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EXPLORING THE CAUSES OF WHOLESALE ELECTRICITY PRICE SPIKE IN 2021 WINTER IN JAPAN -- FROM THE PERSPECTIVE OF POWER SYSTEM FLEXIBILITY

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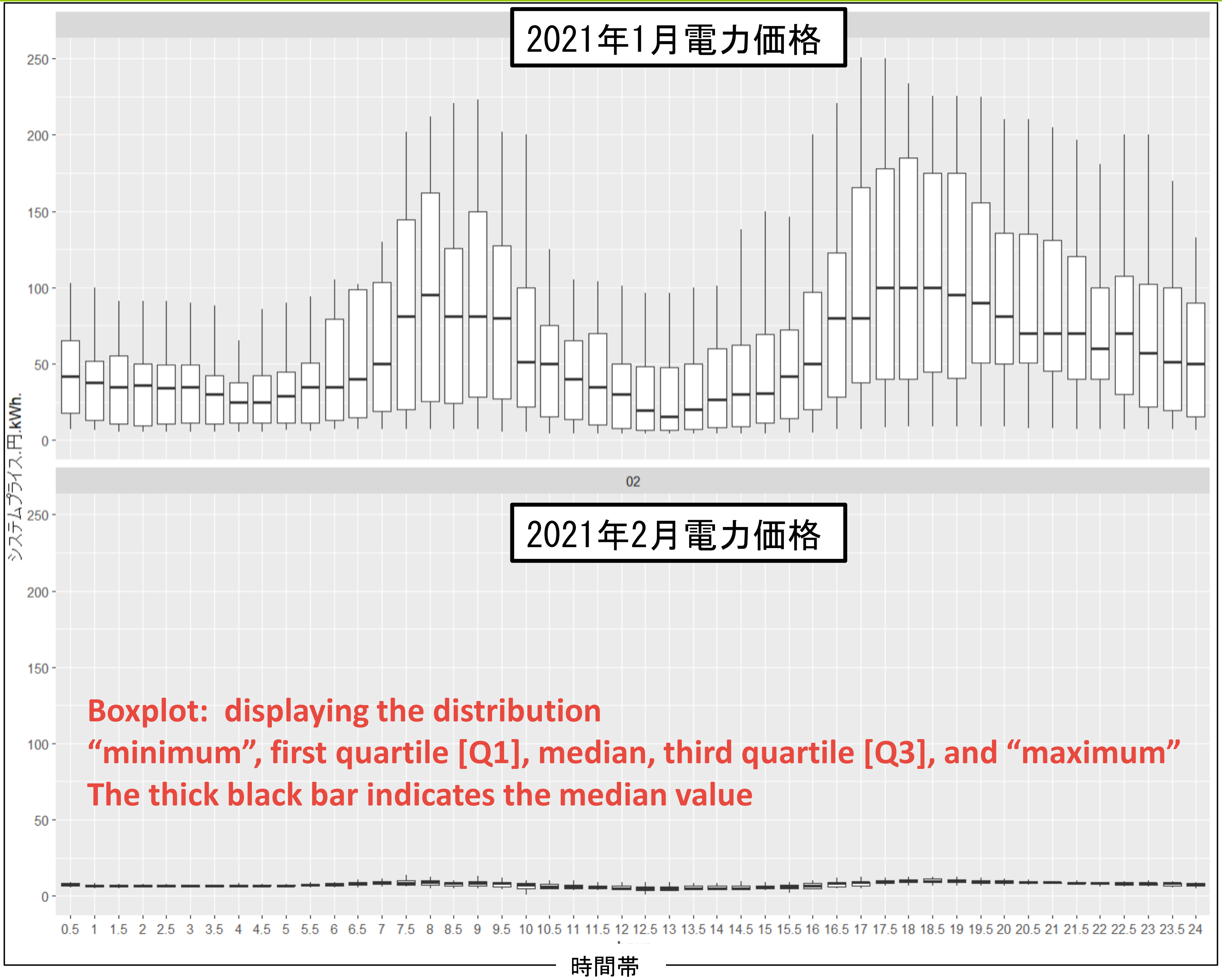
Contents

1. Introduction: Price Spikes and Flexibility Issues in Japanese Power System
2. Methodology: The Optimal Dispatching model
3. Simulation Results
4. Scenario analysis: What-if LNG price were no higher than the annual average price?
5. Discussion, Policy Implications, and Future Studies
   1. Short Term Flexible Measures and Policy Recommendation
   2. Mid and long term Flexible Measures and Policy Recommendations

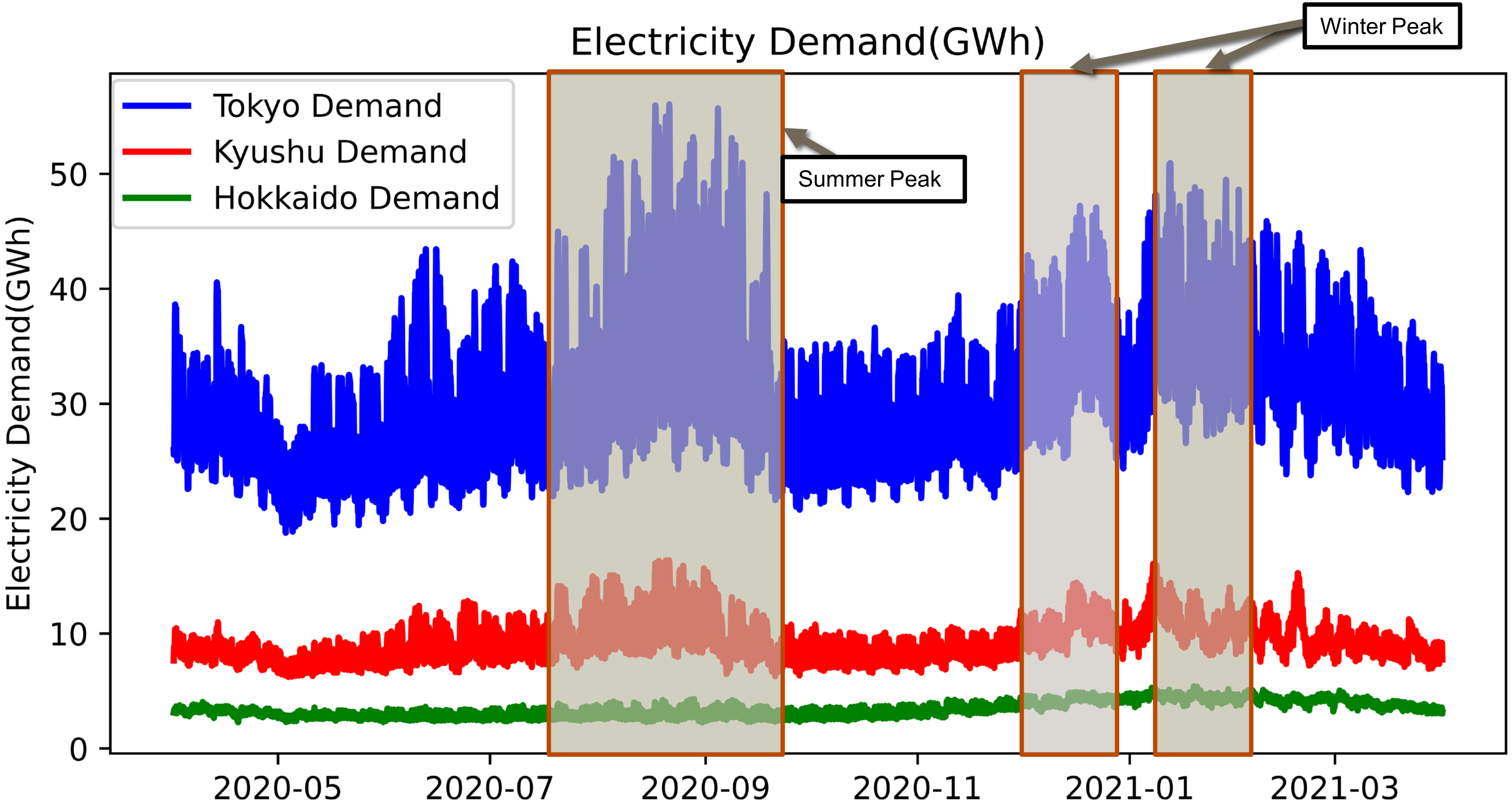
1 Introduction:
Flexibility Issues and Price Spikes in Japanese Power System

価格高騰現象

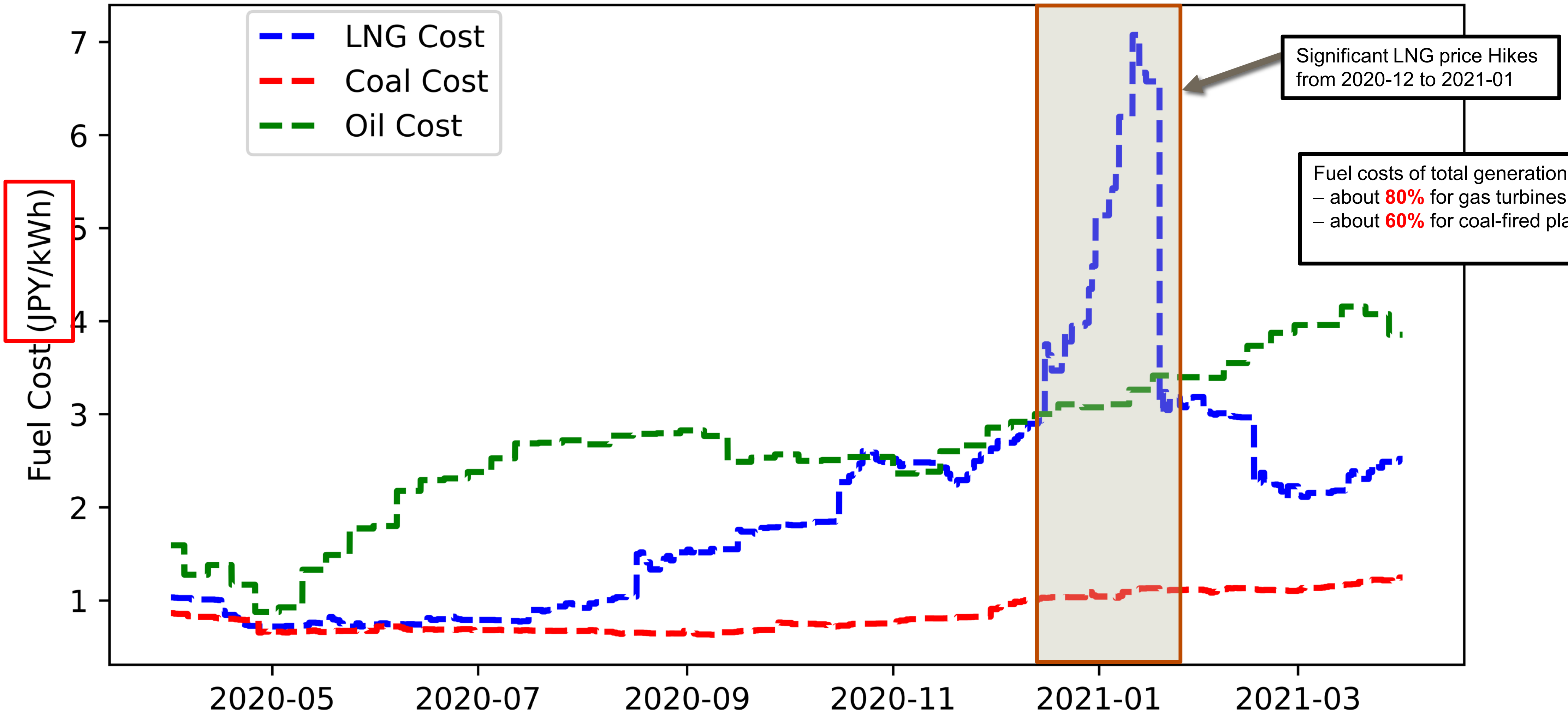
- **Facts**
  - 1 Price hike at each hour of the day ← Fuel Price
  - 2 Price spikes at the morning and afternoon peaks ← demand hikes and **LNG price?**
- **Question:**
  - Whether the electricity grid lacks **the flexibility** to accommodate the hourly profile (Diurnal Fluctuation) of PV outputs and demand variation?



Potential Causes(I): Demand Hikes
Residential Demand hikes due to the cold waves

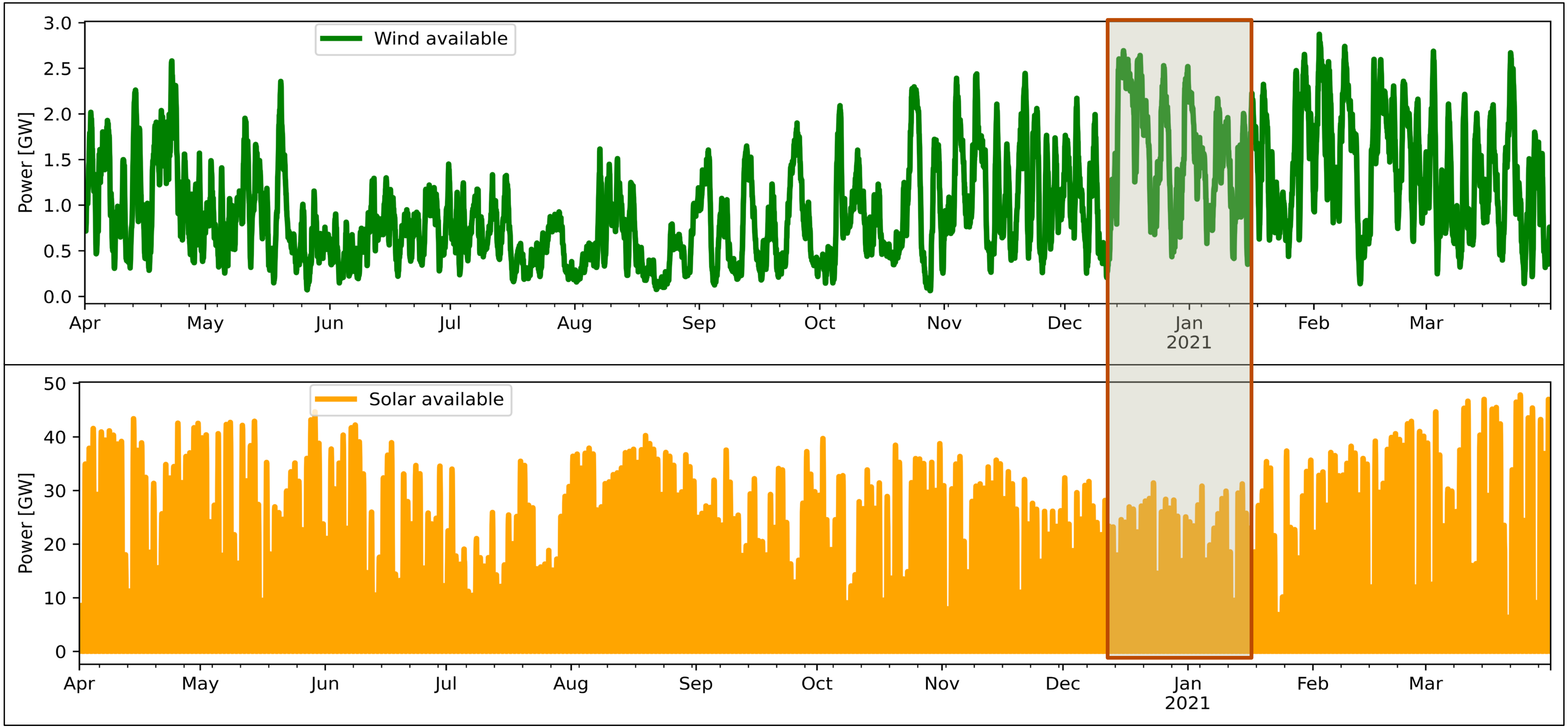


Potential Causes(II): Fuel Cost
The price of fuel containing a heat value of one kWh



Fuel costs of total generation cost :
– about **80%** for gas turbines;
– about **60%** for coal-fired plants;

Potential Causes(III): Renewable Output
Low Renewable Output during the period?



Introduction(II):
Definition of Flexibility
柔軟性とは?

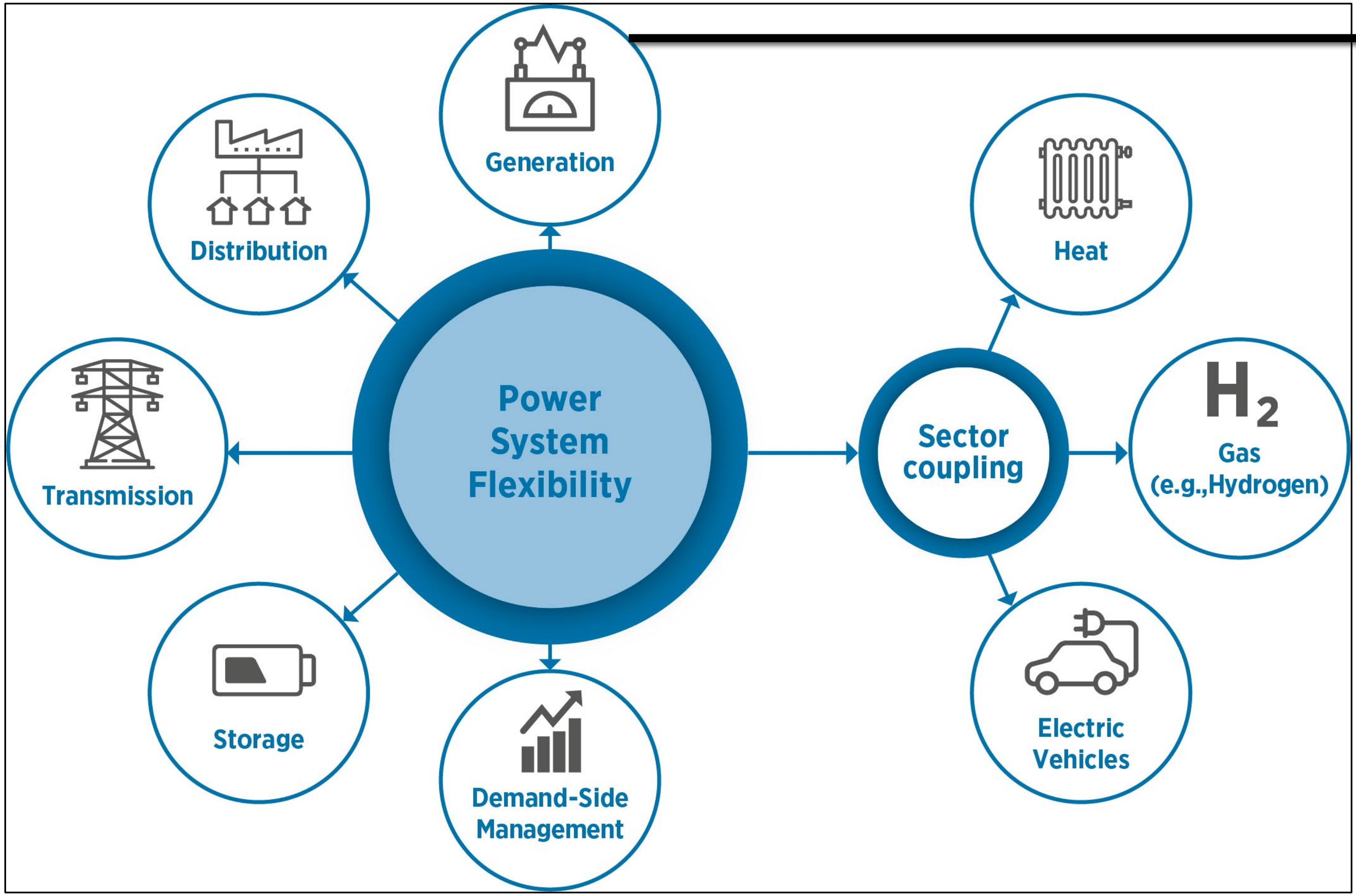
Definitions of Flexibility:

柔軟性では:

- Power System Flexibility
  - The ability of a power system to reliably and cost-effectively manage the **variability and uncertainty** of demand and supply across all relevant timescales" (IEA, 2018).
- High **penetration of renewables** increases the variability in the power system
  - E.g. Diurnal and seasonal fluctuation of solar outputs
- More frequent **extreme weather events**(i.e. cold waves) increases the uncertainty of power demand

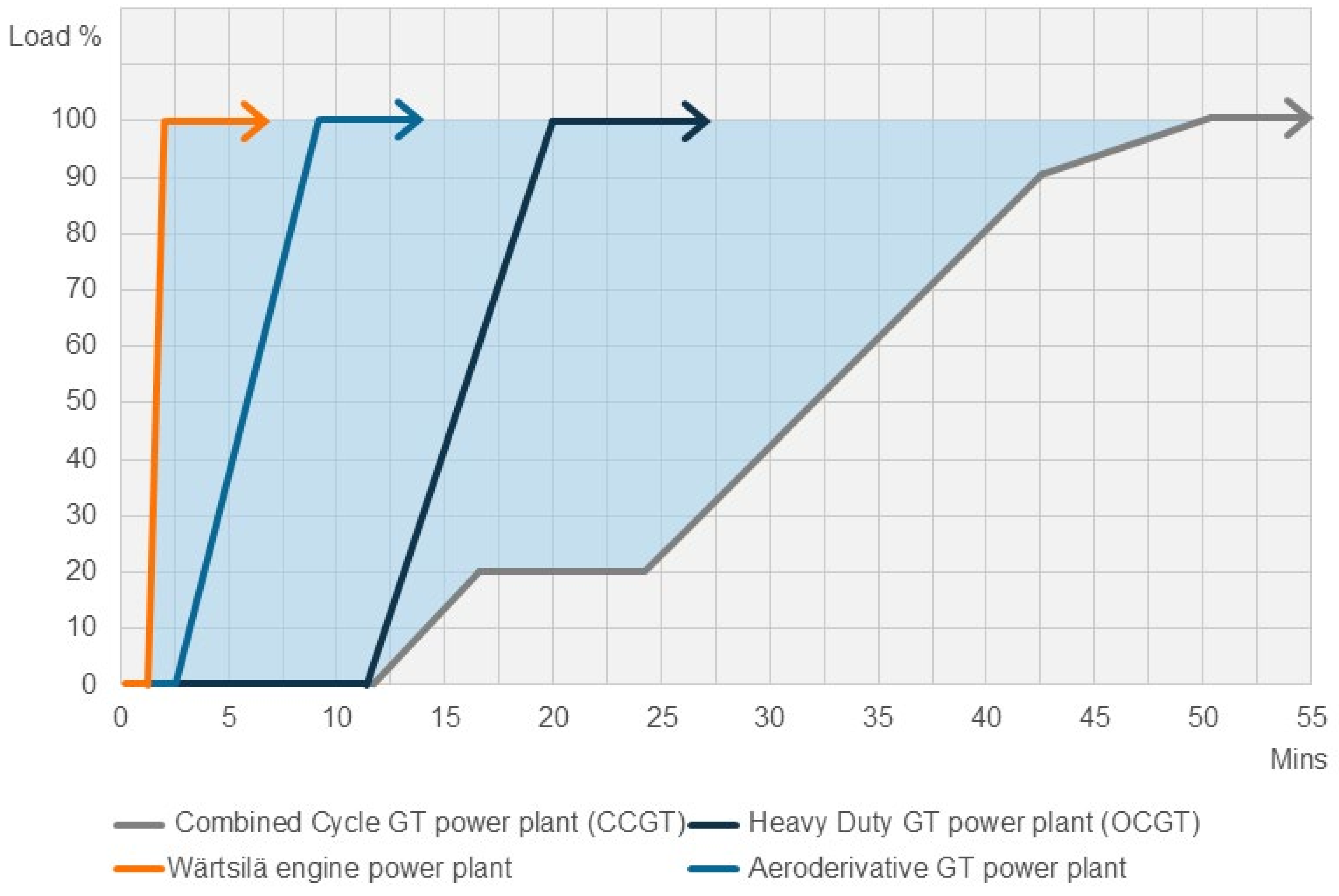
- Supply-side Flexibility
  - Generation units can rapidly ramp up its production in response to demand increases
- Power Storages
  - Pumped Hydro Power Stations
  - Utility-scale battery
  - EV
  - Demand-side Flexibility/Elasticity
    - Demand Response Management
- Grid Flexibility
  - Transmission capacity

A conceptual framework for system flexibility
IRENA(2018): *Power system flexibility for the energy transition*



- **High Ramp up/down Rate**
- **Low Start-up and Shut-Down Costs**
- **Low Minimum Load and high efficiency at minimum load**
- **High efficiency at minimum load**

Flexibility Parameter of Generation Technology: Ramp-up rates of Different Gas Turbines



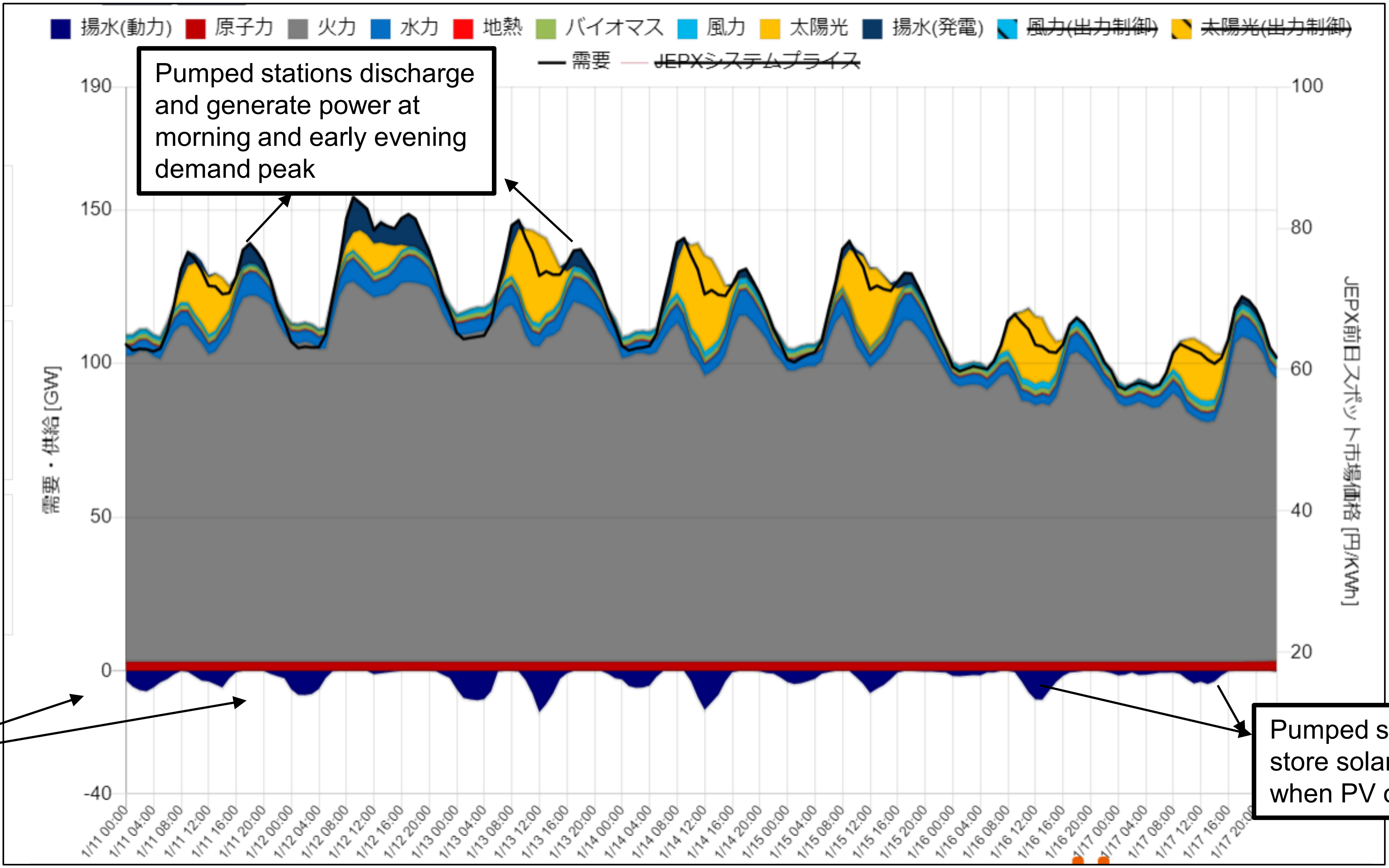
Introduction(III):
Flexibility Issues in Japanese Power System

Regional Demand, Capacity, and Reserve Rates Landscape of System Flexibility

		Hokkaido	Tohoku	Tokyo	Hokuriku	Chubu	Kansai	Shikoku	Chugoku	Kyushu	Total
Demand in 2020(TWh)		30.38	81.13	279.49	28.59	130.30	140.29	26.83	58.45	83.71	859
Installed Capacity(MW)	Gas	569	10,383	34,328	425	14,083	11,175	935	3,882	5,357	81,137
	Oil	1,900	600	8,701	1,240	1,856	3,899	1,350	2,205	649	22,401
	Nuclear	–	–	–	–	–	826	890	–	1,180	2,896
	Biomass	–	–	–	–	–	200	–	112	–	312
	Coal	2,350	8,608	8,804	2,900	4,506	4,586	3,773	4,797	7,604	47,928
	Hydro	796	2,187	3,150	2,033	2,188	2,913	780	771	1,294	16,112
	pumpHydro	800	3,062	8,823	–	4,442	5,271	686	2,123	2,350	27,558
	PV	1,771	5,624	14,310	943	7,962	5,120	2,260	4,359	8,048	50,397
	Wind	406	1,323	420	125	239	124	190	241	370	3,438
	In Total	8,592	31,787	78,536	7,666	35,276	34,113	10,864	18,490	26,852	252,177
Annual Generation Capacity(TWh)		33	126	316	35	131	134	47	69	100	989
Reserve Rate		107%	155%	113%	121%	101%	95%	174%	118%	119%	115%
Flexible Resource	Gas + oil(%)	41.7%	48.1%	75.0%	26.5%	66.8%	61.9%	27.0%	48.4%	33.1%	57.6%
Renewables	Wind(%)	2.3%	1.9%	0.2%	0.7%	0.3%	0.2%	0.7%	0.6%	0.7%	0.6%
	Solar(%)	6.5%	5.4%	5.4%	3.3%	7.3%	4.6%	5.8%	7.6%	9.7%	6.1%
	Hydro(%)	9.8%	7.0%	4.0%	23.5%	6.7%	8.7%	6.7%	4.5%	5.2%	6.5%
Base load & Inflexible Resource	Nuclear(%)	0.0%	0.0%	0.0%	0.0%	0.0%	4.9%	15.3%	0.0%	9.5%	2.3%
	Coal(%)	39.7%	37.7%	15.3%	46.1%	18.9%	18.8%	44.5%	38.1%	41.9%	26.6%

Annual Generation Capacity = Install capacity times the available hours(capacity factors)
供給予備力は、需要電力の8%から10%程度、確保する。--
奈良, 宏一 (2008). 『*電力自由化と系統技術: 新ビジネスと電気エネルギー供給の将来*』

A Typical Weekly Power Dispatch Pattern: The role of flexible sources



Pumped stations discharge and generate power at morning and early evening demand peak

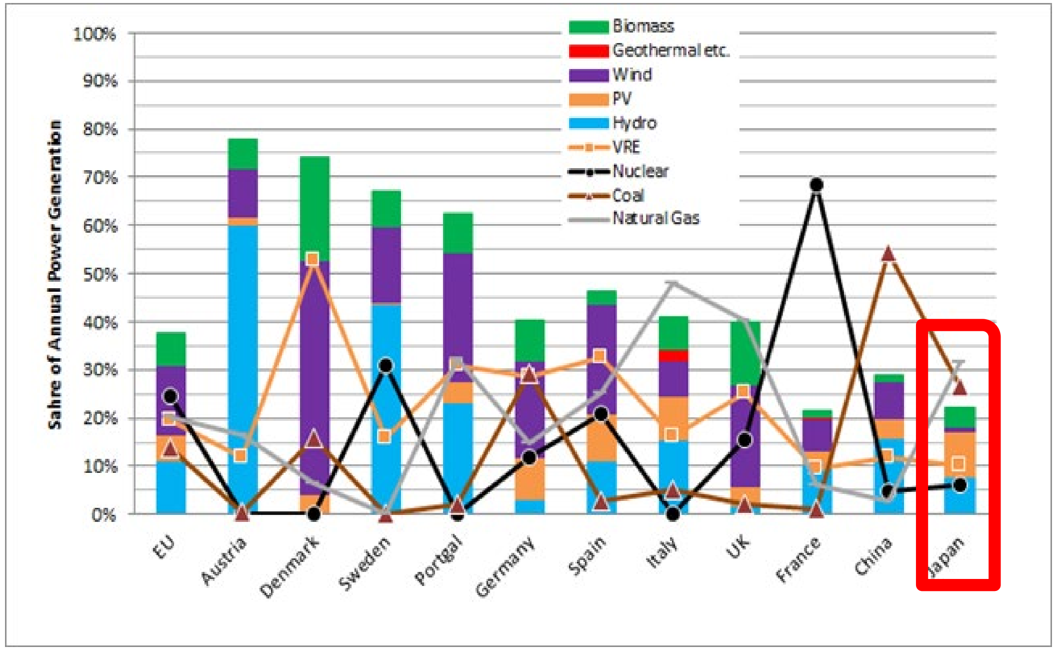
Regional TSOs do not provide individual gas turbine generation information.

Pumped stations store power **before dawn at low demand hours.**

Pumped stations recharge and store solar power at noon when PV output is high.

Power System with high PV rate:
High PV rate and Flexible issues within a day

Inflexible Issues may arise at the morning and early evening demand peak at which the solar output is low



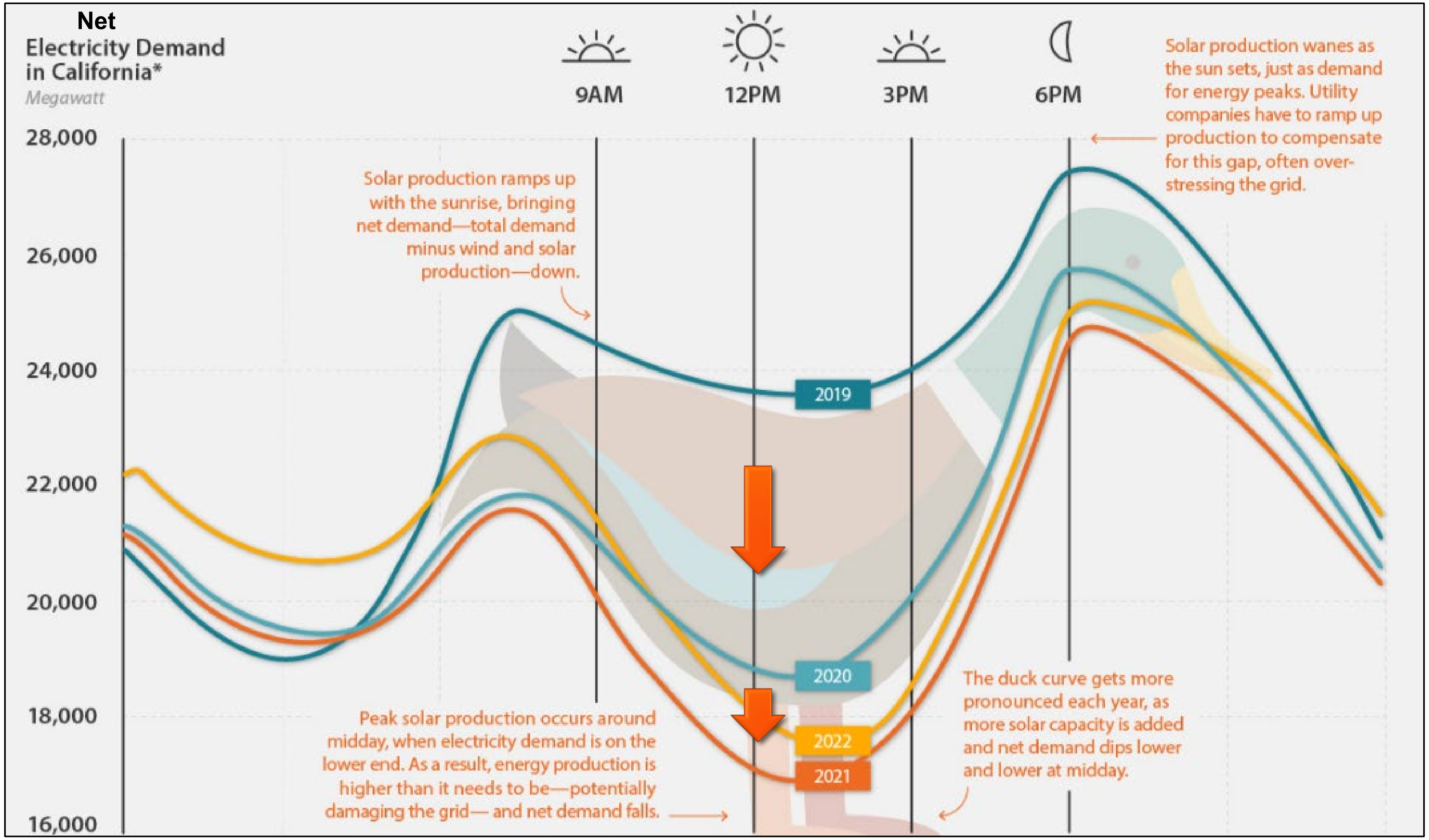
The Japanese Power system is among the systems with highest PV rates

Merit-order effects at noon?
Ramp down effects?

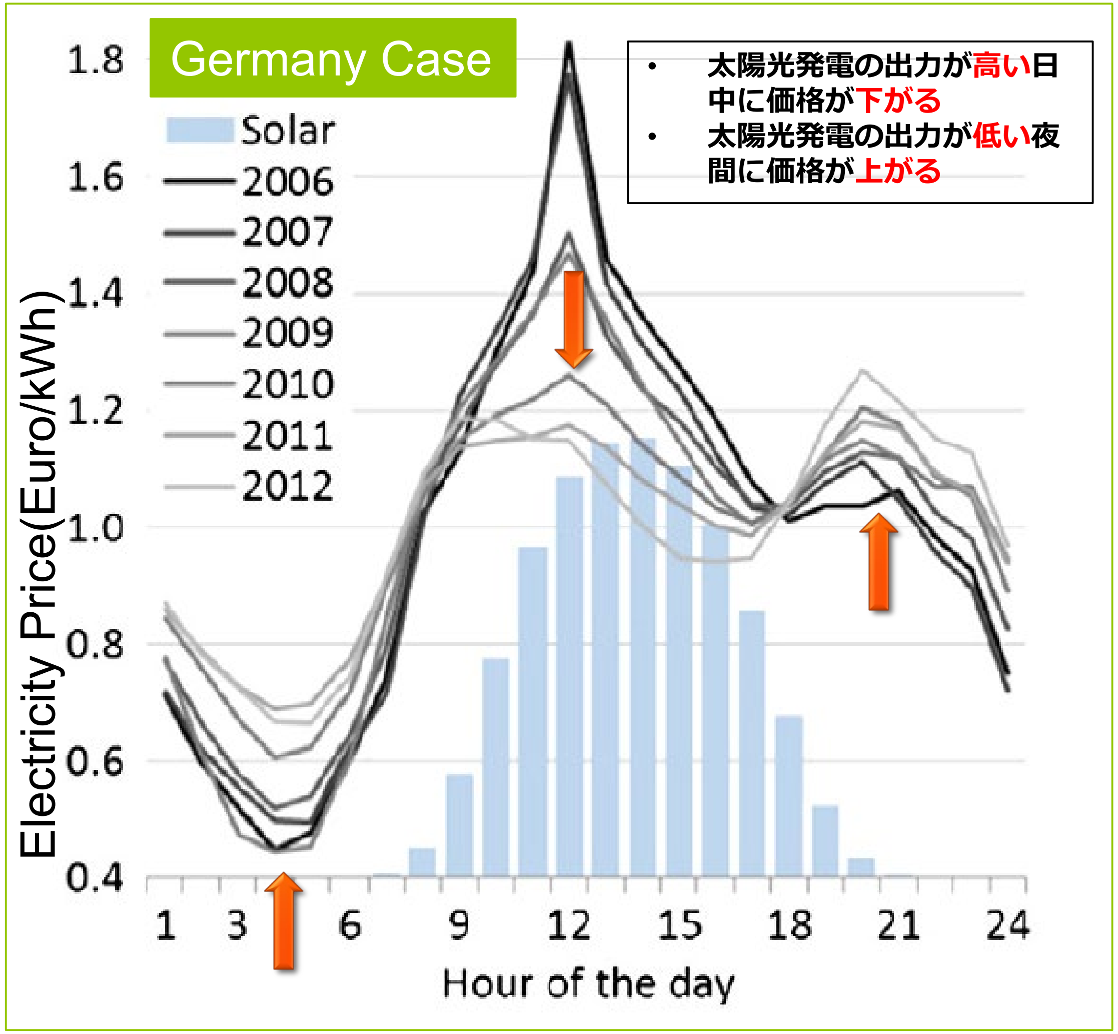
Inflexible Issues may arise at the morning and early evening demand peak at which the solar output is low

Solar Power Duck Curve in California

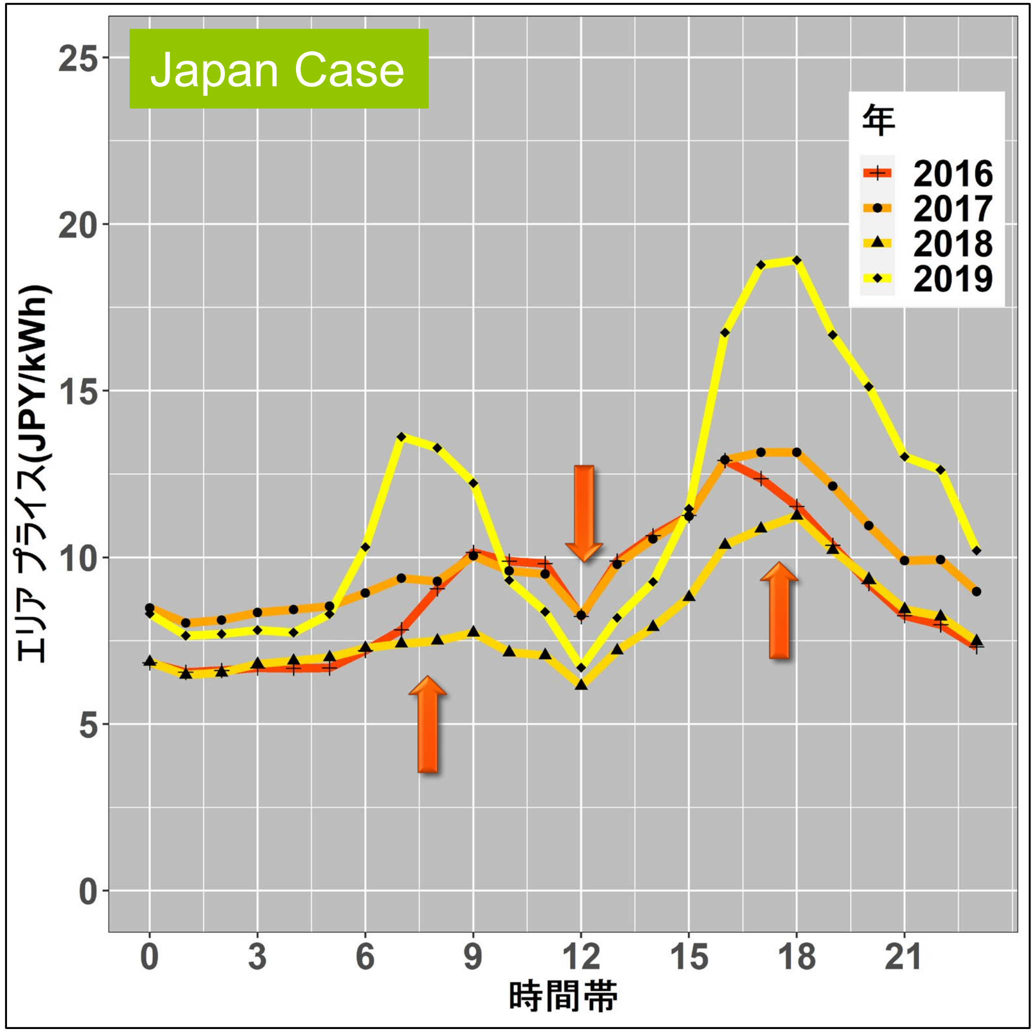
- Flattering the Duck Curve



太陽光発電の出力は、1日以内に電力価格のダイナミクスを変更する



出所:Hirth, L. (2013).



出所: JPEX データ に基づいて筆者作成.

2 Methodology:
The Optimal Dispatching Model

The Optimal Dispatching Model

$$\min_{\{Outputs\ of\ dispatchable\ Plants\ i\}} \quad Total\ Cost \quad = \sum_{t=1}^{24} \sum_{i=1}^{n} costs\ of\ individual\ dispatchable\ plants$$

$$subject\ to \begin{cases} \sum Demand_m = \sum Supply_n & for\ Node\ i \quad (1) \\ \sum flow_i \leqslant Tranmission\_Capacity_t & for\ each\ branch\ t \quad (2) \\ Other\ Constraints... \end{cases}$$

- (1) is Equality Constraint; (2) is Inequality Constraint
- The existence and the uniqueness of the solution are ensured by the convex conditions for the generating cost functions, and the decreasing marginal utility assumptions for the demand functions

The Optimal Dispatching Model

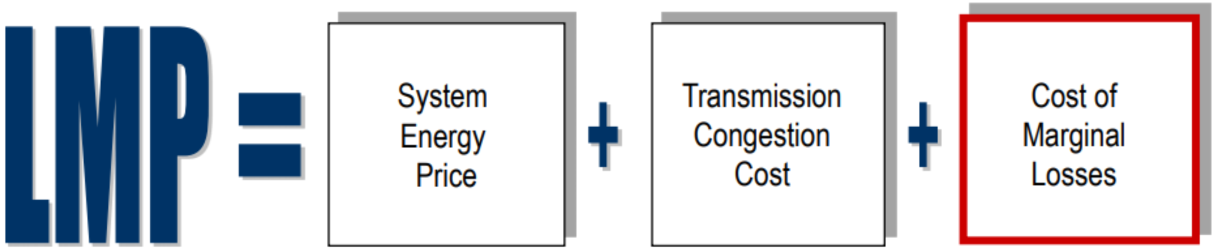
- Social Planners(TSO) Optimal Problem: "The second theorem of welfare economics"
  - Simultaneously accounting for many factors: installed capacity, hourly demand, transmission capacity, transmission loss, renewable variability, reserve requirements, ramp up and down time, storage…
  - High spatial and time resolution with nonlinear characteristics
- Shadow Price/Valuation for energy, transmission capacity, reserve capacity, …
- It has been used widely for energy planning:
  - Komiyama and Fujii, 2019: EMF35 JMIP & IEEJ-NE
  - 安田陽 and 濱崎博, 2020: TIMES model
  - 内藤克彦, 栗山昭久 et al. ,2021: PROMOD Security constrained unit commitment model
  - Shiraishi Sensei, 2022: PLEXOS
- It could also be used for exploring historical outrage events and other Extreme Events:
  - A recent study by Wu et al. (2021) uses the optimal dispatch model to explore the causes of the 2021 Texas power outage and provides corrective measures to mitigate the severity of outages.
  - UNIT COMMITMENT AND ECONOMIC DISPATCH model usually has similar results to the optimal dispatch model but is quite time-consuming.

Shadow Energy Price: Locational Marginal Price(LMP)

- LMP is defined as the least cost to **service the next increment of demand** at that location consistent with all power system operating constraints(Fu & Li, 2006).

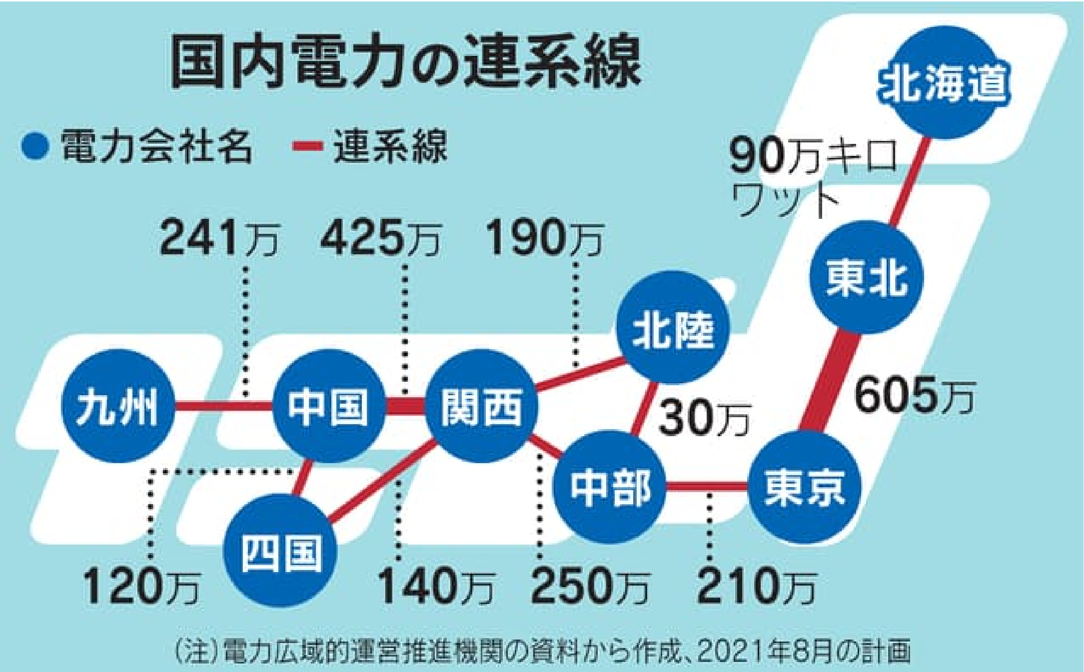
$$LMP_{it} \triangleq \frac{\partial Cost_{it}^{*}\left(Q_{it},\ldots\right)}{\partial Q_{it}^{*}}$$

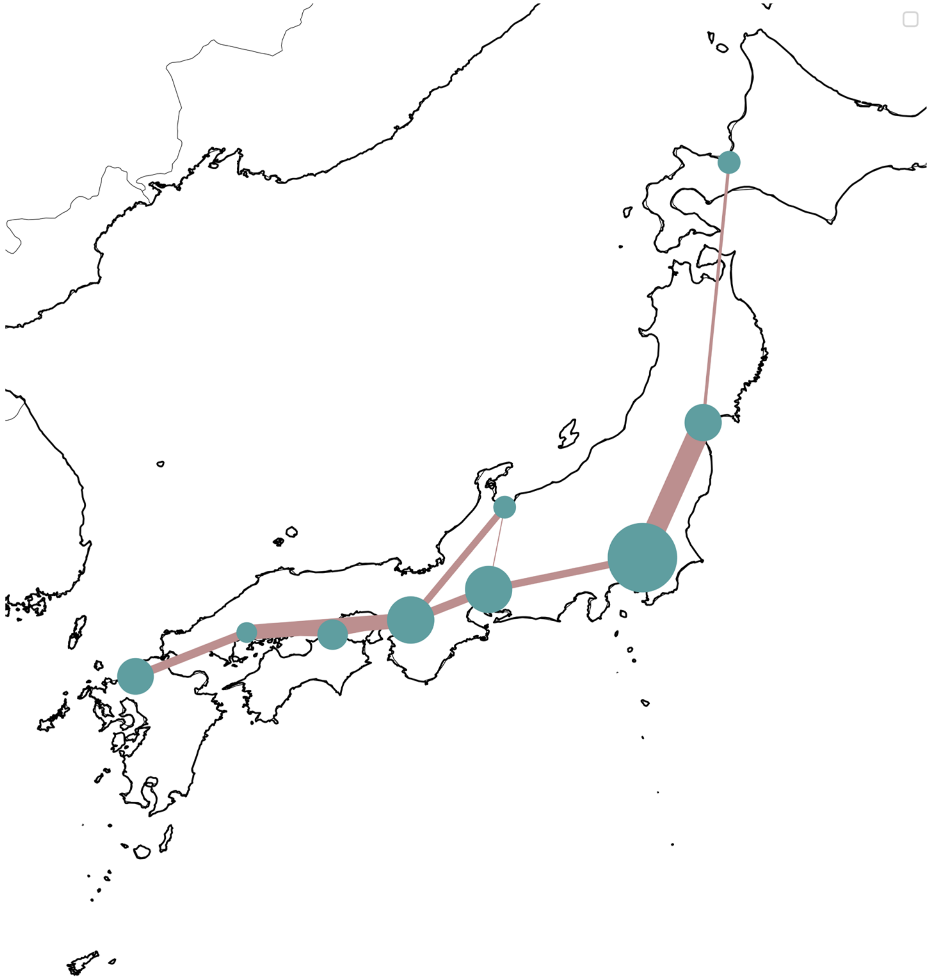
- And therefore, could be decomposed into three components, including the system energy price, the transmission congestion price, and the cost of marginal losses.



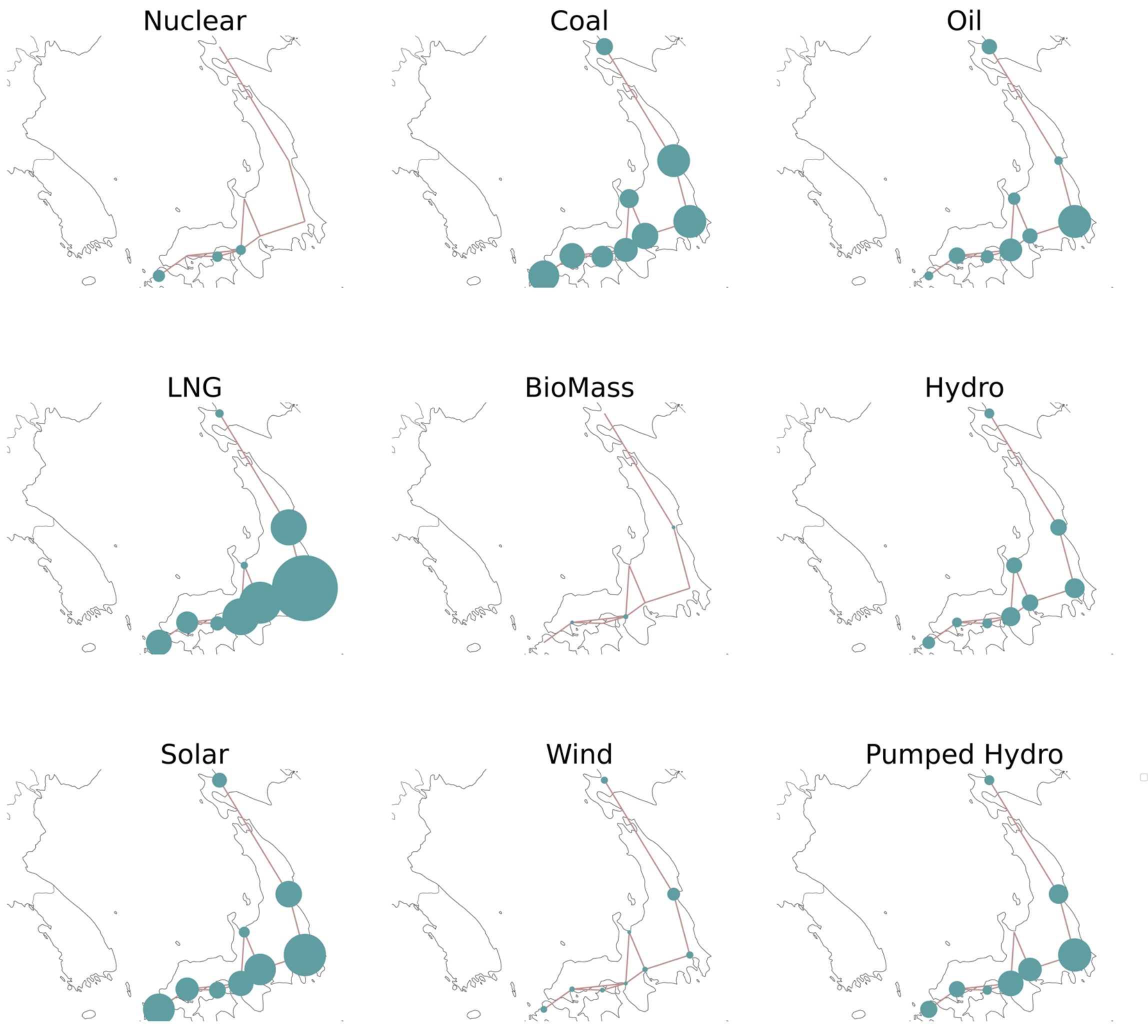
- LMP is comparable with the wholesale price in the electricity market
  - The wholesale price equals the highest marginal cost of the generators at serving
  - LMP = Wholesale price**(??)**

Dispatch Zones and Transmission Lines



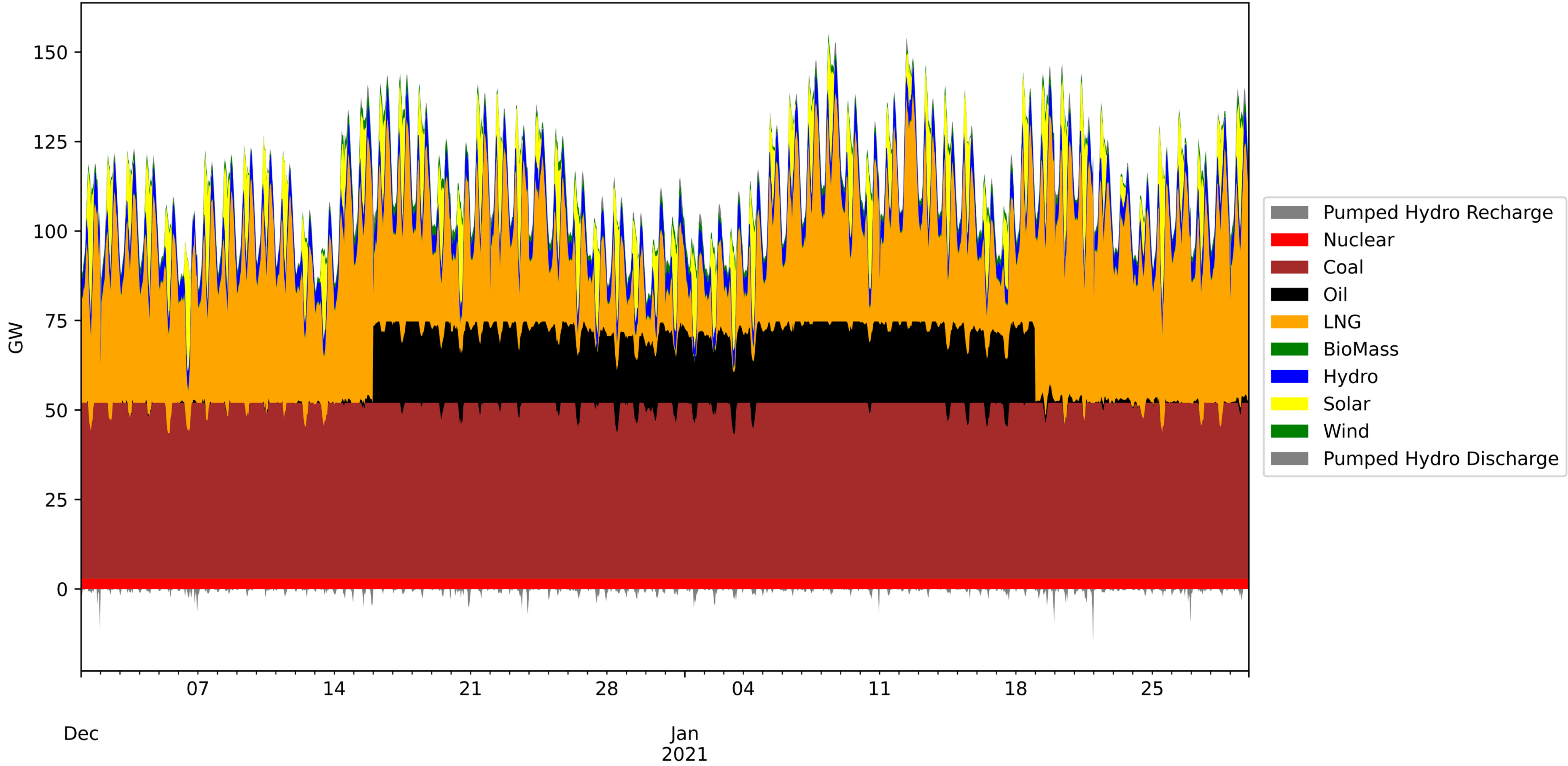


Geographical Distribution of Generation Capacity (Slide Page 13)

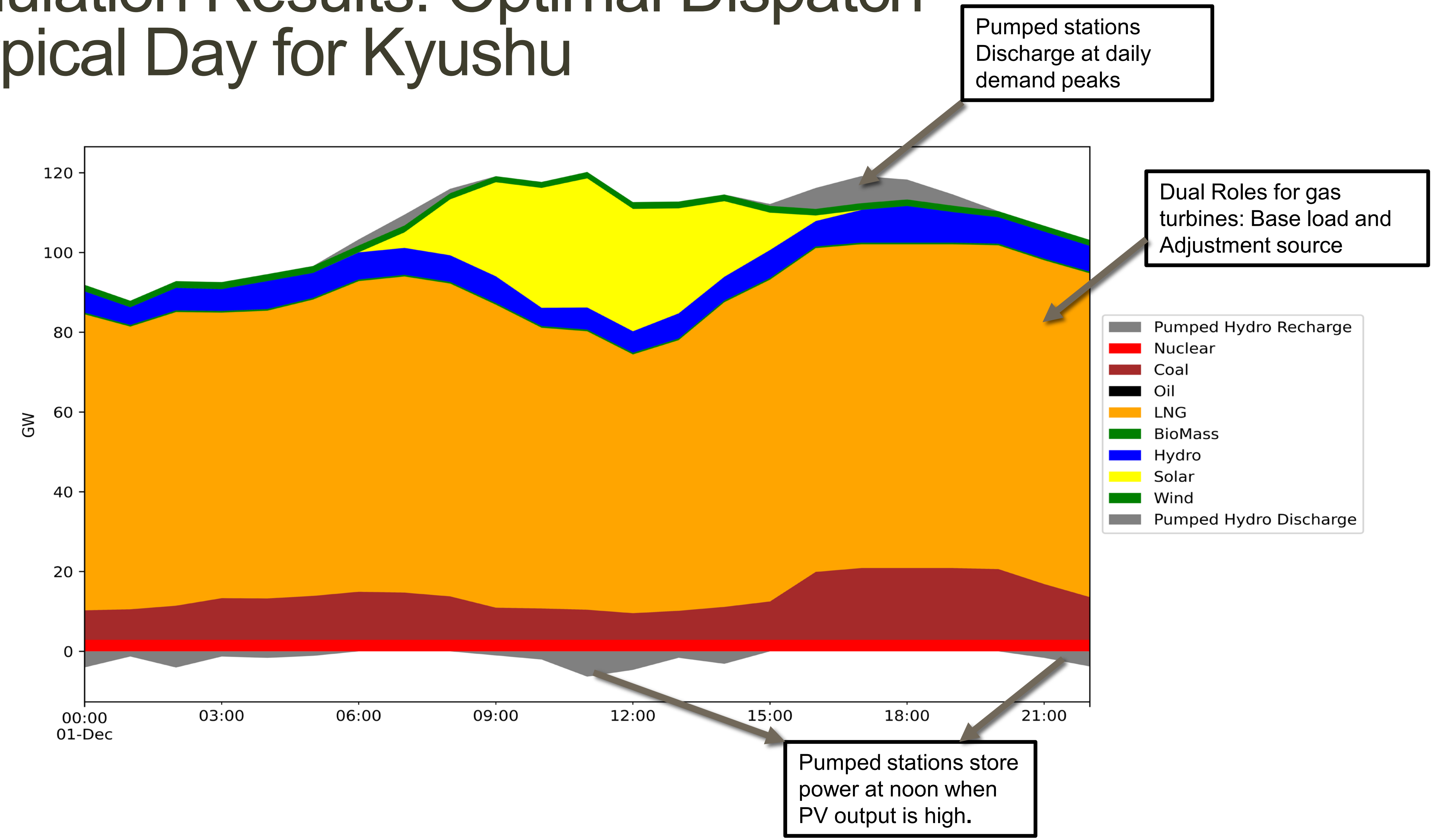


3 Simulation Results

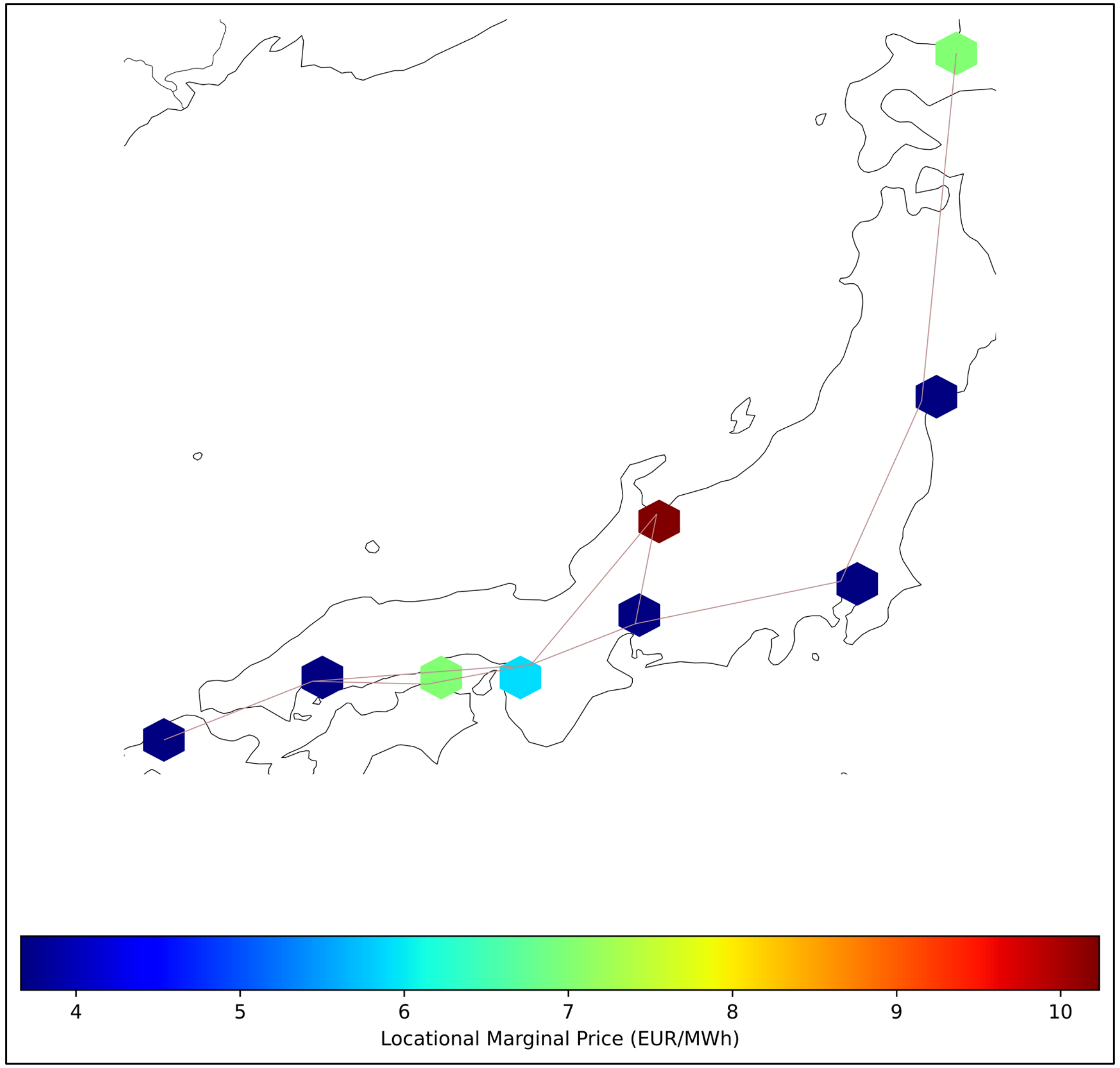
Simulation Results: Optimal Dispatch
Optimal Dispatch from Dec 2020 to Jan 2021



Simulation Results: Optimal Dispatch A typical Day for Kyushu

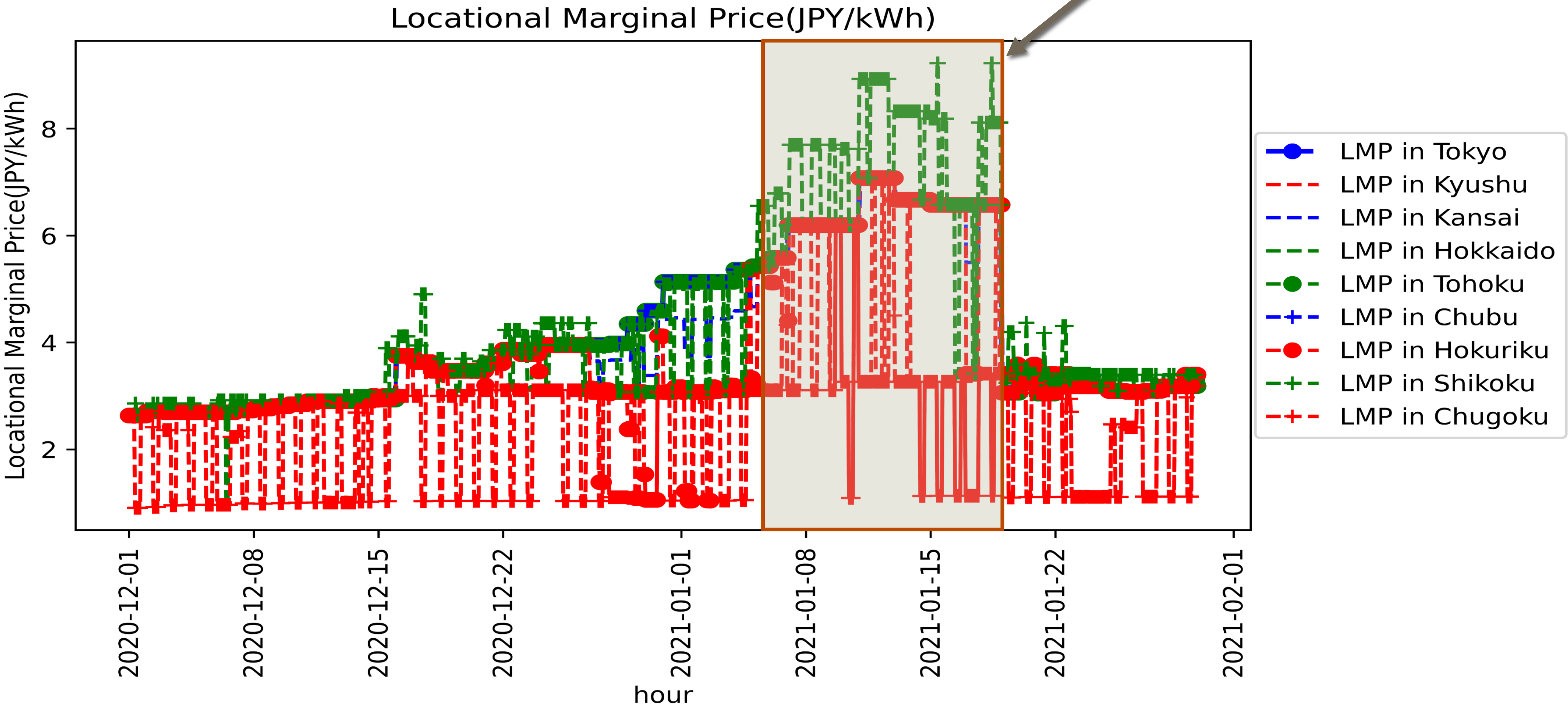


Simulation Results: Regional LMP(I) Geographical Distribution of LMPs

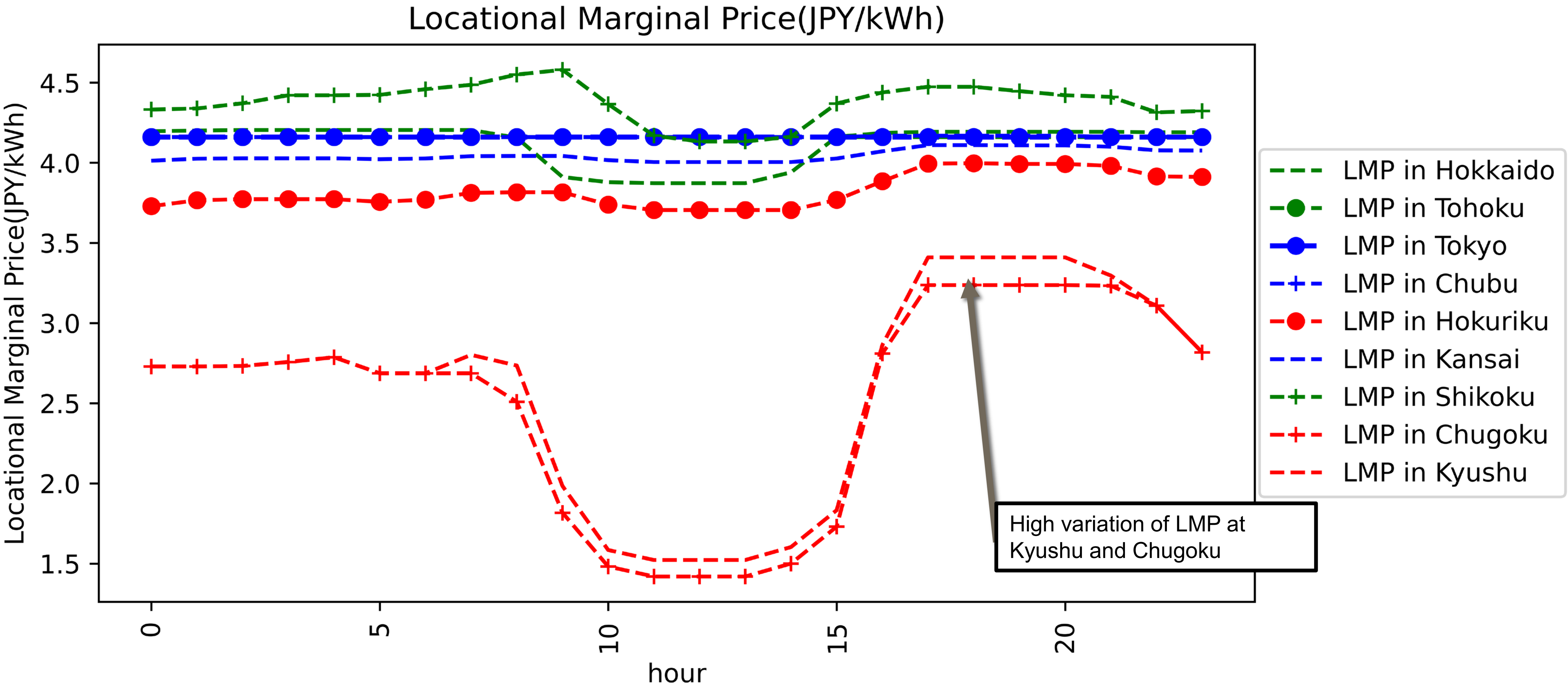


Simulation Results: Regional LMP(I) Price Peaks in Mid-January

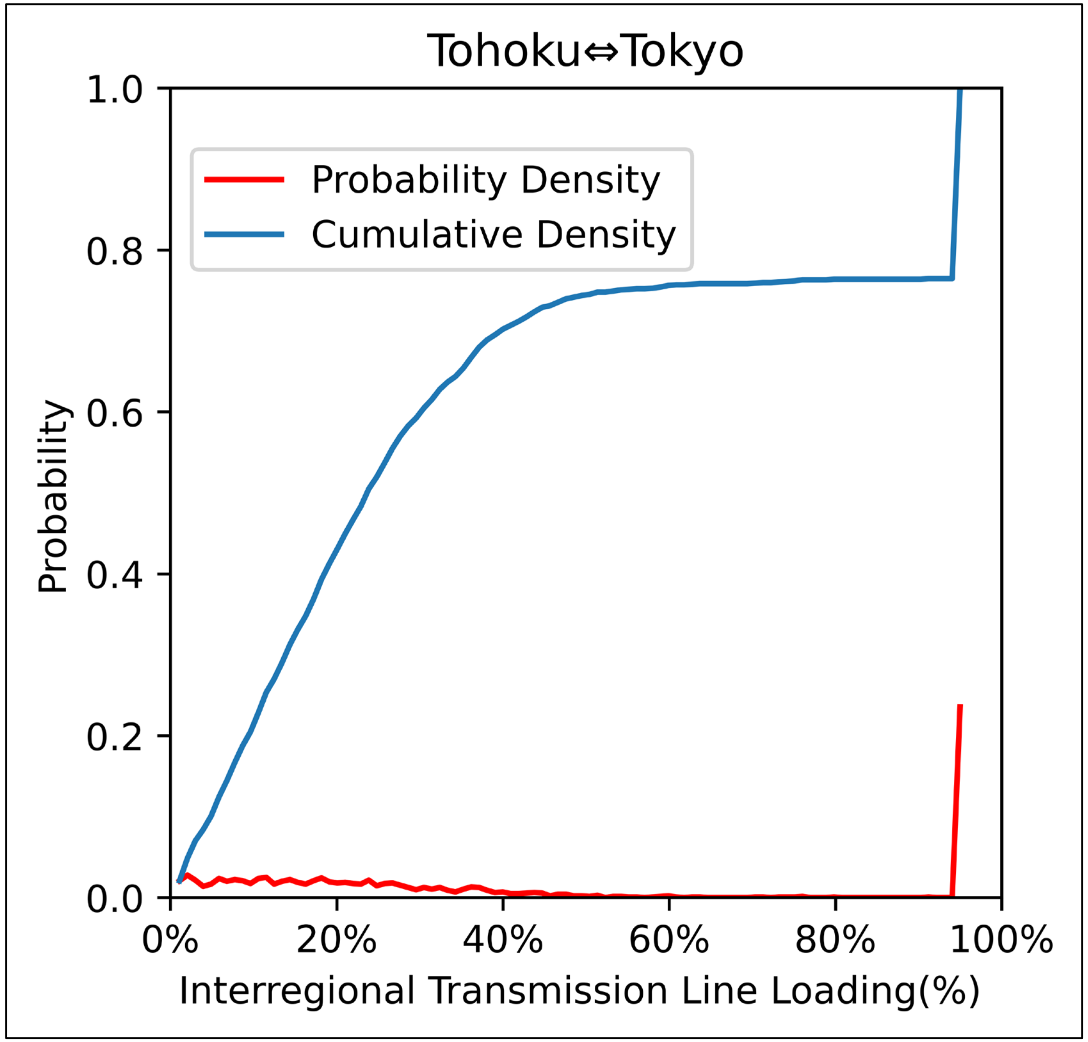
Price spikes at mid-January

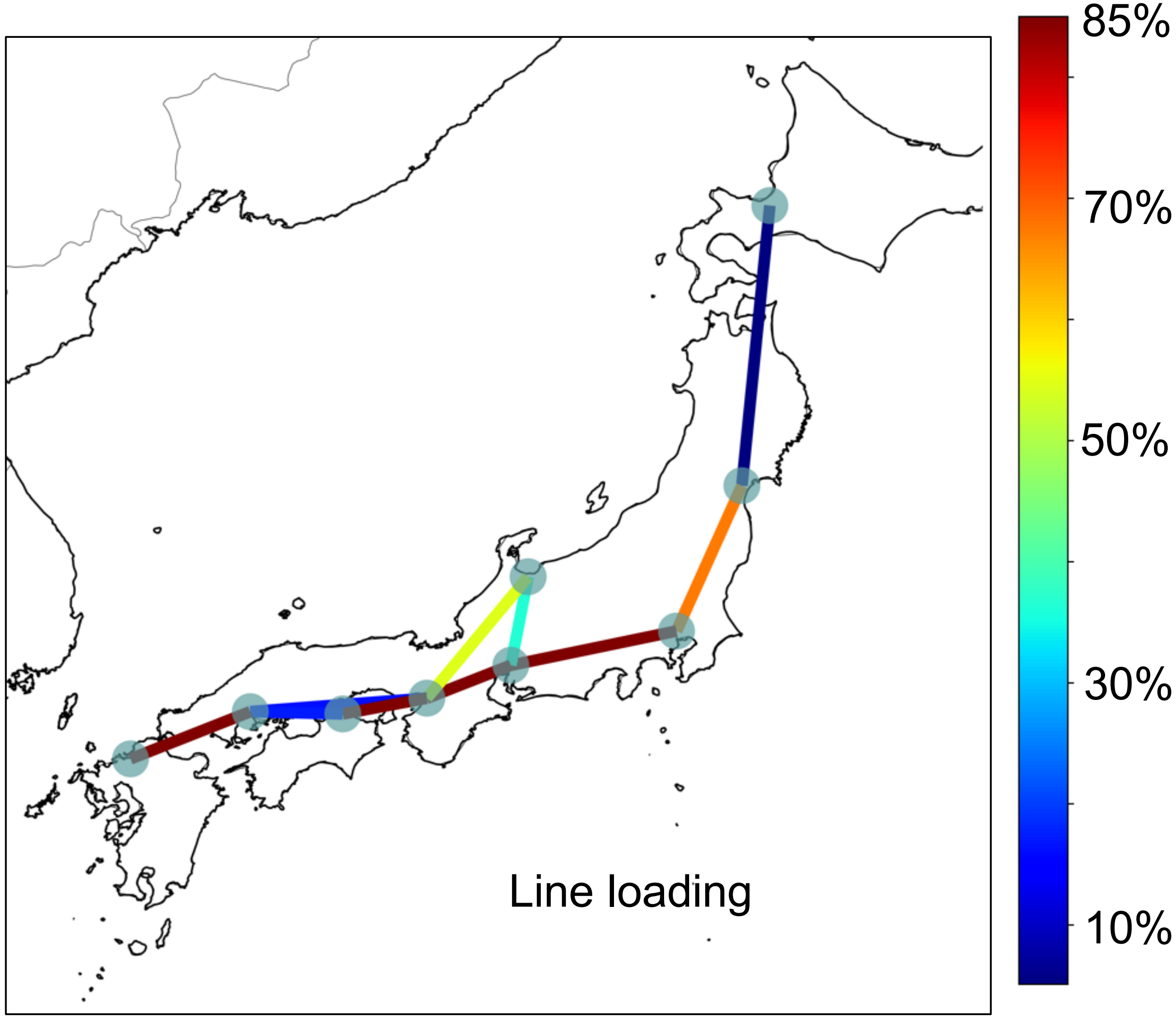


Simulation Results: Regional Average LMP by Hour(II) Price Spikes at the Morning and early Evening Peaks



Other results from the models: Interregional Transmission, Economic Valuation of storage and capacity market, renewable curtailment, carbon emission policy, required system reserve, loss/excess of load, integration costs …

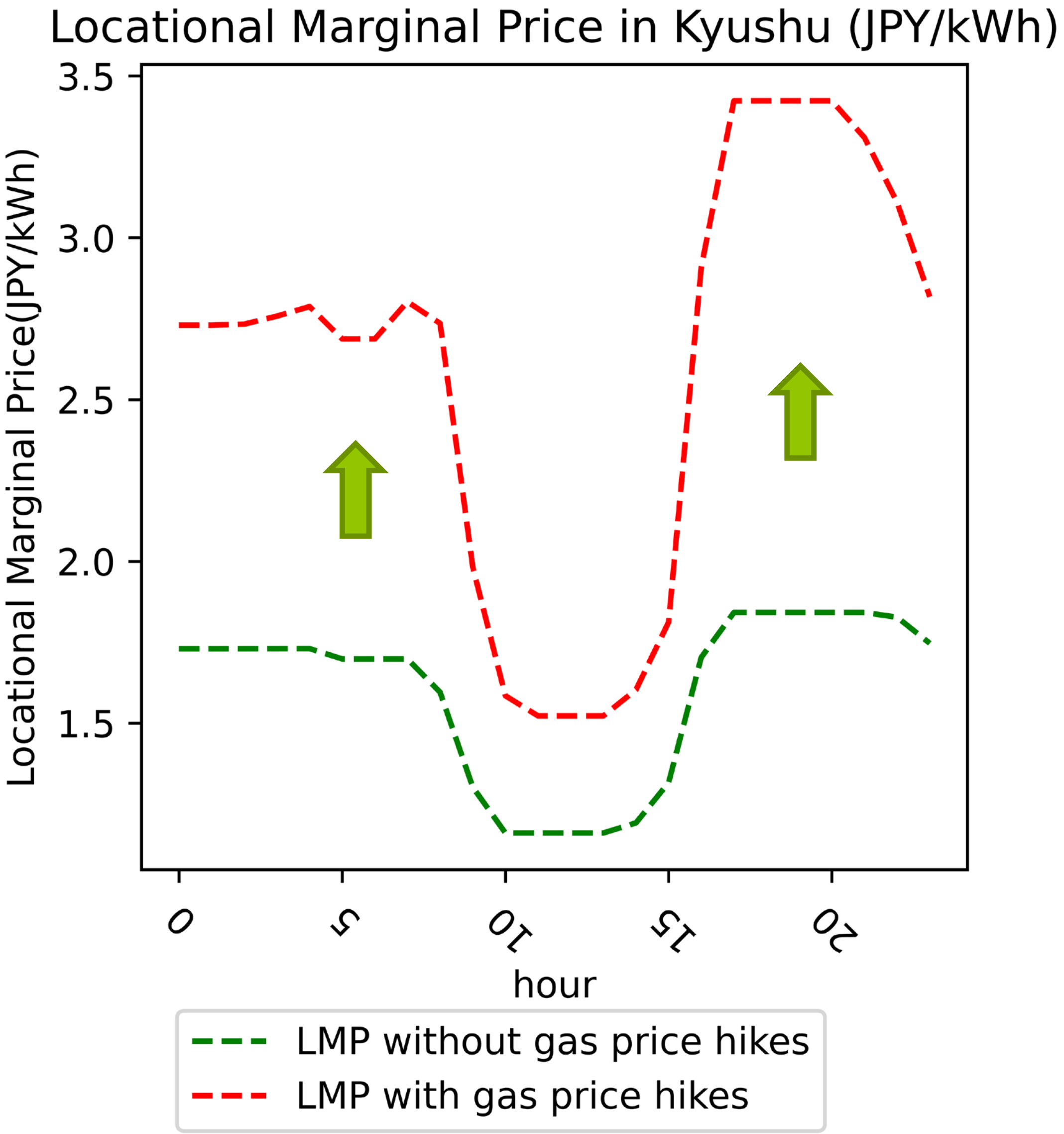




4 Scenario analysis: What-if LNG price were no higher than the annual average price?

The impacts of LNG price: Kyushu Case

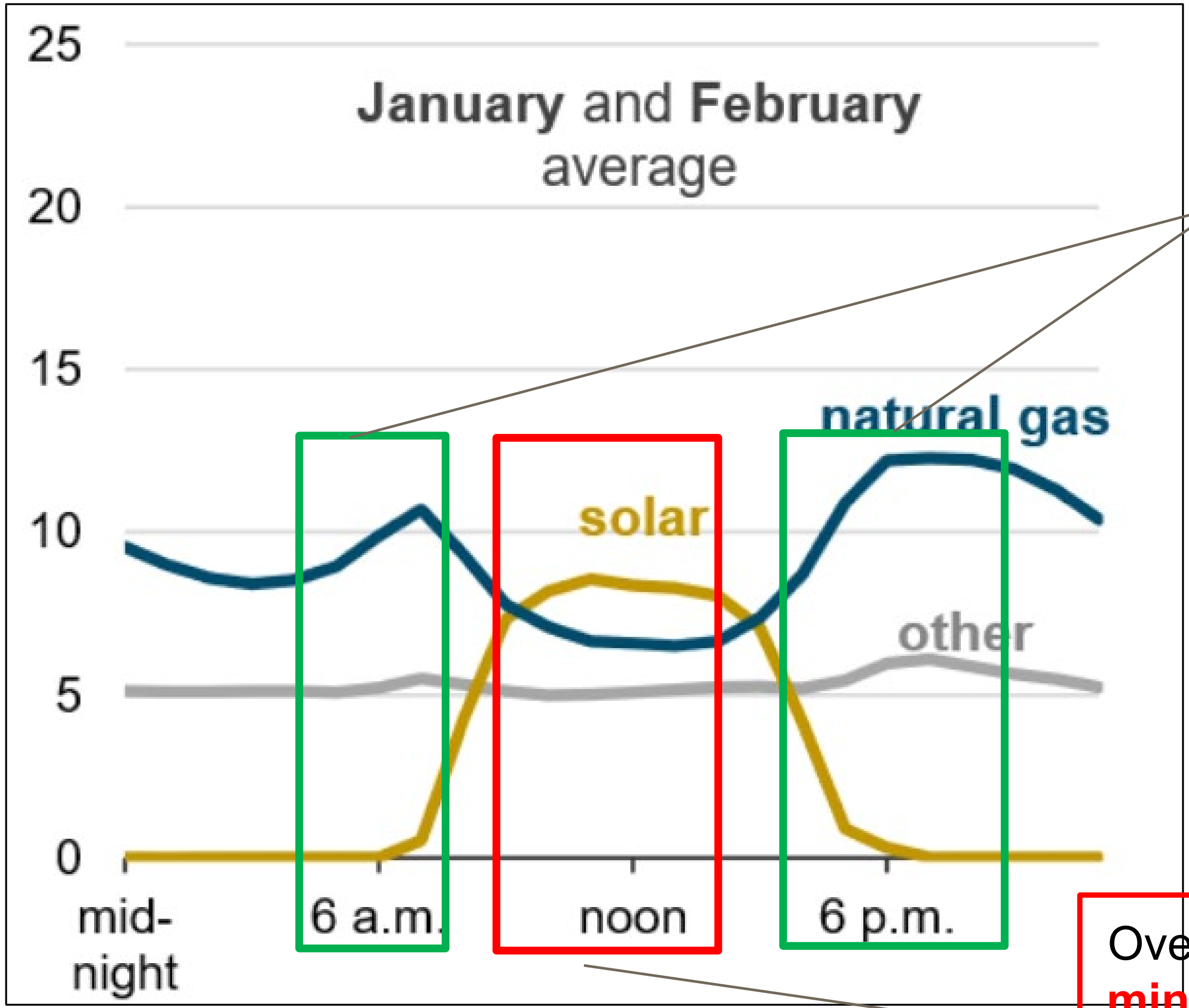
- Kyushu has the highest proportion of solar power output
- LNG price hike will increase the power price throughout the day
- But has disproportionate impacts
  - Low impacts during Demand Valley
  - High impacts during Demand Peak
- In other words, high LNG price magnifies the duck curve effects and threatens the system flexibility



Interpretation of Simulation Results: The roles of Gas Turbines in System Flexibility

- During the morning peak, demand is increased and gas turbines start to work and increase the cost.
- During midday, PV production progressively increases as solar radiation increases.
- Gas turbines are either shut down or are kept working at their minimum load when PV reaches its peak load.
- However, owing to their minimum-up time and ramp-down rate limits, gas turbines continue to provide energy to the power system, resulting in an overgeneration issue and a negative power price.
- During the evening peak, PV output fades away with sunset. The gas turbines are turned on or ramped up to ensure that the electricity supply is enough to meet the peak demand. The generation cost is high due to the start-up and ramp-up costs.

The roles of Gas Turbines in System Flexibility(II)



Demand peak period, gas turbines **ramp up** and increase their output; Pumped hydro stations **discharges**; Power price spikes.

Therefore, increases in LNG price will increase the power price at demand peak period but has less impact on the power price at the over-supply periods.

Over-supply period, gas turbines work **at their minimum loads** with **low efficiency**; Pumped Hydro stations **recharge**; Price dropped to **negative or zero**.

Back to the model…

  - OPF model could be used to identify the inflexibility issues and to plan for the future power system with high renewable penetration.
  - OPF model cannot be used to identify the monopoly problem or the information asymmetry issues.
- OPF model *versus* Merit Order model
  - The merit order curve model solely takes into consideration the varying generating costs of various generator types.
  - By contrast, the Optimal Power Flow model further accounts for the ramp-up/down activities of flexible sources, including ramp rate and costs.
  - For instance, in the high renewable penetration era, variability of RES output increases the importance of ramp-up/down activities.
  - Therefore, OPF is better than the merit order curve.
  - Merit order model cannot explain the zero price at midday because there is no 100% of RE supply in Japan.
  - By contrast, the OPF model indicates that the zero price at midday is due to the excess supply of electricity.

Conclusions & Policy Implications

Conclusions & Policy Implications

- The OPF simulation model works as a sandbox. We could change the parameters to **mimic the various changes** in the real world.
- This study focuses on the impacts of high LNG prices on flexibility capacity in the power system and electricity price by using the OPF model.
- Major Results
  - The power system needs **cost-effective flexible sources** to compensate for the intraday variation of PV outputs as well as the hourly variation of power demand,
  - Increases in the LNG price have a **disproportionate impact** on the electricity price in the wholesale market:
    - At midday, there would be an **over-generation issue**, which leads to negative prices
    - At demand peak, there would be **a lack of flexible issues**, which leads to price spikes.
  - The high LNG price raised ramp-up costs, which ultimately led to a price spike during peak hours.

Policy Implications:
Flattering the Duck Curve through Enhancing Flexibility

- In the **short** run, more flexible sources are needed to reduce the fluctuation of power price and prevent the power outage, especially with the growing RES penetration.
  - ✓E.g. **Renewal & Upgrading** of conventional power plants to scale up their ramp up/down rates
  - ✓E.g. Increasing the **minimum capacity of conventional plants** to avoid shut-down during the over-supply hours at midday and to reduce the corresponding start-up and shut-up costs
  - ✓DR measures: Governments calls for a **reduction of electricity demand** during peak hours.
- In the **long** run, promoting the system flexibility through:
  - ✓E.g. Adoption of utility-scale batteries,
  - ✓E.g. Enhancing the interregional transmission capacities,
  - ✓E.g. building VPPs to increase the demand-side flexibility
  - ✓E.g. building the capacity market
  - ✓E.g. Charge and discharge of EVs have the potential to flatter the duck curve

Future Studies:

- More Calibration of the current OPF model
- Interpretation of more results from the model
- **Optimal Investment** to improve system flexibility and prevent power outages in extreme events
  - The flexible measures such as investment in storage, transmission expansion, and upgrade of conventional internal combustion units are **completing each other**.
  - What is the best policy mix to reduce the generation costs under high RES penetration and in extreme events?

参考文献

- Alizadeh, M., Moghaddam, M. P., Amjady, N., Siano, P., & Sheikh-El-Eslami, M. (2016). Flexibility in future power systems with high renewable penetration: A review. *Renewable and Sustainable Energy Reviews, 57*, 1186-1193.
- Cretì, A., & Fontini, F. (2019). *Economics of electricity: Markets, competition and rules*: Cambridge University Press.
- Fu, Y., & Li, Z. (2006). *Different models and properties on LMP calculations.* Paper presented at the 2006 IEEE Power Engineering Society General Meeting.
- Hirth, L. (2013). "The market value of variable renewables: The effect of solar wind power variability on their relative price." *Energy Economics* 38: 218-236.
- Komiyama, R., & Fujii, Y. (2019). Optimal integration assessment of solar PV in Japan’s electric power grid. *Renewable Energy, 139*, 1012-1028.
- Komiyama, R., & Fujii, Y. (2021). Large-scale integration of offshore wind into the Japanese power grid. *Sustainability Science, 16*(2), 429-448.
- Liu, H., Tesfatsion, L., & Chowdhury, A. A. (2009). Derivation of locational marginal prices for restructured wholesale power markets. *Journal of Energy Markets, 2*(1), 3.
- Wu, D., Zheng, X., Xu, Y., Olsen, D., Xia, B., Singh, C., & Xie, L. (2021). An open-source model for simulation and corrective measure assessment of the 2021 Texas power outage. *arXiv preprint arXiv:2104.04146*.
- Yasuda, Y., et al. (Forthcoming). "Flexibility Chart 2.0: A simple tool to evaluate flexibility resource in various areas."

ご清聴ありがとうございました