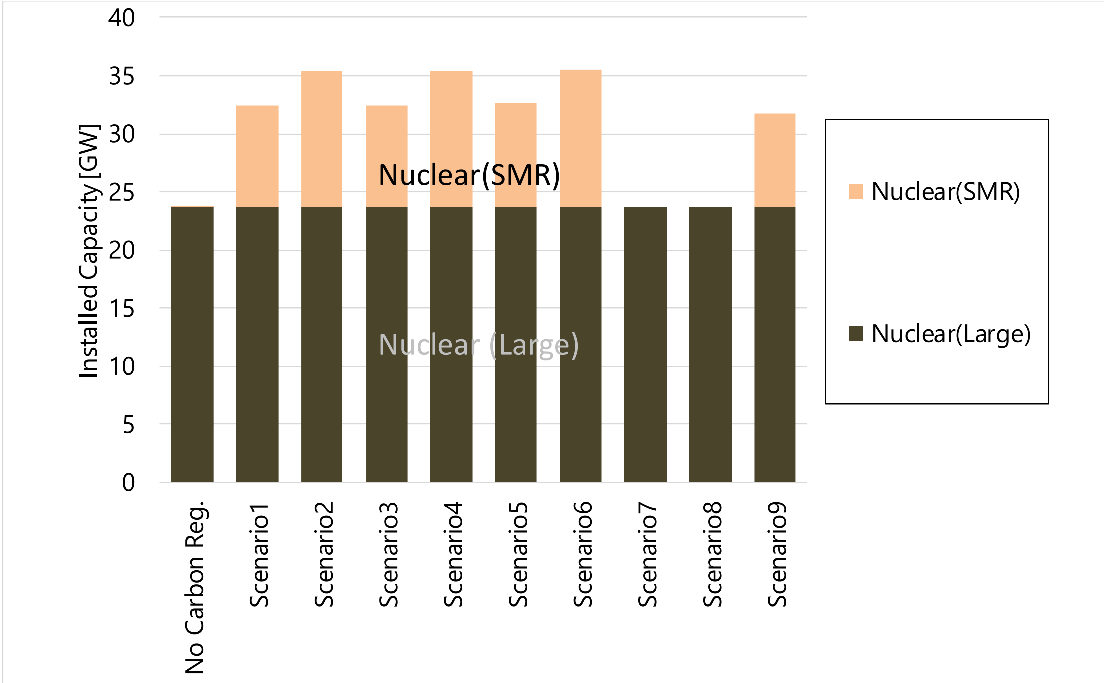
SMR Installation

- SMR→ Increased deployment by lower construction cost; Large-scale reactor generation→decrease
- Large-scale nuclear reactor decreases under extensive integration of renewable energy
- SMR is an important option for maintaining nuclear power under massive renewable energy integration

Nuclear Power Generation

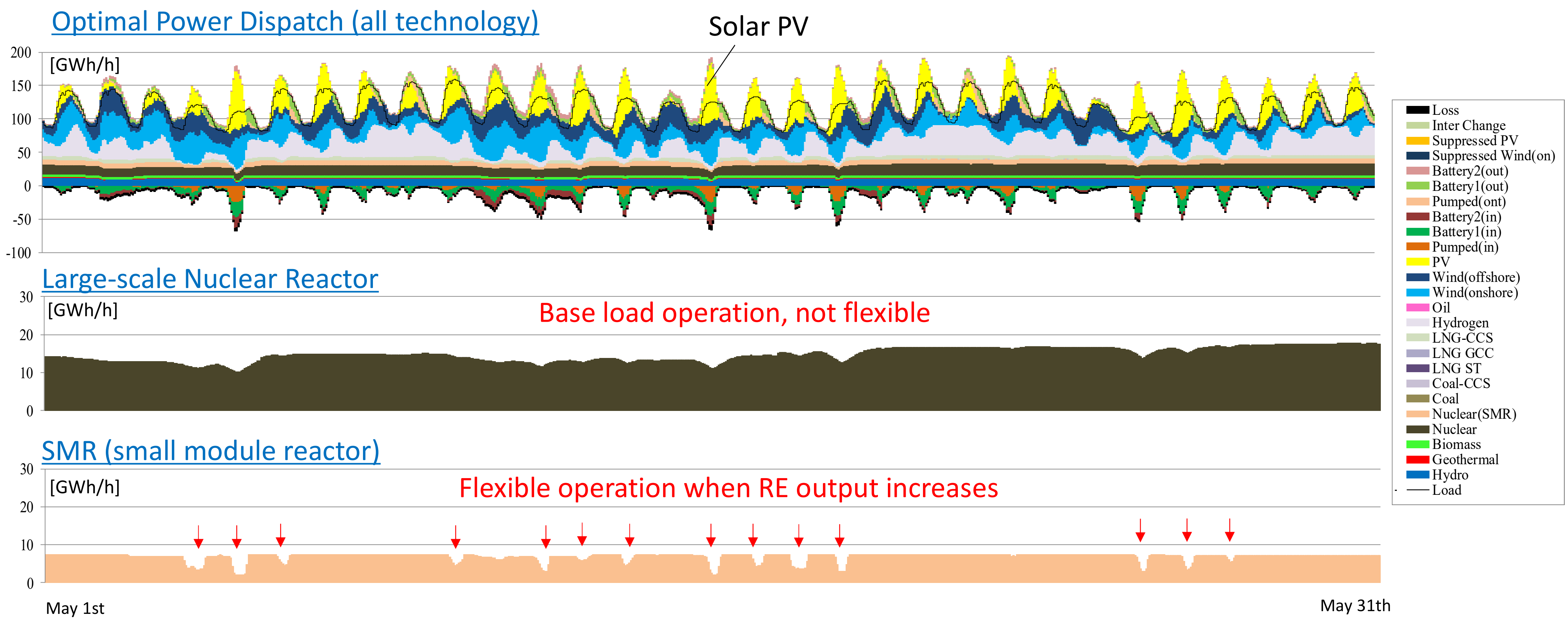


Nuclear Power Capacity



Optimal Power Dispatch (Scenario1, May)

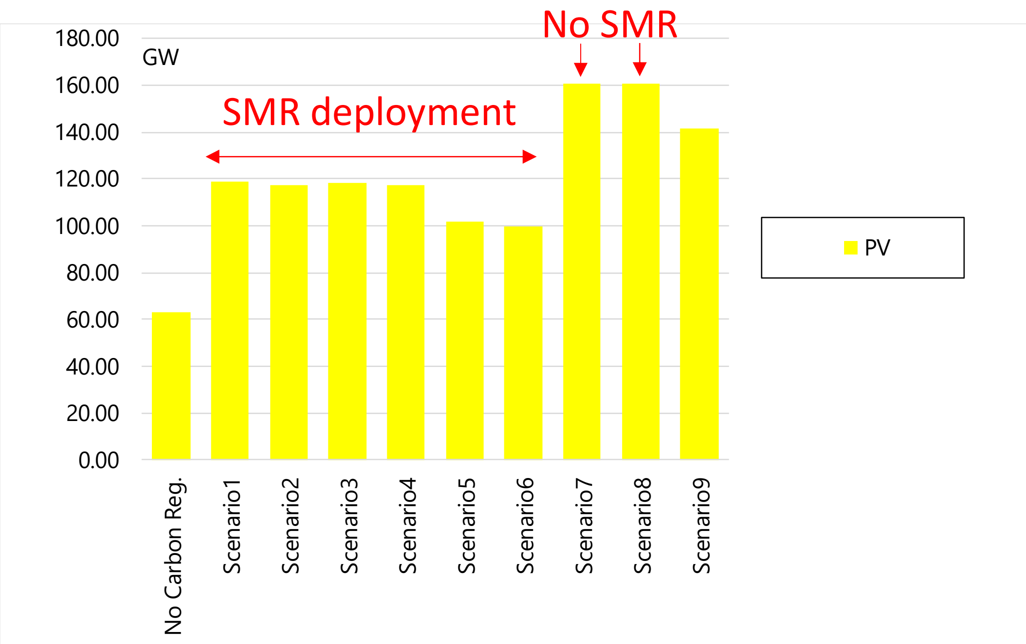
SMR flexibility operation contributes to ensure supply and demand balance under extensive RE integration



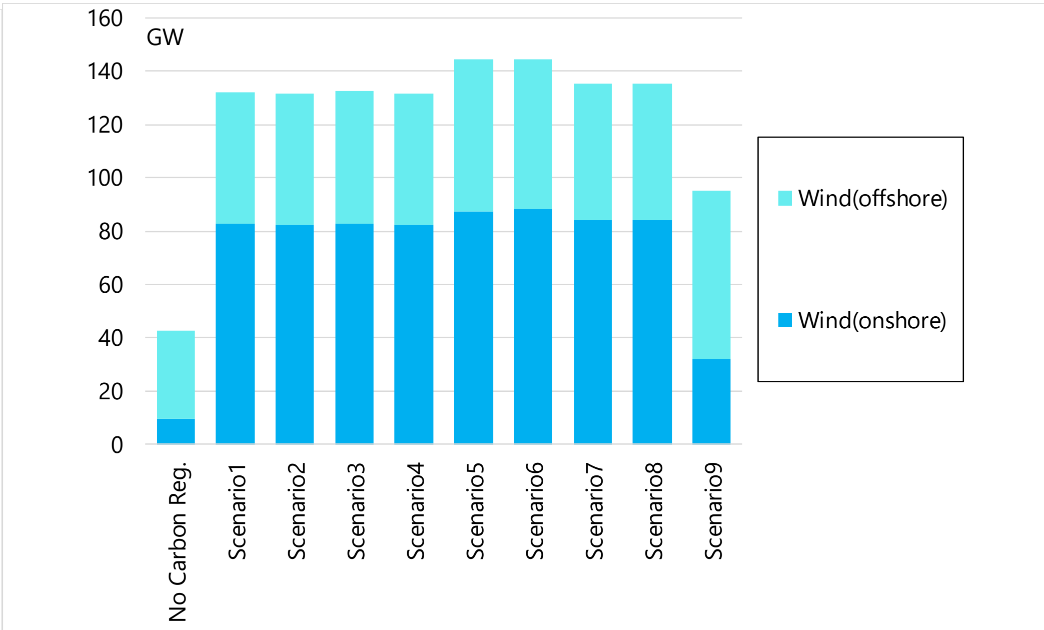
Renewable Energy

SMR contributes to save solar PV investment required for decarbonization

Optimal Capacity (PV)

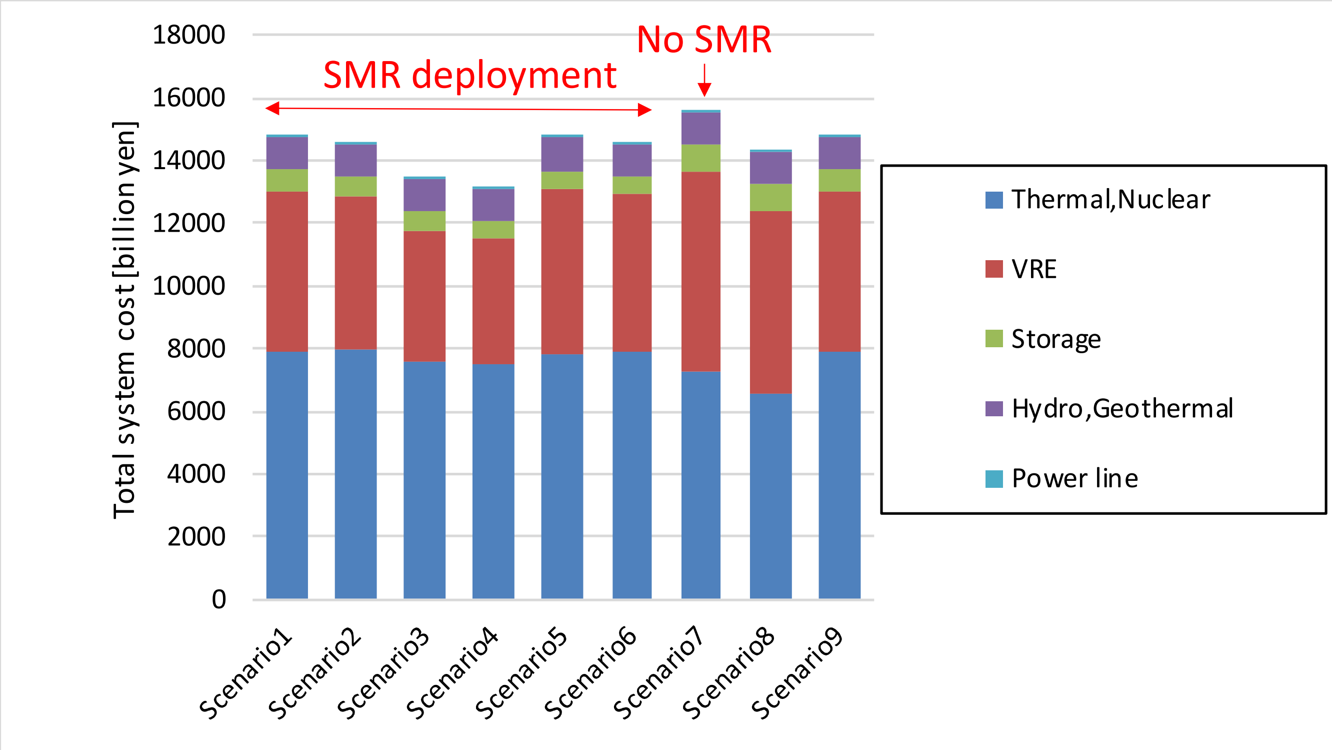


Optimal Capacity (Wind)



Total Power System Cost

Total system cost in Scenario 1～6 (SMR deployment) is lower than Scenario 7 (No SMR)
→SMR contributes to reduce total power system cost



Conclusions

- For evaluating the optimal SMR and VRE integration into power system, this paper develops an optimal power generation mix model characterized by 383 nodes with 472 bulk power transmission lines with hourly temporal resolution through 8,760 hours.

- The results suggest that SMR is significant for both enabling massive VRE integration and achieving carbon neutrality of power system in an cost-effective manner.

Future Challenge

- Consideration of HTGR and Fast SMR

Thanks for your kind attention.

Ryoichi Komiyama
Department of Nuclear Engineering and Management,
The University of Tokyo

Acknowledgment
This work was supported by MEXT Innovative Nuclear Research and Development Program Grant Number JPMXD0220354480, by JSPS KAKENHI Grant Number JP20H02679 and by the Environment Research and Technology Development Fund 2-2104 of the Environmental Restoration and Conservation Agency.

THE UNIVERSITY OF TOKYO