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Nuclear Power Plants Shutdown and Alternative Power Plants Installation:
A nine-region spatial equilibrium analysis of the electric power market in Japan

HOSOE Nobuhiro
National Graduate Institute for Policy Studies (GRIPS)

Research Institute of Economy, Trade & Industry, IAA
The Research Institute of Economy, Trade and Industry
http://www.rieti.go.jp/en/

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A nine-region spatial equilibrium analysis of the electric power market in Japan*

HOSOE Nobuhiro†

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Abstract

After the Great East Japan Earthquake and the subsequent nuclear accident, nuclear power stations no longer can be presumed to be perfectly safe and thus hardly can be allowed to restart in Japan. In this study, we develop a nine-region spatial equilibrium model of the Japanese power market and simulate two-part situations: (a) none of the nuclear power plants can operate any longer and (b) gas turbine combined cycle (GTCC) power plants are installed to fully cover the lost capacity of the nuclear power plants. If all of the nuclear power plants are shut down, average power prices would rise by 1.5-3 yen/kWh. By replacing that lost capacity with the GTCC power plants, we could compress the average price rise by as high as 0.5-1.5 yen/kWh compared with the status quo. Their impact, however, would differ by region on the basis of the share of nuclear power in their plant portfolios. When nuclear power is fully available, inter-regional transmission is mainly driven by the abundant base-load capacity, including nuclear power, at night. After the nuclear power plant shutdown, regions with abundant nuclear power capacity would not be able to afford to sell their power to other regions, causing less serious congestion at the inter-regional transmission links. The installation of GTCC power plants would make the plant portfolios more similar among regions and reduce inter-regional transmission further, which would very rarely cause congestion. When we assume only boiling water reactors or old plants are shut down, the results indicate less serious impacts.

Keywords: Great East Japan Earthquake, Nuclear power station, Power prices, Inter-regional transmission

JEL Code: Q41, L94

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† Author correspondence: 7-22-1 Roppongi, Minato, Tokyo 106-8677, Japan. E-mail: nhosoe@grips.ac.jp

1. Objective

The Great East Japan Earthquake (hereinafter, just “the earthquake”) brought huge damage to the power system in Japan in two aspects. One is serious physical damage of the power plants and facilities in eastern Japan, including the Fukushima Daiichi Nuclear Power Station. The other is the loss of people’s confidence in nuclear technology and its regulatory system, which led to a long suspension of all the nuclear power plants whether they were destroyed by the tsunami after the earthquake, safely shut down, or not damaged by the earthquake at all. This resulted in a shortfall of plant capacity of as large as a quarter of the total capacity in Japan and triggered a power crisis in which there remains little prospect for restarting nuclear reactors (Figure 1.1). Takahashi and Nagata (2011) estimated that the total power generation costs would increase by 17% due to additional costs for nuclear safety and fossil fuels to cover their lost capacity in 2030 if no replacement were permitted for nuclear plants. Their estimate also indicated that the total nuclear plant capacity would become only 19GW in 2030 although it was 49GW before the earthquake.

Figure 1.1: Share of Nuclear Power Plant Capacity and its Generation by Region in 2010 [%]

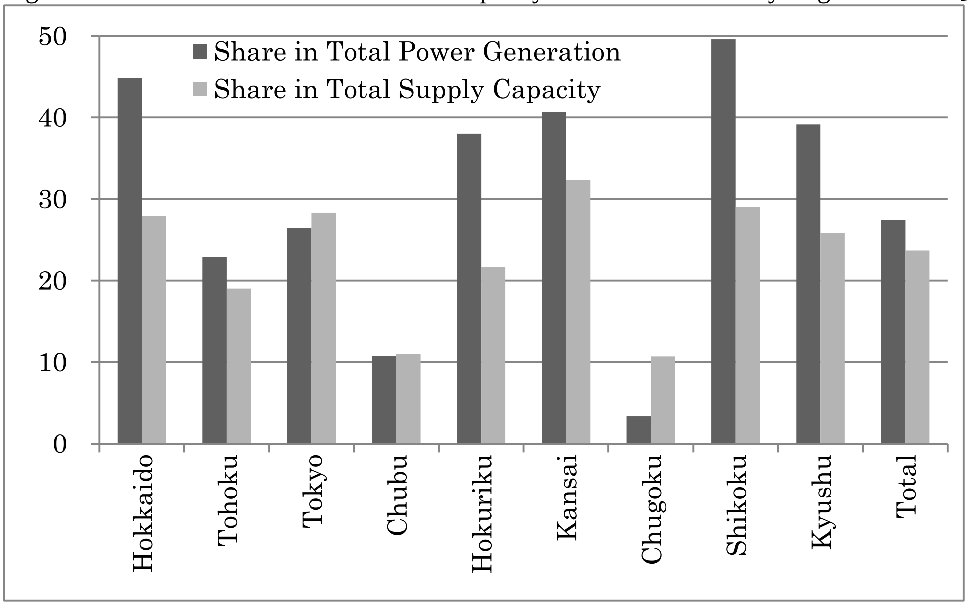
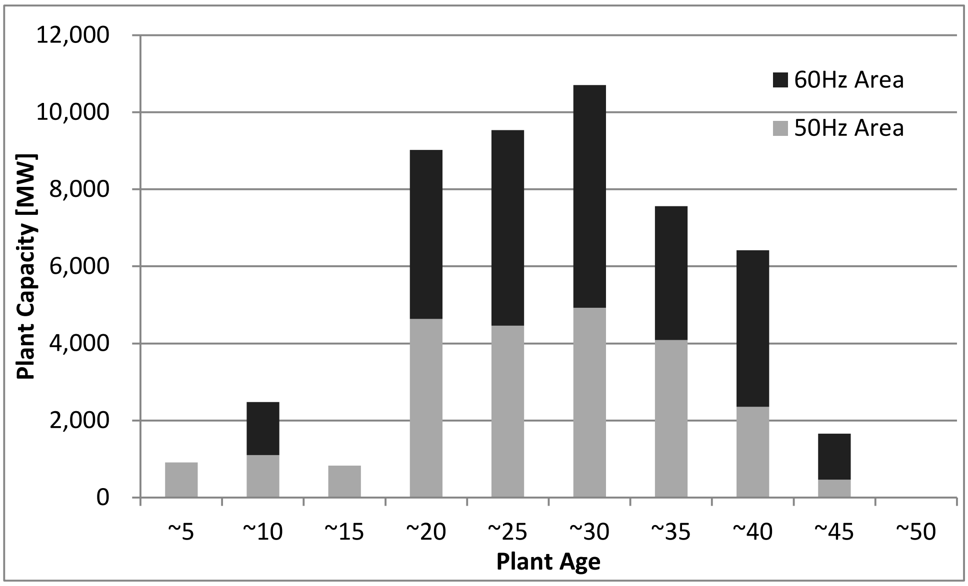


Figure 1.2: Age Distribution of Nuclear Power Plants in 50 Hz and 60 Hz Frequency Areas [MW]



Note: As of August 2013.

On the other hand, the crisis that we face now occurred because of the total nuclear power shutdown in 2013 and the utter uncertainty about the possibility and timing of resuming their operation. Therefore, we need to develop drastic and quick solutions to manage the crisis. However, the solution will not be simple. When a region suffers a capacity shortage of domestic power plants, its inbound transmission will be intensified and often cause congestion at such links, which will not allow any more imports. This concern is serious especially for the small-capacity link with frequency converters (FC) between the 50-Hz and the 60-Hz areas in the power network in Japan. (Hereinafter, we call it "the FC-link".) We need to consider whether their network capacity constraints, which were not considered by Takahashi and Nagata, could be bottlenecks in the power system. Akiyama and Hosoe (2011) examined the significance of these bottlenecks in the context of a transmission charge reform. After the earthquake, we have faced a power crisis with such bottlenecks in the network.

In our study, we simulate the power crisis caused by the nuclear power shutdown and examine its impacts on (a) regional power charges (in the wholesale markets) and (b) inter-regional transmission patterns by using a nine-region spatial and temporal price and allocation (STPA) model à la Akiyama and Hosoe (2011). We consider the cases of (a) nuclear power shutdown and (b) installation of gas-turbine combined cycle (GTCC) plants as their substitutes. Our simulation results show that a complete nuclear power shutdown would cause a price hike of 1.5-3 yen/kWh on average and that GTCC installation would be able to compress the hike to 0.5-1.5 yen/kWh. The GTCC installation would be effective especially during daytimes and/or peak seasons. A partial shutdown of old nuclear plants or boiling water reactor (BWR)-type nuclear power plants would not cause serious congestion in the power network.

Our paper proceeds as follows. The next section shows our STPA model and its estimation methods. Section 3 describes simulation scenarios and examines simulation results. Section 4 concludes our paper with policy implications. The appendix shows the results of sensitivity analysis with respect to the assumed price elasticity of demand.

2. STPA Model

2.1 Model Framework

We employ the Akiyama-Hosoe (2011) model, which distinguished nine regions in the Japanese power network and was based on the STPA model by Takayama and Judge (1971). We assume marginal-cost pricing in our analysis for simplicity. Details of the model framework were provided by Akiyama and Hosoe (2011); thus, we omit its description but focus on the model estimation method in the following part.

2.2 Model Estimation

2.2.1 Supply Side

To describe supply behavior for nine regions, we estimate merit-order curves, which are described by step-functions, based on the capacity, fuel consumption and prices, and power generation of major plants. Those major plants are held by nine vertically-integrated power companies, two major wholesalers, and joint-venture power producers with *Denryoku-jukyu-no-gaiyo* (*Abstract of Power Demand and Supply*) for 2004 and *Karyoku-genshiryoku-hatsudensho Setsubi-yoran* (*Thermal and Nuclear Power Plants Catalogue*) *for 2008*. Using fuel prices estimated with trade statistics, we can estimate the generation costs for each plant.[1] In addition to the existing plants, we also take account of

[1] Other than fuels, operation and maintenance costs can be considered but are omitted in our study for simplicity.

plants currently being constructed (Table 2.1). The generation costs of hydro, nuclear, and geothermal power stations as well as independent power producers are assumed to be zero yen/kWh. Although this assumption looks simple, this would not cause a serious bias in our simulation analysis as they can be very unlikely to be marginal plants in Japan.

Table 2.1: Fuel Costs [Yen/kWh] and Capacity of Thermal Plants [MW]

Hokkaido	Fuel Costs [Yen/kW]	Capacity [MW]
Tomato-Atsuma	3.11	1,650
Sunagawa	4.35	250
Naie	4.85	350
Shiriuchi2	7.16	350
New-GTCC[*1,*3]	7.44	0
Tomakomai (JV)	10.16	250
Shiriuchi1	10.44	350
Tomakomai	10.47	250

Tohoku	Fuel Costs [Yen/kW]	Capacity [MW]
Haramachi	3.07	2,000
Shinchi (JV)	3.19	2,000
Noshiro	3.22	1,200
Sakata (JV)	3.33	700
Niigata 4	5.01	250
Nakoso 7-9 (JV)	6.31	1,450
Sendai[*3]	7.44	446
Joetsu[*2,*3]	7.44	1,440
Higashi-Niigata[*3]	7.74	4,600
Shin-Sendai 2	8.54	600
Shin-Sendai 1	10.41	350
Nakoso6 (JV)	10.59	175
Akita	10.97	1,300

Hokuriku	Fuel Costs [Yen/kW]	Capacity [MW]
Tsuruga	3.11	1,200
Nanao-Ota	3.17	1,200
Toyama-Shinko (Coal1-2)	3.39	500
Toyama-Shinko (New)[*2,*3]	7.44	0
Fukui (Mikuni1)	10.90	250
Toyama-Shinko	11.21	1,000

Tokyo	Fuel Costs [Yen/kW]	Capacity [MW]
Hitachi-Naka	2.94	2,000
Hirono 5-6[*3]	2.94	1,200
Isogo (J-Power)	3.19	1,200
Kimitsu (JV)	3.95	1,365
Kashim (JV)	4.83	1,400
Shinagawa	5.95	1,140
Chiba	6.69	2,880
Yokohama	6.99	3,425
Kawasaki LNG[*3]	7.44	847
Ogishima Power[*3]	7.44	814
Futtsu[*2]	7.44	5,040
Higashi-Ogishima	8.26	2,000
Sodegaura	8.36	3,600
Goi	8.51	1,886
Kawasaki	8.59	3,420
Minami-Yokohama	8.72	1,150
Anegasaki	9.24	3,600
Yokosuka	9.92	4,400
Hirono1-4	10.07	3,200
Yokosuka	10.46	2,130
Oi	10.64	1,050

Chubu	Fuel Costs [Yen/kW]	Capacity [MW]
Hekinan	3.14	4,100
Shin-Nagoya	6.76	2,992
Kawagoe	7.12	4,802
Joetsu[*2,*3]	7.44	2,380
Chita-Daini	8.32	1,708
Yokkaichi	8.65	1,245
Chita	8.70	3,966
Nishi-Nagoya	10.12	1,190
Owase-Mita	10.35	875
Atsumi	10.37	1,900

Kansai	Fuel Costs [Yen/kW]	Capacity [MW]
Maizuru[*3]	2.94	1,800
Takasago (J-Power)	3.80	500
Wakayama (JV)	4.54	306
Himeji-Daiichi	6.89	1,442
Senboku-LNG[*3]	7.44	1,109
Himeji-Daini[*3]	7.44	2,919
Sakaiko[*2,*3]	7.44	2,000
Nanko	8.58	1,800
Miyazu-Energy Lab.	10.12	750
Tanagawa-Daini	10.18	1,200
Ako	10.23	1,200
Gobo	10.42	1,800
Kainan	10.43	2,100
Aioi	10.57	1,125

Chugoku	Fuel Costs [Yen/kW]	Capacity [MW]
Fukuyama (JV)	0.50	844
Kurashiki (JV)	0.70	613
Misumi	2.97	1,000
Shin-Onoda	3.13	1,000
Shimonoseki 1	3.22	175
Osaki	3.25	250
Mizushima 2	3.32	156
Takehara (J-Power)	3.47	1,300
New-GTCC[*1,*3]	7.44	0
Yanai	7.49	1,400
Mizushima 3	8.51	340
Mizushima 1	8.70	285
Shimonoseki 2	10.20	400
Tamashima	10.32	1,200
Kudamatsu	10.43	700
Iwakuni	10.45	850

Shikoku	Fuel Costs [Yen/kW]	Capacity [MW]
Tachibanawan	3.16	700
Tachibanawan (J-Power)	3.25	2,100
Saijo	3.32	406
Niihama-Nishi (JV)	3.65	150
Niihama-Higashi (JV)	3.97	23
Sakaide 2-3	5.19	1,150
Nyugawa (JV)	6.76	250
Sakaide 1[*2,*3]	7.44	296
Sakaide 4	8.51	350
Anan	10.34	1,245

Kyushu	Fuel Costs [Yen/kW]	Capacity [MW]
Oita (JV)	0.81	506
Reihoku	3.22	1,400
Matsuura	3.23	700
Matsuura (J-Power)	3.27	2,000
Karita (New 1)	3.29	360
Matsushima (J-Power)	3.58	1,000
Tobata (JV)	4.02	781
Shin-Oita	7.25	2,295
New-GTCC[*1,*3]	7.44	0
Shin-Kokura	8.73	1,800
Buzen	10.23	1,000
Aiura	10.72	875
Karita (New 2)	11.07	375
Sendai	11.31	1,000
Karatsu	11.34	875

Note:

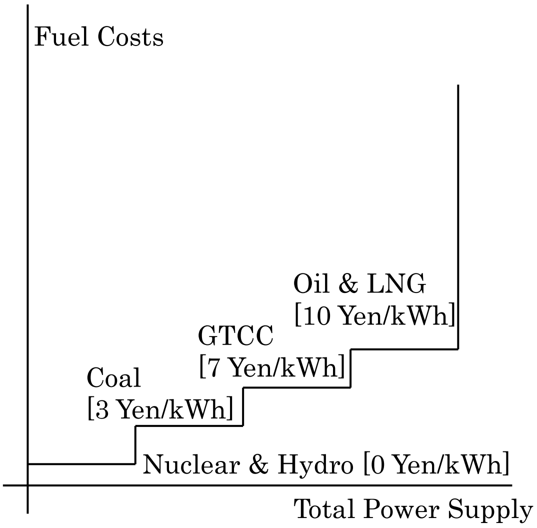
*1 Hypothetical one considered in the GTCC scenarios.

*2 Plants whose capacity is assumed to increase in the GTCC scenarios.

*3 Fuel costs are estimated/assumed based on fuel costs of similar plants.

As the fuel efficiency of newly- or hypothetically-installed plants is not yet known, we assume that the fuel efficiency of such coal-fired thermal plants (e.g., Tokyo Electric Power Company's (TEPCO) Hirono power plants No. 5 and 6 and Kansai Electric Power Company's (KEPCO) Maizuru No. 1 and 2) is equivalent to that of TEPCO's Hitachi-Naka power plant and similarly that the fuel efficiency of such GTCC plants is equivalent to that of TEPCO's Futtsu power station.[1] Power plants that have been remodeled to LNG-fired thermal or GTCC plants are assumed to be as fuel-efficient as TEPCO's Goi and Chubu Electric Power Company's (CEPCO) Chita power stations, which have had similar conversion, respectively. These marginal costs and capacity data for individual power plants are used to estimate so-called merit-order curves (Figure 2.1).

Figure 2.1: A Merit-order Curve



Note: The marginal costs indicated in this figure are typical ones while their details are shown in Table 2.1.

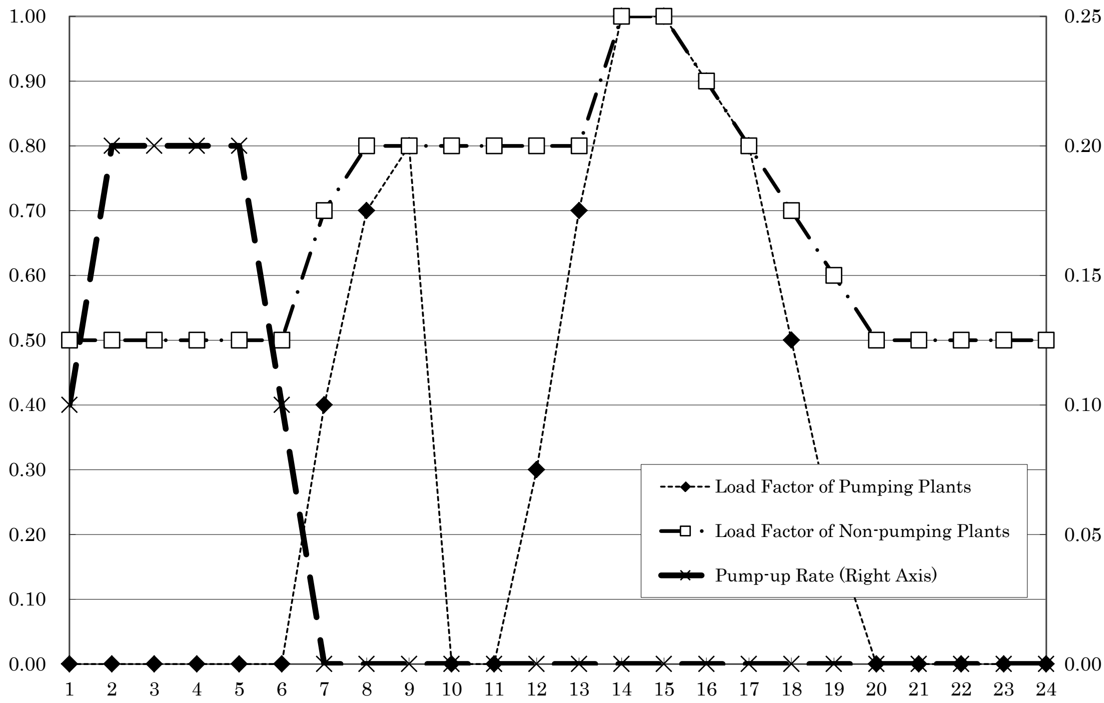
For simplicity, we do not assume any scheduled suspension of these thermal plants for inspection and maintenance as no public data of their schedules are available. This simplifying assumption will not crucially affect our results because most oil- and LNG-fired thermal plants are

[1] The Futtsu Power Station has first-generation GTCC plants, which are less fuel efficient than the third-generation ones most recently installed; thus, our assumption is conservative in this sense. However, we can use such an alternative assumption that conventional or aged plants are used to cover the supply capacity shortage. In this case, our assumption appears to be optimistic.

usually suspended during off-peak seasons, when they are not economical to operate. In contrast, while the assumption of full operation for base-load plants (i.e., nuclear and coal-fired thermal plants) may be restrictive, this assumption will not so seriously affect the results in the complete nuclear power shutdown case, which is the focus of our analysis.

Hydropower stations are operated flexibly to meet demand. Although their marginal costs can be estimated as their option prices, which determine their operation patterns, this makes our model too complicated. For simplicity, we assume exogenous typical operation patterns for pumping and other hydro plants, respectively, as shown in Figure 2.2. They are assumed to be zero-cost plants. Following Akiyama and Hosoe (2011), we assume that 50% of the pumping hydropower capacity is available for the (active) power supply in Tokyo while 100% of that is so in other regions.[2]

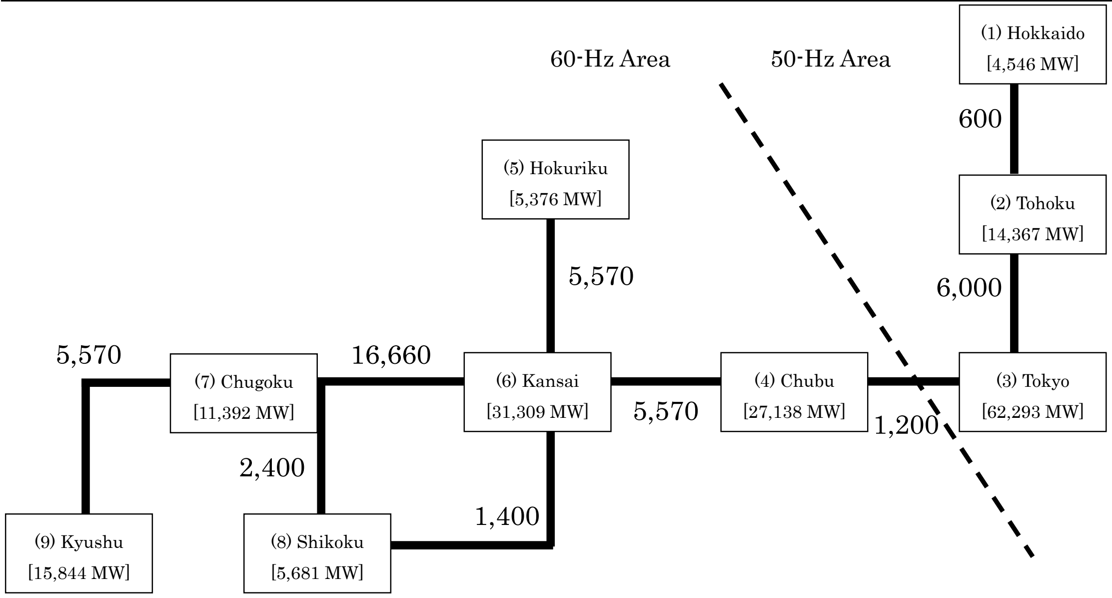
Figure 2.2: Hourly-operation Patterns of Hydro Plants
[Left axis: Load factor of hydro plants, maximum capacity=1.00,
Right axis: Portion of hourly pump-up operation in daily-total pump-up operation, total=1.00]



[2] Akiyama and Hosoe (2012) tried various patterns of availability of pumping hydro capacity in terms of active power supply and found that reasonable inter-regional transmission patterns were estimated when they assumed 40% or 50% of that capacity was available in Tokyo and 100% in the other regions.

Nine major inter-regional links connect the nine jurisdictions with each other and have their transmission capacity constraints (Figure 2.3). The FC-link is one of the nine major links and is often considered to be a critical bottleneck because it has a transmission capacity of only 1,200 MW, which is comparable to only 2% of the maximum load in the Tokyo region. The solution of the numerical model reports regional power generation, consumption, and power charges as well as inter-regional transmission patterns subject to transmission capacity constraints with postage-stamp style transmission charges.

Figure 2.3: Regional Peak Demand and Inter-regional Transmission Links and their Capacity [MW]



Source: Adopted from Akiyama & Hosoe (2012).

2.2.2 Demand Side

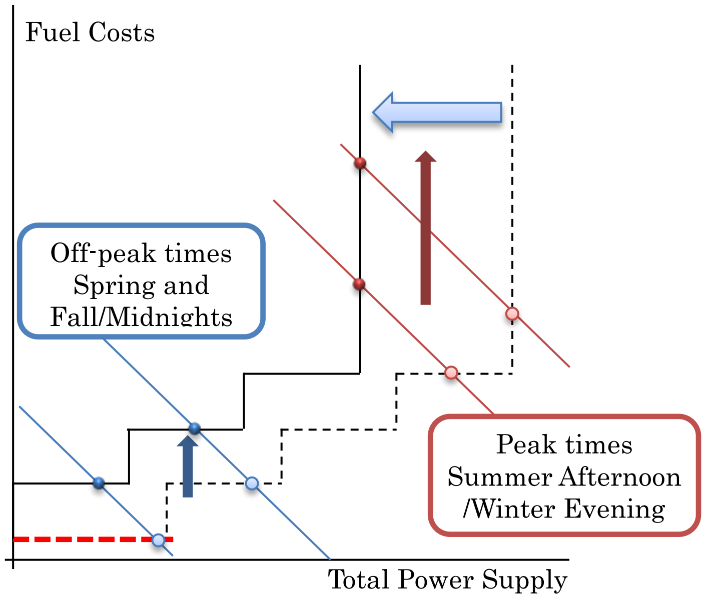
We assumed linear regional demand functions and calibrate their slope coefficients to demand the price elasticity (0.086–0.297) estimated by Hosoe and Akiyama (2009) and the demand at 3pm in August.[3] Their intercept terms were calibrated to the hourly demand of a representative day in every month. We prepared demand functions for 288 patterns (=24 hours x 12 months).

[3] We selected three days with maximum load in each month and computed the average of their hourly load from April 2010 to March 2011. Data source: METI Webpage: http://www.meti.go.jp/setsuden/performance.html

2.3 Impact of Nuclear Power Shutdown and Effect of Alternative Plants Installation

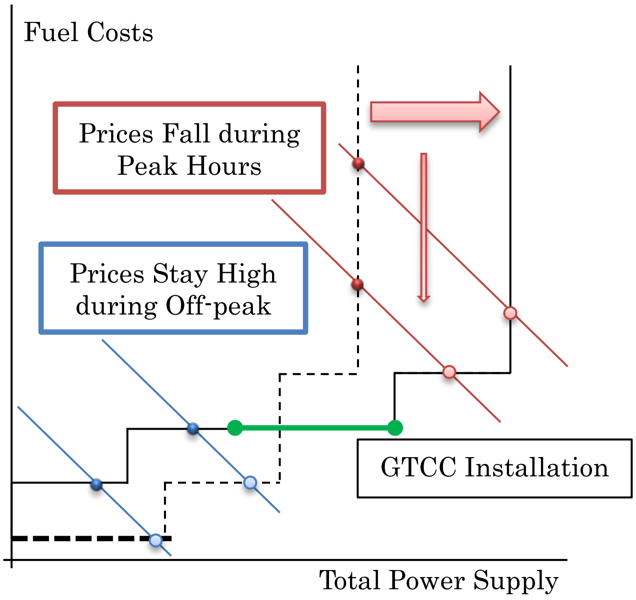
The unavailability of nuclear power plants can be represented by a drop of the lowest (red) segment of a merit-order function and its leftward shift (Figure 2.4). This does not cause a rise of the market price evenly among different times. In the off-peak hours, such as spring and fall, or midnights, it would not be large, but it would markedly rise during peak hours in summer and winter.

Figure 2.4: Nuclear Power Shutdown and Price Rise



The installation of alternative plants can be described with an insertion (or extension) of a middle (green) segment in the merit-order function (Figure 2.5). This lowers prices in peak hours, which are higher than the marginal costs of GTCC plants, to the original level, while it does not in off-peak hours. When we assume a smaller capacity of newly-installed plants than that of the lost nuclear power plants, the magnitude of the price fall will be accordingly smaller. Similarly, when we assume other types of plants as the substitute, the position of the green segment should be adjusted according to their assumed marginal costs at, say, 3 yen/kWh for a coal-fired thermal plant.

Figure 2.5: Effect of Alternative Plants Installation



While the single-region examination of the unavailability of nuclear power plants and the installation of substitute plants is simple as discussed above, the impact becomes more complicated in a multi-region setup with such capacity constraints for inter-regional transmission links that are shown in Figure 2.3. Nuclear power shutdown would cause a price rise in a region, which indicates a power shortage. If sufficient inbound transmission is made from other regions, the power price would fall as predicted above. However, this is possible only when transmission capacity constraints are not binding. Newly-installed power plants are supposed to ease power shortages not only in the domestic market but also in the foreign market. The allocation of power between these two markets would be also affected and constrained by the transmission capacity. Among many inter-regional links, the FC-link is recognized as the most critical bottleneck in Japan's power network. In the next section, we simulate the unavailability and installation of power plants with the STPA model and empirically predict their impact on the regional power markets.

3. Simulations

3.1 Base Run and Counter-factual Scenarios

We use the STPA model first to describe the base run without any shocks as a reference equilibrium while we validate our model in light of observed prices in the wholesale market. Then, we simulate a counter-factual situation without all the nuclear power plants (Scenario ALL) and the installation of new GTCC plants with capacity as large as the nuclear power plants have (Scenario ALL + GTCC). In addition to these extreme scenarios, we consider two variants. One is the case without any BWR-type nuclear power plants (Scenario BWR) and another includes new GTCC plants as large as the lost BWR nuclear power (Scenario BWR+GTCC). We also simulate the case without any nuclear power plants over 30 years old as of August 2013 (Scenario OLD) and the case assuming the installation of new GTCC plants that have capacity as large as the old nuclear power plants had (Scenario OLD + GTCC).

We depict the power demand and supply in 288 hours (= 24 hours x 12 months) based on the actual power demand in fiscal 2010. The base run result shows that prices ranges of 3-7 yen/kWh at night and 8-10 yen/kWh at peak times (Figure 3.1 and Table 3.1). Our estimates are reasonable in light of the actual spot market prices observed at Japan Electric Power Exchange (JPEX) before the earthquake (Figure 3.2).

Figure 3.1: Price Estimates in the Base Run [yen/kWh]

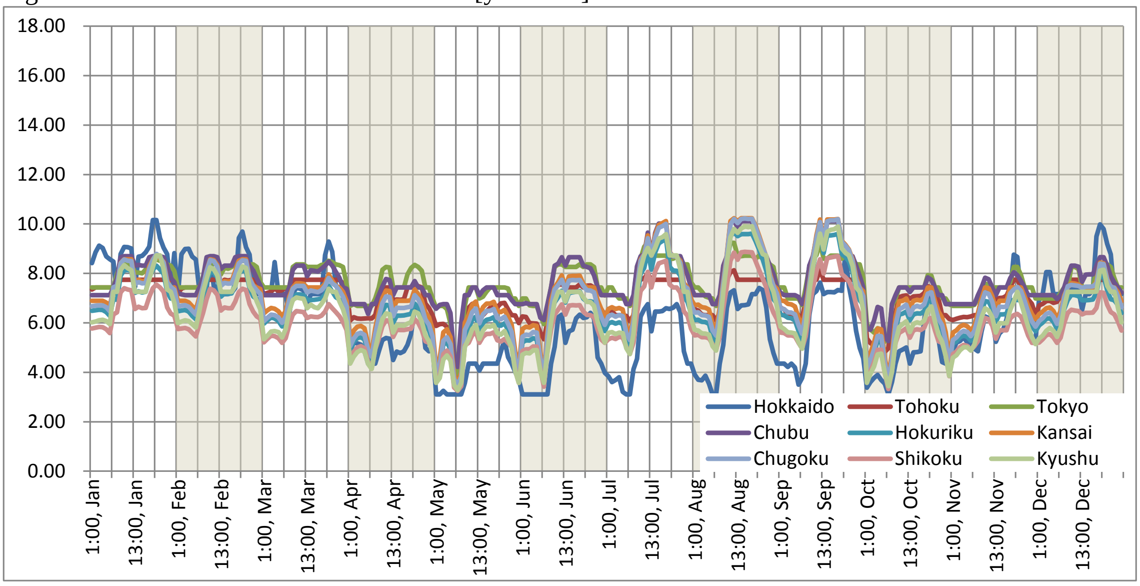
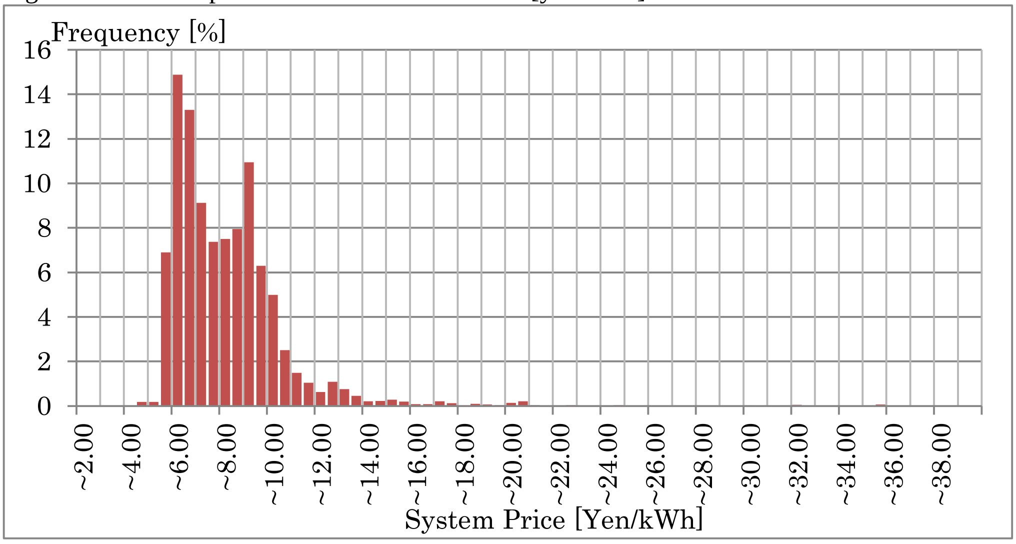


Table 3.1: Regional Power Charge Estimates [Annual Simple Mean, yen/kWh]

	Hokkaido	Tohoku	Tokyo	Chubu	Hokuriku	Kansai	Chugoku	Shikoku	Kyushu
24 hours	6.08	7.07	7.66	7.70	6.63	7.15	6.97	6.03	6.47
Day time [9–22h]	6.66	7.46	8.11	8.25	7.31	7.85	7.71	6.64	7.28
Night time [23–8h]	5.26	6.52	7.02	6.94	5.69	6.16	5.93	5.18	5.35
Peak time [14–16h]	6.37	7.40	7.99	8.43	7.41	7.99	7.84	6.75	7.35

Figure 3.2: JEPX Spot Market Price Distribution [yen/kWh]



Note: Price distribution of 17520 products in 2010.
Data source: JEPX Webpage <http://www.jepx.org/market.html>

3.2 Simulation Results

3.2.1 All Nuclear Power Shutdown and Gas Turbine Installation (Scenario ALL, ALL+GTCC)

When we assume that all the nuclear plants are shut down, prices will rise at all times but especially at peak times. That is, the price band, which was around 3-10 yen/kWh in the base run, would shift upward to 7-16 yen/kWh (Figure 3.3).[4] Regions which have large nuclear capacity, such as the Kansai and many other western regions, would suffer a larger price rise (Figure 3.4). Hokkaido, which is the only region that has peak times in winter and offers cheap power with its abundant capacity in summer, would experience the largest price rise. Its 24-hour average price would rise by more than 3 yen/kWh. In contrast, Tohoku, Tokyo, and Chubu would show relatively smaller price rises of 1.5-2.0

[4] Depending on the assumed price elasticity of demand, the magnitude of this shift would differ especially at the peak times in summer. Results of sensitivity analysis with respect to this parameter are shown in the Appendix.

yen/kWh. When we examine their price rises by month, in all the seasons except summer these three regions would show a price rise of 1.5 yen/kWh, which is clearly lower than the price rise of around 3 yen/kWh in the other regions. In summer, the price rises in all the regions except Hokkaido would converge.

Figure 3.3: Price Levels with All Nuclear Power Shutdown (Scenario ALL) [yen/kWh]

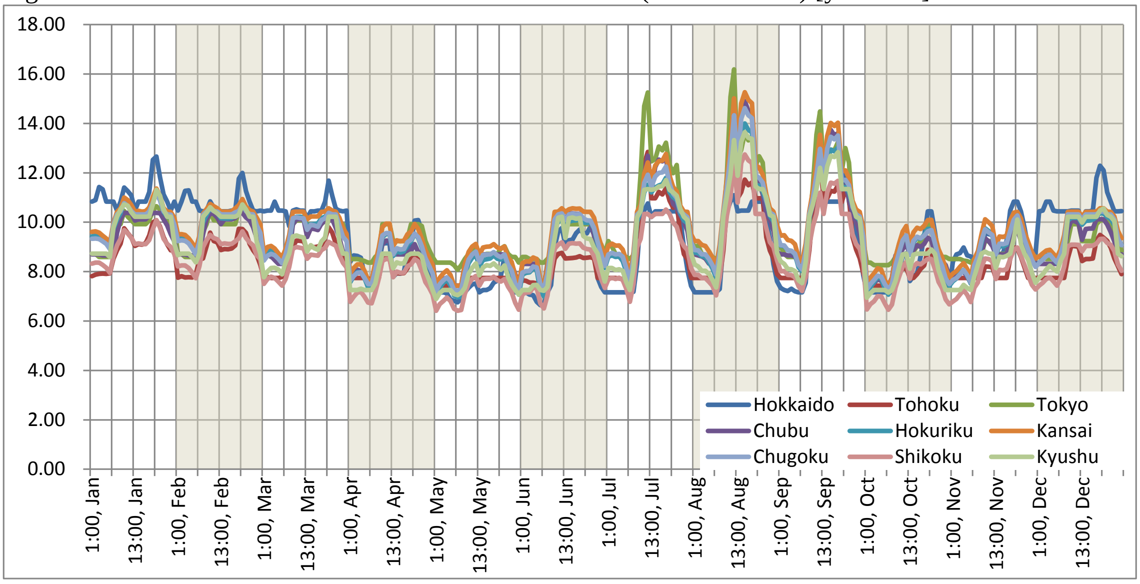
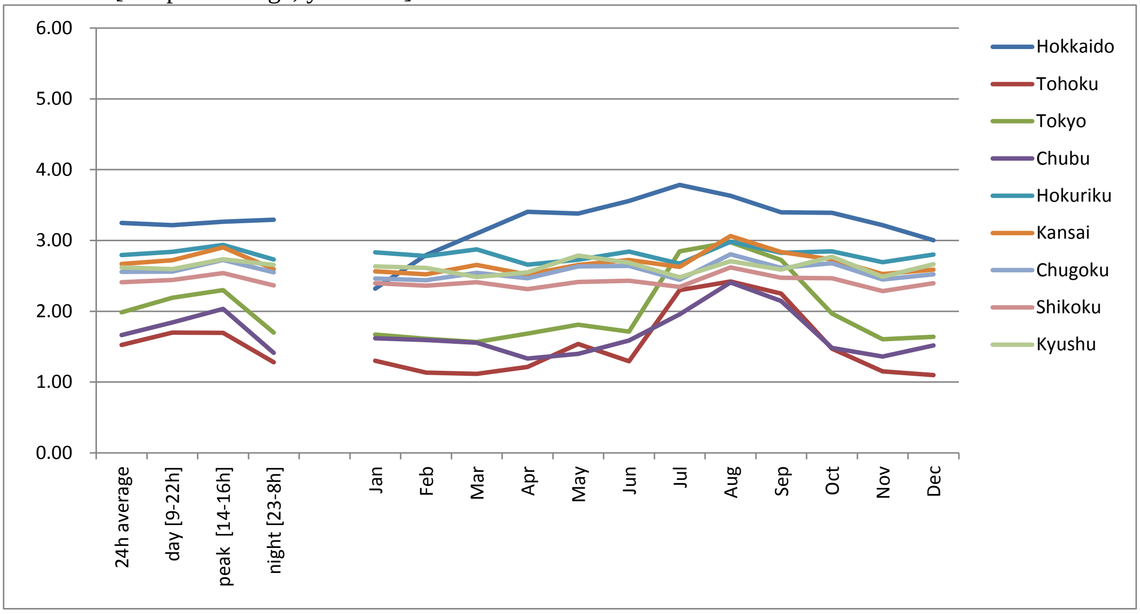


Figure 3.4: Average Price Rises by All Nuclear Power Shutdown (Scenario ALL)
[Simple Average, yen/kWh]



When the lost nuclear power supply is assumed to be made up by GTCC (Scenario ALL+GTCC), prices during peak times–especially when prices are higher than the supply price of GTCC (i.e., 7.44yen/kWh)–would fall sharply. The price band would become very narrow around 7-10 yen/kWh (Figure 3.5). In contrast, prices in off-peak times, when prices are lower than 7.44 yen/kWh even in the absence of nuclear power and, thus, GTCC is less competitive, would be affected little by the GTCC installation. The rise of 24-hours average prices would become as low as 0.5-1.5 yen/kWh compared with the base run prices. When we focus on peak times, we can find the GTCC installation is very effective. While Hokkaido would show the largest price rise of 1.5 yen/kWh, small price rises would arise in Tohoku, Tokyo, and Chubu (Figure 3.6). The price hikes by month show similar results. The price hikes triggered by the nuclear power shutdown would be compressed, especially in the peak times of summer and winter. As GTCC is not competitive in spring and fall, when demand is small and thus prices are not high enough to operate GTCC, its installation would not contribute to reducing the size of price hikes.

Figure 3.5: Price Levels with Nuclear Power Shutdown and GTCC Installation (Scenario ALL+GTCC)

[yen/kWh]

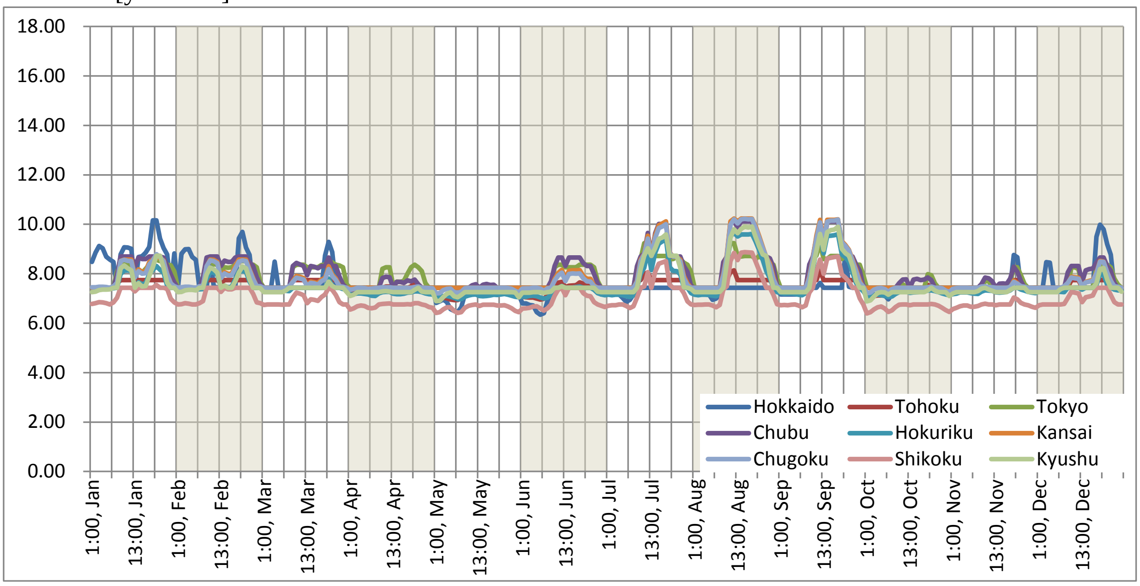
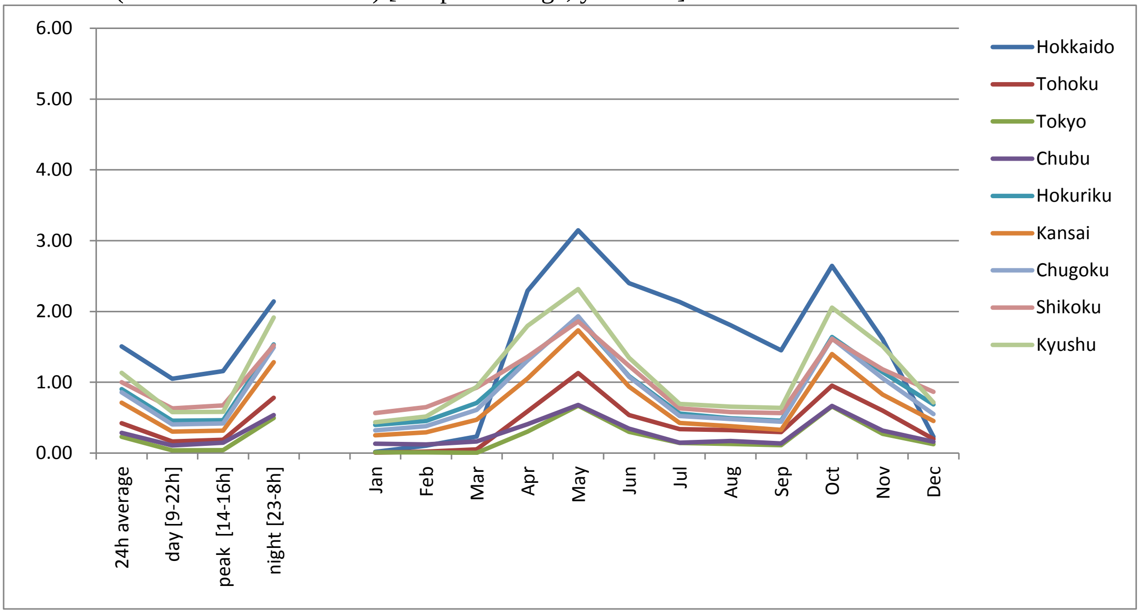
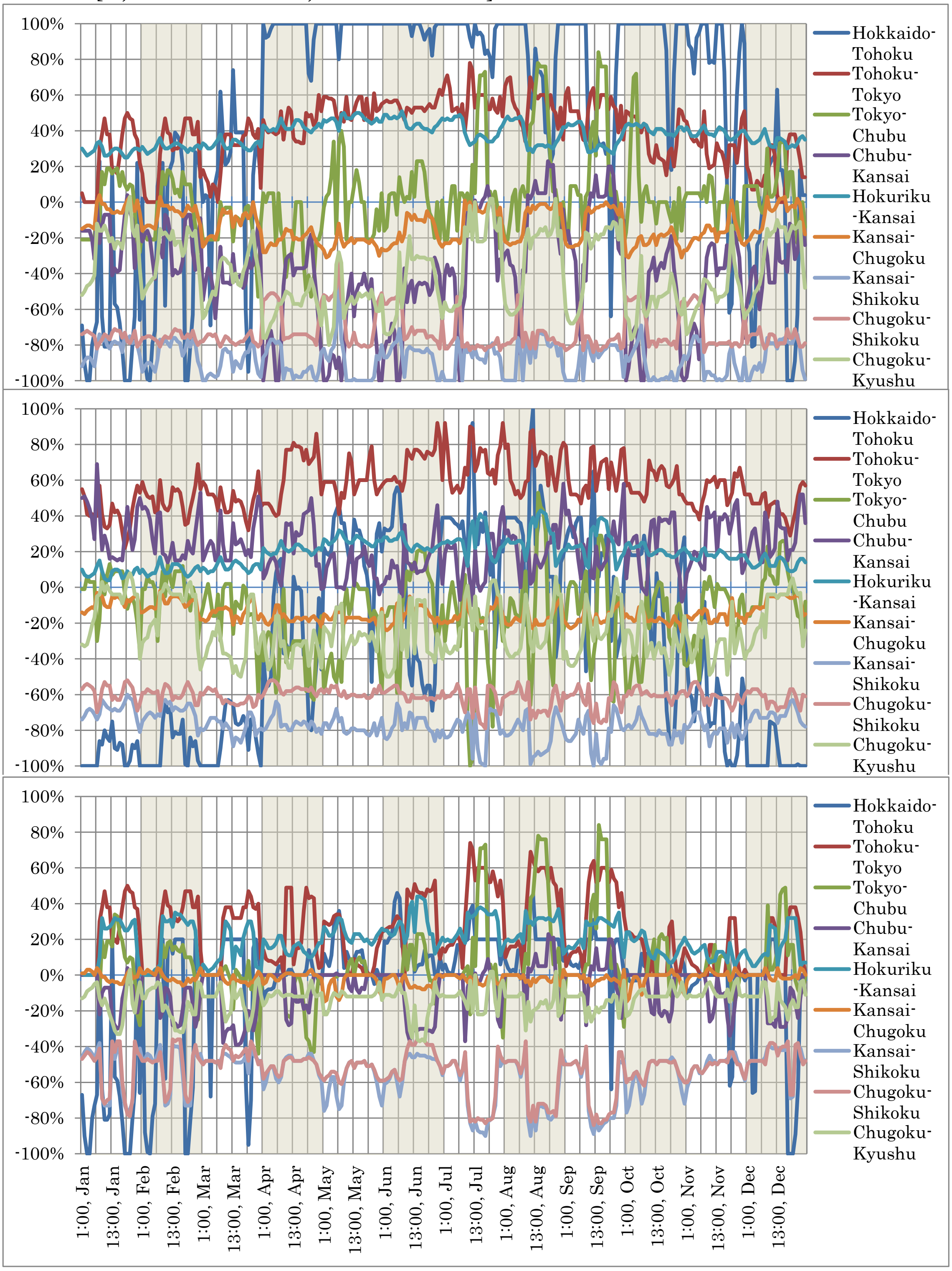


Figure 3.6: Average Price Rise by All Nuclear Power Shutdown and GTCC Installation (Scenario ALL + GTCC) [Simple Average, yen/kWh]



The transmission patterns in the base run (the upper panel of Figure 3.7) shows frequent and sizable transmissions between regions reflecting regional factors, such as plant portfolios shown in Figure 1.1 and the difference of peak seasons. We can see two typical patterns that generate high load factors in transmission links: (a) peak times in peak seasons (e.g., winter evening in Hokkaido and summer afternoon in the other eight regions) and (b) off-peak times in off-peak seasons (i.e., night times in spring and fall). The former happens when price spikes are observed as shown in Figure 3.3. The latter is caused by inter-regional transmission of cheap power generated with abundant (nuclear) capacity. Congestion would occur sometimes at the links between Kansai and other 60Hz areas and often at the link between Hokkaido and Tohoku.

Figure 3.7: Load Factor of Interregional Transmission Links in the Base Run (upper panel), Nuclear Shutdown Case (Scenario ALL, middle panel), and GTCC Installation Case (Scenario ALL+GTCC, lower panel)
[%, south/westbound>0, north/eastbound<0]



When all the nuclear plants become unavailable (Scenario ALL), all regions would suffer from losses of their base load capacity. This shock would tighten regional power markets and significantly reduce interregional transmission, especially among 60Hz areas (the middle panel of Figure 3.7). Congestion would occur more often at the links between Hokkaido and Tohoku. The FC-link, which bridges the two different frequency areas, would show more eastbound transmission while its power flow is overall neutral in the base run.

The GTCC installation (Scenario ALL + GTCC) would make regional plant portfolios converge further and result in smaller price variations by hour and season (Figure 3.5). Finally, this would lead to much less interregional transmission in general (the bottom panel of Figure 3.7). One exception is observed at the peak times in summer, when prices would skyrocket against the peak demand and make GTCC competitive. Therefore, power generated by GTCC would intensify interregional transmission at this particular time. This would result in a high but not full usage of the FC-link. Installation of GTCC, which makes up the lost nuclear capacity, would ease congestion at the Hokkaido-Tohoku link and reduce transmission between Tohoku and Tokyo. People seriously argued after the earthquake if transmission capacity expansions at such bottleneck links as the FC-link and the Hokkaido-Tohoku link were needed. Our simulation results suggest that an installation of new plants with similar technology for all regions would reduce the variations of plant portfolios and the price gaps among regions. Therefore, the capacity expansion of transmission links would not be so important when an installation of GTCC is made.

3.2.2 BWR Plants Shutdown and Gas Turbine Installation (Scenario BWR, BWR+GTCC)

While we assumed all nuclear plants shut down in the above scenarios, we next consider a partial shutdown of nuclear plants. Among many possibilities, we assume that only pressurized water reactor (PWR) nuclear power plants are allowed to resume operation but that BWR ones are not (Scenario BWR). As BWR plants are mainly located in the 50Hz (eastern) area, this scenario can describe a situation where the eastern area suffers a power shortage. That induces more eastbound transmission over and thus congestion at the potential bottleneck of the FC-link.

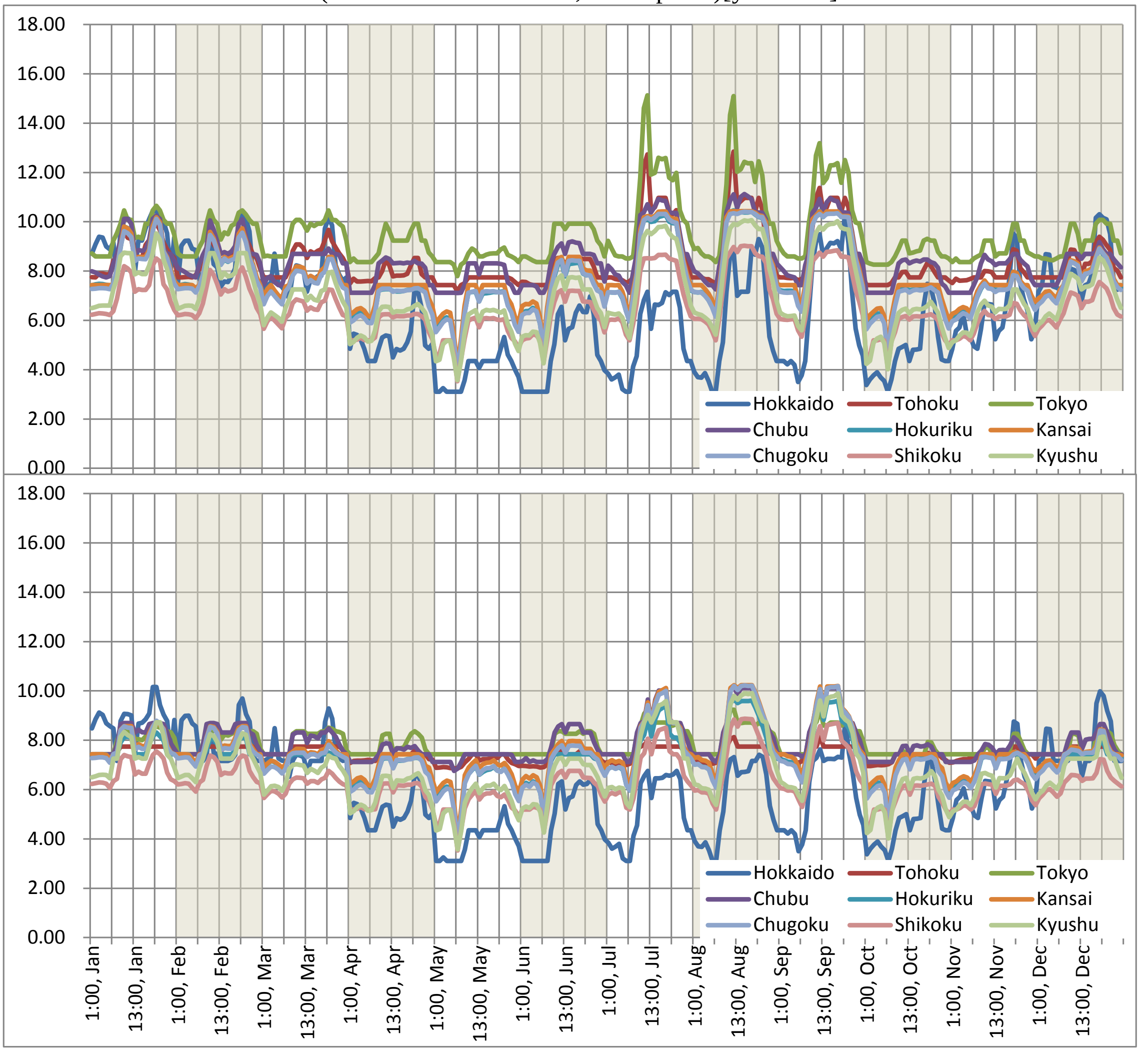
Table 3.2: Nuclear Power Capacity by Type of Reactor and Region [MW]

	PWR	BWR (to be shut down)	Total	Share of Shutdown Capacity [%]
Hokkaido	2,070	0	2,070	0.0
Tohoku	0	3,274	3,274	100.0
Tokyo	0	18,408	18,408	100.0
Subtotal of the 50Hz Area	2,070	21,682	23,752	91.3
Chubu	0	3,617	3,617	100.0
Hokuriku	0	1,898	1,898	100.0
Kansai	10,928	357	11,285	3.2
Chugoku	0	1,280	1,280	100.0
Shikoku	2,022	0	2,022	0.0
Kyushu	5,258	0	5,258	0.0
Subtotal of the 60Hz Area	18,208	7,152	25,360	28.2
Total	20,278	28,834	49,112	58.7

Note: We consider full capacity of power plants that had already been installed as of 2011.

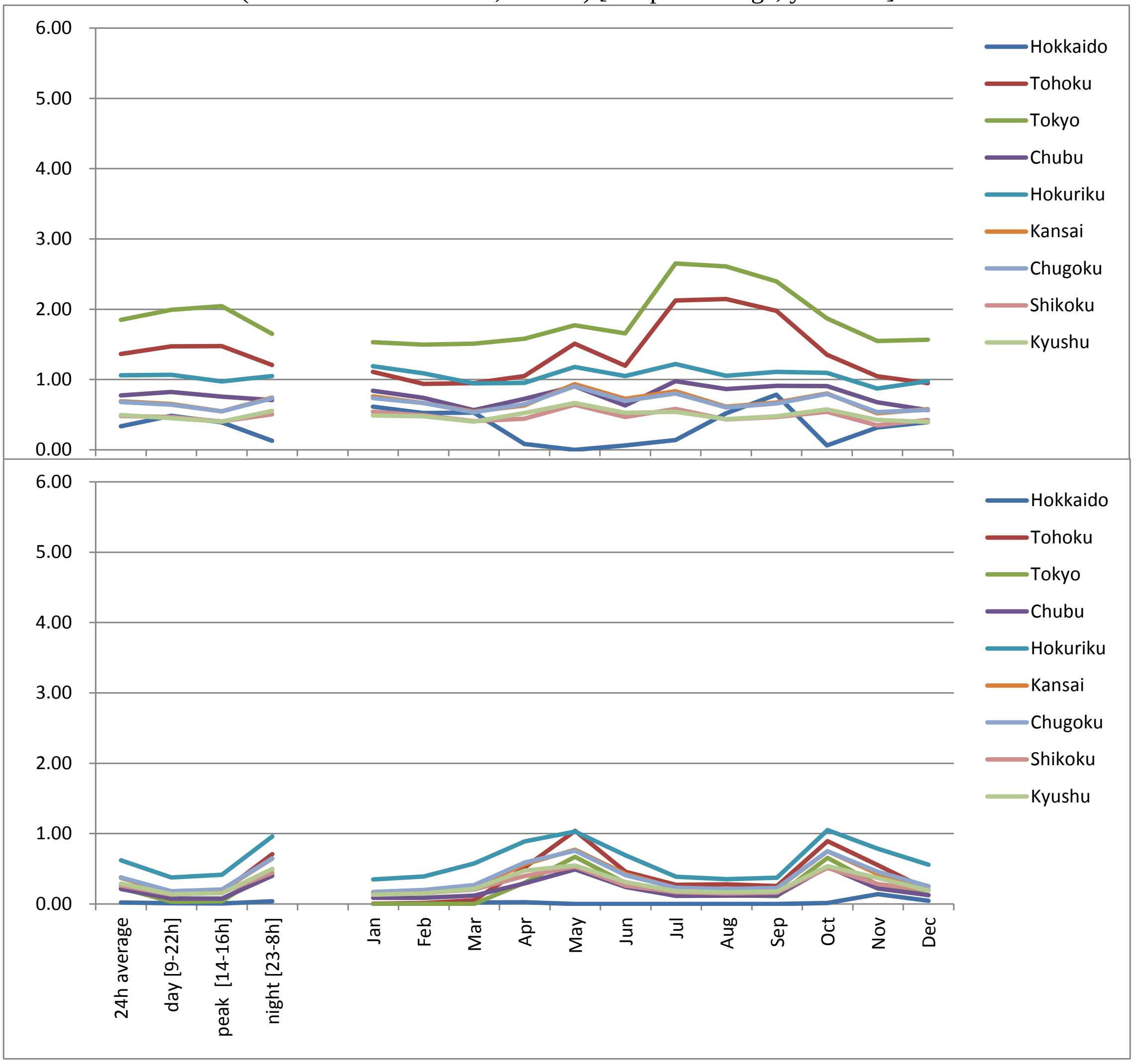
While Scenario ALL showed a price hike about 7-16 yen/kWh, Scenario BWR shows a smaller hike of around 4-15 yen/kWh compared with the base run. Among the nine regions, Tohoku and Tokyo would suffer a relatively larger price rise (the upper panel of Figure 3.8). In contrast, Hokkaido and the 60Hz regions (with smaller BWR capacity) would be affected less. The GTCC installation (Scenario BWR+GTCC) would restore the price hikes exceeding the supply price of GTCC (7.44 yen/kWh) to the base run levels during peak times just as we observed in Scenario ALL+GTCC (the lower panel of Figure 3.8). In contrast, the GTCC installation would be found marginally effective on other occasions.

Figure 3.8: Price Levels with the BWR Nuclear Power Shutdown (Scenario BWR, upper panel) and GTCC Installation (Scenario BWR+GTCC, lower panel)[yen/kWh]



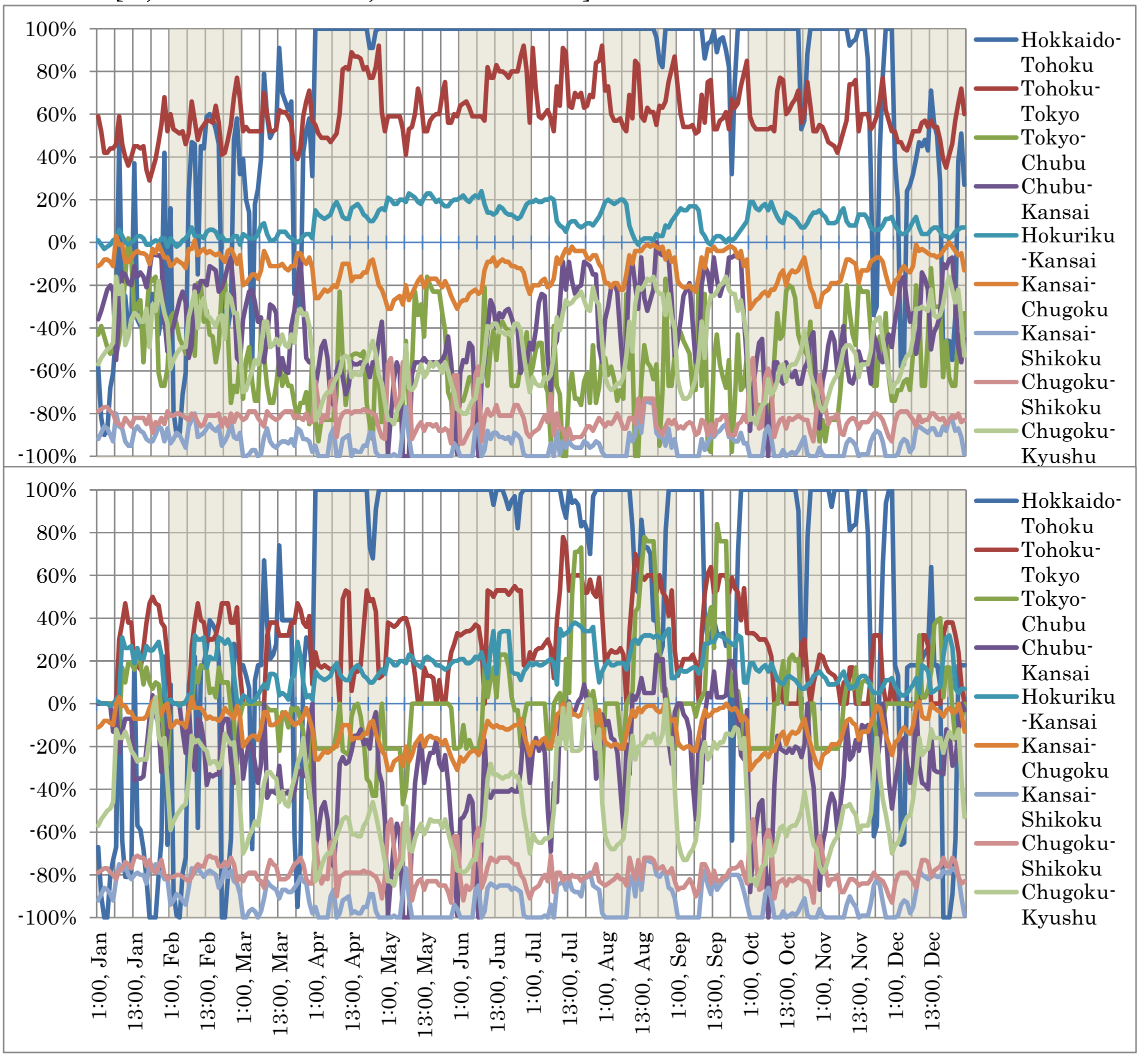
A shutdown of BWR plants would push up the 24-hour average prices only by 0.5-2 yen/kWh (the upper panel of Figure 3.9), which are smaller than the impact of the all nuclear power shutdown by 1.5-3 yen/kWh (Figure 3.4). While Tohoku and Tokyo would suffer a 2-2.5 yen/kWh rise in summer, other regions with moderate or no losses of BWR nuclear power capacity would have only a 1 yen/kWh rise. Although GTCC installation could not fully compress the price hikes, these hikes in off-peak times would be no higher than 1 yen/kWh (the lower panel of Figure 3.9).

Figure 3.9: Average Price Rises by the BWR Plant Shutdown (Scenario BWR, top) and GTCC Installation (Scenario BWR+GTCC, bottom) [Simple Average, yen/kWh]



When BWR plants stop their operation (Scenario BWR), plant portfolios become uneven among regions. This motivates interregional transmission for "gains from trade" (the upper panel of Figure 3.10). Compared with the results of Scenario ALL (Figure 3.7), some links would become congested more often, such as the links from Hokkaido to Tohoku and from Shikoku to Kansai/Chugoku. Hokkaido and Shikoku have only PWR plants and thus would carry out more intensive outbound transmission to regions with a plant capacity shortage. However, due to congestion at their outbound links, they could not send all the power that they want to and have abundant capacity to meet their domestic demand. Therefore, their domestic prices would rise the least among the nine regions while other regions would show price hikes (the upper panel of Figure 3.9). Although the FC-link, which has long been considered as the most serious bottleneck in Japan's power network, would show larger eastbound transmission to the 50Hz area, which suffers a larger loss of plant capacity, this link would be only occasionally congested for exchange of abundant power in off-peak times (the upper panel of Figure 3.10). That is, this anticipated congestion indicates an insufficiency of transmission capacity for cheap power (often generated by nuclear power) in off-peak times, not a critical capacity shortage that could cause a power shortage or crisis at peak times.

Figure 3.10: Load Factor of Interregional Transmission Links in the BWR Nuclear Power Plant Shutdown Case (Scenario BWR, upper panel) and GTCC Installation Case (Scenario BWR+GTCC, lower panel)
[%, south/westbound>0, north/eastbound<0]



As we have discussed so far, the GTCC installation would contribute to lowering prices only in peak times which experience market prices higher than the GTCC supply price of 7.44 yen/kWh. That is, the power generated by GTCC is too expensive to transmit to other regions and is therefore dispatched mostly to domestic users. The transmission pattern would become more oriented toward domestic markets (the bottom panel of Figure 3.10). The sole exception is observed at the peak times in summer, when very high demand allow imports of expensive power generated by GTCC from other regions. While the FC-link would show a neutral transmission pattern overall, westbound transmission would stand out in daytime in summer.

3.2.3 Old Power Plant Shutdown and Gas Turbine Installation (Scenario OLD, OLD + GTCC)

We assume that nuclear power plants over 30 years old as well as all the power plants in Fukushima Daiichi Power Station are shut down. Figure 1.2 shows that, in this scenario, 29% and 34% of the total nuclear power capacity in the 50 Hz and the 60 Hz areas would be lost, respectively. More old plants are located in the 60 Hz region. In contrast to Scenario BWR above, the losses of these plants are expected to intensify uses of the FC-link for eastbound transmission.

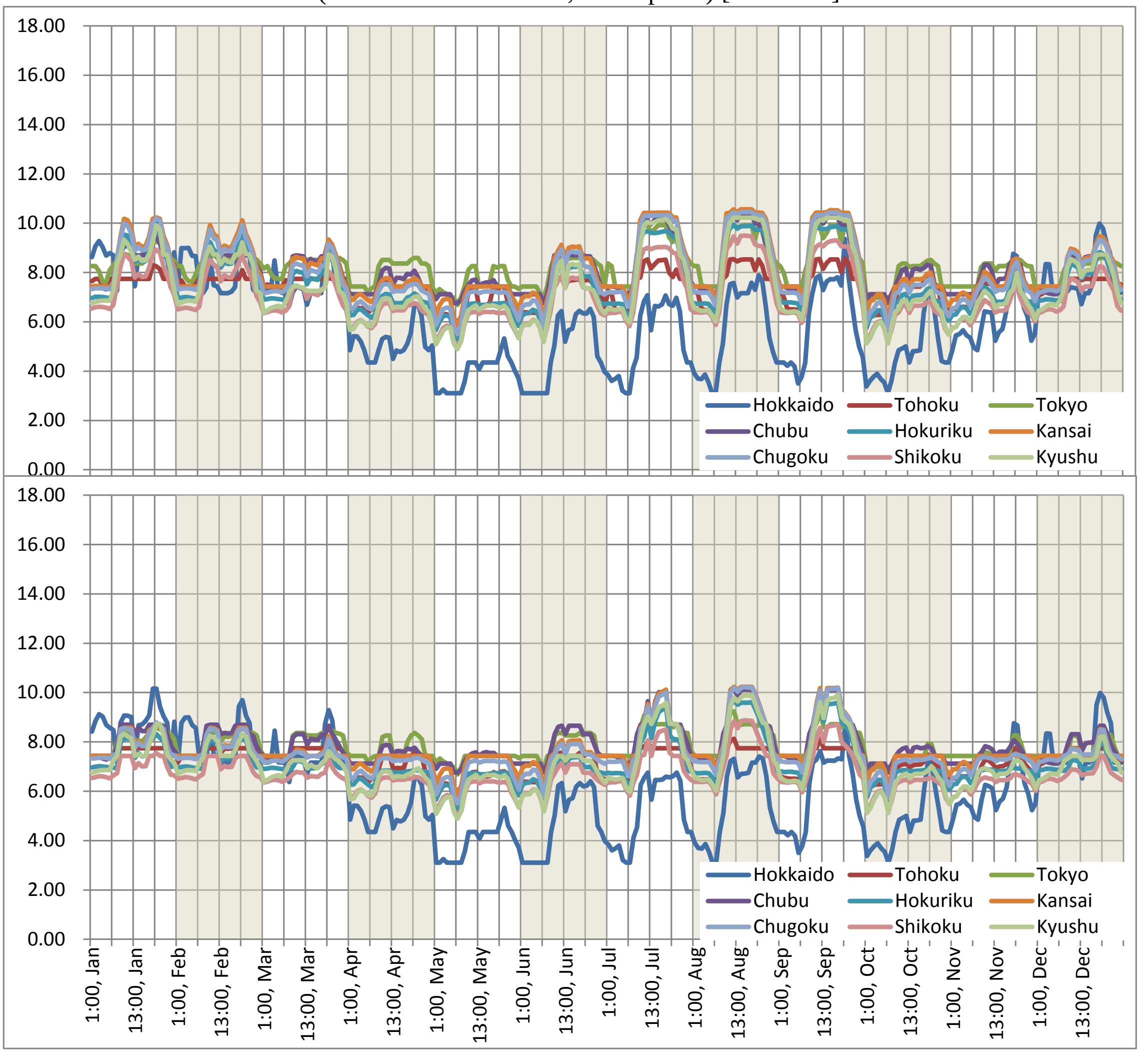
Table 3.3: Capacity of Old Plants (over 30 years old as of August 2013) by Region [MW]

	Newer Plants	Old Plants (to be shutdown)	Total	Share of Old Plants [%]
Hokkaido	2,070	0	2,070	0.0
Tohoku	3,274	0	3,274	0.0
Tokyo	11,512	6,896	18,408	37.5
Subtotal for the 50Hz Area	16,856	6,896	23,752	29.0
Chubu	3,617	0	3,617	0.0
Hokuriku	1,898	0	1,898	0.0
Kansai	5,260	6,025	11,285	53.4
Chugoku	820	460	1,280	35.9
Shikoku	890	1,132	2,022	56.0
Kyushu	4,140	1,118	5,258	21.3
Subtotal for the 60 Hz Area	16,625	8,735	25,360	34.4
Total	33,481	15,631	49,112	31.8

Note: We consider only plants that had already started their operation in 2011.

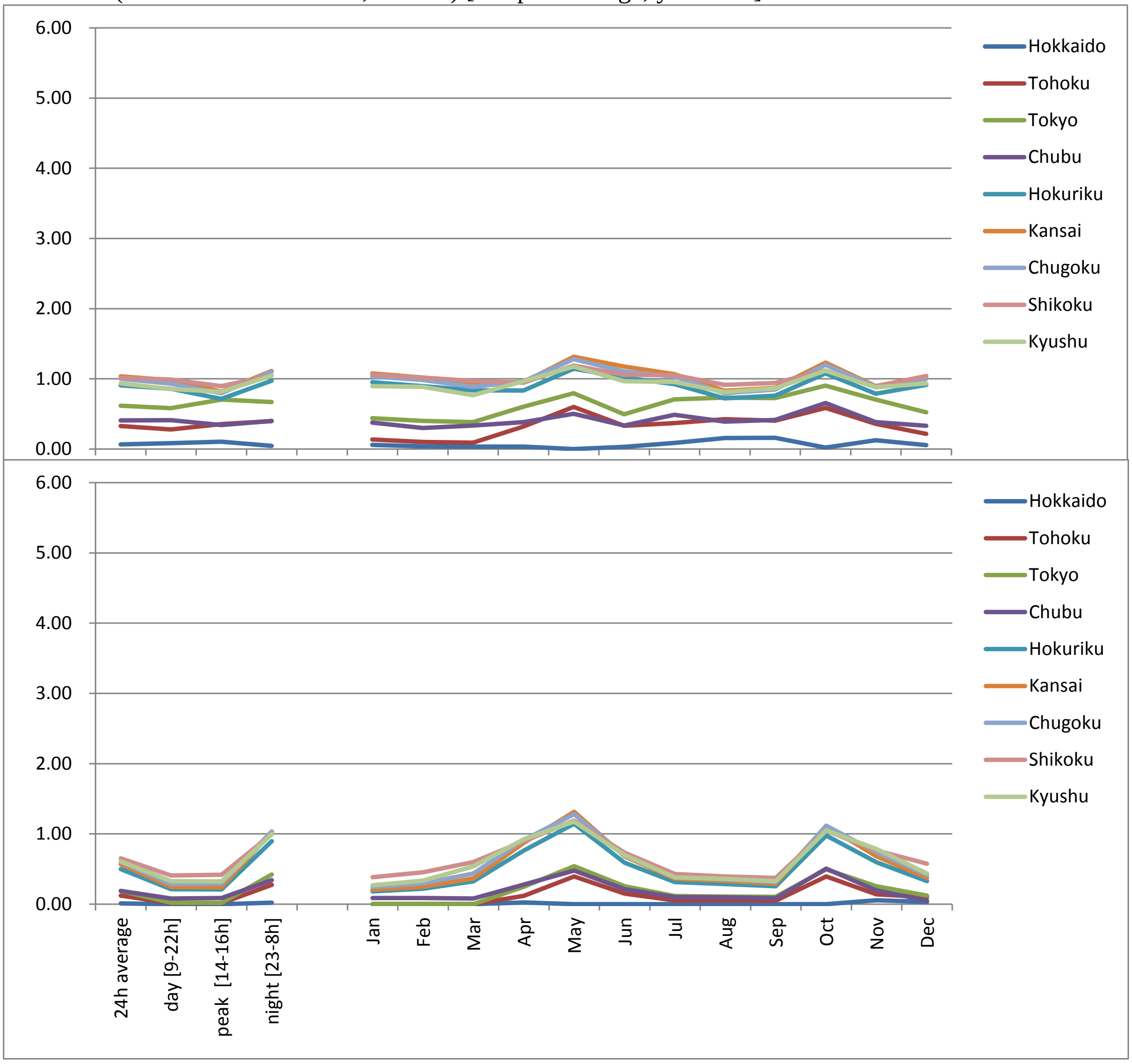
The shutdown of old plants (Scenario OLD) would raise the prices in general only moderately (the upper panel of Figure 3.11). For example, the peak prices would be almost as high as the original ones in Figure 3.1. Hokkaido owns only new plants and would not be directly affected by the old plant shutdown. As Hokkaido is isolated due to congestion at its westbound outlet (discussed later), its domestic prices would be little affected. In other regions, while peak time prices would not be affected much, prices would rise moderately at other times. Because the impact of the old plant shutdown would not be sizable, the installation of GTCC would not be found effective, either (the lower panel of Figure 3.11).

Figure 3.11: Price Levels with the Old Plant Shutdown (Scenario OLD, upper panel) and the GTCC installation (Scenario OLD+GTCC, lower panel) [Yen/kWh]



The impact of the old plant shutdown would be larger in many 60 Hz regions. Their price rises would be relatively large in spring and fall, exceeding 1 yen/kWh (the upper panel of Figure 3.12). Compared with their impacts, Tohoku, Tokyo, and Chubu would suffer only a smaller price rise. The GTCC installation would almost eliminate those moderate price rises in many times except spring and fall.

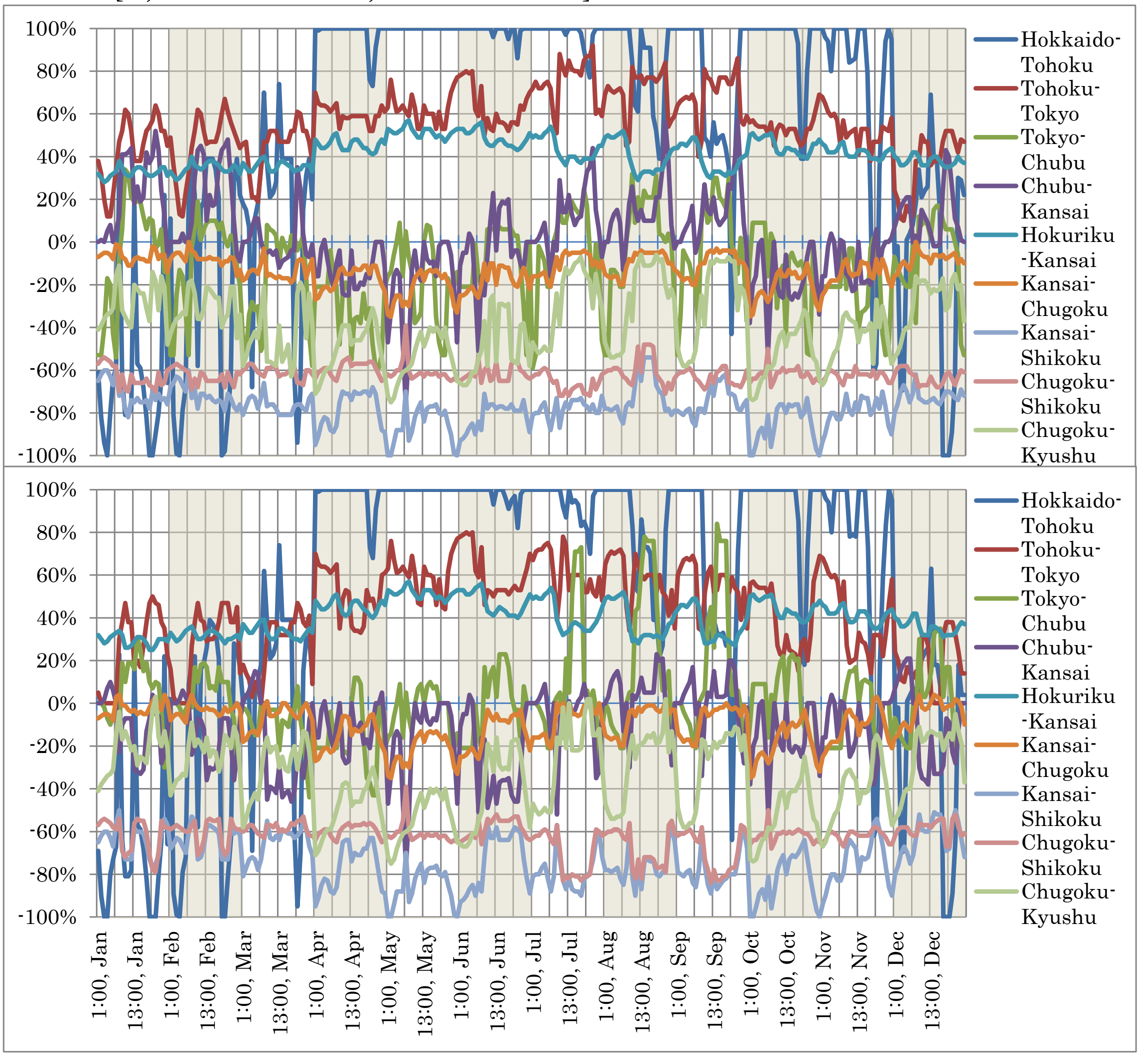
Figure 3.12: Average Price Rises by the Old Plant Shutdown (Scenario OLD, top) and GTCC Installation (Scenario OLD+GTCC, bottom) [Simple Average, yen/kWh]



The 60 Hz area has a larger number of old nuclear power plants than the 50 Hz area has. Indeed, this imbalance would increase westbound transmission, but the increase would not be large enough to cause congestion at inter-regional transmission links. For example, while westbound transmission dominates at the FC-link in peak times in summer in the base run (the upper panel of Figure 3.7), the

westbound transmission would decrease due to the loss of cheap nuclear power capacity (the upper panel of Figure 3.13). Since the assumed total loss of plant capacity is smaller in this scenario than Scenario ALL, the GTCC installation would not cause conspicuous impacts in the transmission patterns or volume (the lower panel of Figure 3.13).

Figure 3.13: Load Factor of Interregional Transmission Links in the Old Nuclear Power Plant Shutdown Case (Scenario OLD, upper panel) and GTCC Installation Case (Scenario OLD + GTCC, lower panel)
[%, south/westbound>0, north/eastbound<0]



4. Conclusion

In this study, we empirically examined the impact of nuclear power shutdown and the installation of GTCC plants to make up the lost nuclear capacity using a nine-region STPA model that describes the electric power market in 2010, just before the earthquake. When we assumed all the nuclear power plants were shut down, we found that the power price rise would reach 1.5-3 yen/kWh, which would significantly differ by region and would be conspicuous in the 60-Hz area and Hokkaido. The GTCC installation would be effective particularly in the daytime and would succeed in compressing those price hikes down to 0.5-1.5 yen/kWh (compared with the prices before the shocks).

This implies that the GTCC installation could not perfectly control the price hike and that we would still suffer a price rise of 0.5-2 yen/kWh at night. This adverse impact would hit a certain group of customers. The power companies have striven to reduce usage at daily and seasonal peak times (i.e., in mid-afternoon and in summer) by providing electric-powered heating system and other electric appliances with concessional power tariffs for their users in off-peak times. Customers who have committed to these peak-shift offers by investing in such equipment would be more severely affected by the nuclear power shutdown. Electric vehicles, which are often considered a key device in a so-called “smart-grid” power system and are supposed to be charged at night to exploit the cheap power supplied mainly by nuclear power plants, would become less attractive.

Besides the above-mentioned extreme scenarios assuming complete nuclear power shutdown, we considered more moderate and realistic cases in which only BWR plants or old plants are shut down. These partial shutdown scenarios assume smaller losses of plant capacity but cause uneven allocation of supply capacity among regions, which could lead to congestion at inter-regional links. Our simulation results predicted no serious congestion at any links except the Hokkaido-Tohoku link. It should be noted that the FC-link, which is often considered the most serious bottleneck in Japan’s power network, would not suffer congestion from the nuclear power plant shutdown. We can thus respond to the frequently-asked question of whether we should invest in power plants or network capacity that even if and *because* we lose the cheap power capacity comparable to a quarter of the total supply capacity in Japan, we do not need to invest in networks except for the Hokkaido-Tohoku link.

In our simulation experiments, we considered a time span within which we can install new GTCC plants (typically, a few years or so) and assumed that no customers change their behavior drastically in reaction to the anticipated power price hikes. In the longer run, they can install energy-saving facilities and equipment that can reduce their power demand, shift their peak demand to off-peak times, and make their demand more price-elastic. On the other hand, equipment that is designed to use cheap power at nighttime would become less attractive for customers. More nighttime energy demand would be covered by town gas and kerosene, rather than electricity. These inter-temporal and/or inter-fuel demand shifts could reduce the anticipated price rises in off-peak times. However, as the anticipated price rises would be only 2-3 yen/kWh even in the completely non-nuclear case, such renewable energy sources as wind and photovoltaic would not be competitive in the power market.

We can consider alternative counter-factual scenarios by assuming that the nuclear power plants are not fully replaced by GTCC power plants but are partly replaced by coal-fired thermal plants, which need a longer lead time for installation but have lower fuel costs. The LNG price can be affected by many factors, such as a surge of LNG demand after the earthquake and the development of shale gas. These features can be reflected by different assumptions of supply prices for newly-installed plants, as shown in Figure 2.5.

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Appendix Sensitivity Analysis

We estimated the STPA model by calibrating its key parameters in the model to the hourly load reported on the METI website and the price elasticity of demand estimated by Hosoe and Akiyama (2009) for each region while we used standard merit-order curves that are estimated on the basis of fuel costs and plant capacities. Depending on the assumed price elasticity, the estimated magnitude of price hikes would differ quantitatively and qualitatively in our numerical experiments. Therefore, we conduct a sensitivity analysis with respect to this price elasticity and examine the robustness of our simulation results. We assume alternatively the lower and the upper bounds of 95% confidence intervals of the elasticity estimates by Hosoe and Akiyama (2009) (Table A.1).

Table A.1: Price Elasticity of Regional Power Demand and its 95% Confidence Intervals

Regions	Lower Bound	Point Estimate	Upper Bound
Hokkaido	0.221	0.295	0.369
Tohoku	0.168	0.262	0.356
Tokyo	0.017	0.086	0.155
Chubu	0.047	0.148	0.249
Hokuriku	0.135	0.250	0.365
Kansai	0.001*	0.090	0.189
Chugoku	0.170	0.271	0.372
Shikoku	0.195	0.297	0.400
Kyushu	0.154	0.241	0.329

Source: Hosoe & Akiyama (2009).
Note: As the lower bound for Kansai is negative, we use a small, positive ad hoc value of 0.001.

The simulation results with the lower-bound elasticity values are shown in the left panels of Figures A.1-A.4 while those with the upper-bound values are shown in the right panels. Comparing the left panels with the corresponding right panels, we can find that smaller elasticity would allow demand to adjust less flexibly and thus result in larger impacts on prices. In the lower elasticity case, the highest price would reach 28 yen/kWh in Tokyo and 23 yen/kWh in Chubu and Kansai. This sensitivity to the assumed price elasticity is, however, conspicuous only at the very peak times (i.e., daytime in summer) in the nuclear shutdown case (Scenario ALL). Other times and scenarios (the base run and Scenario ALL +

GTCC) would show little differences in the predicted impacts on prices. Our confidence intervals of the estimated price rises would be around 0.5-1 yen/kWh for the 24-hour average and 1.5-2 yen/kWh for the peak times. When we assume the installation of GTCC plants, we do not see any significant differences in the price estimates at any times.

Figure A.1: Price Levels in the Base Run (upper panel), with All Nuclear Power Shutdown (Scenario ALL, middle panel), and the GTCC installation (Scenario ALL+GTCC, lower panel) [Yen/kWh]

<Lower-bound Elasticity Case> <Upper-bound Elasticity Case>

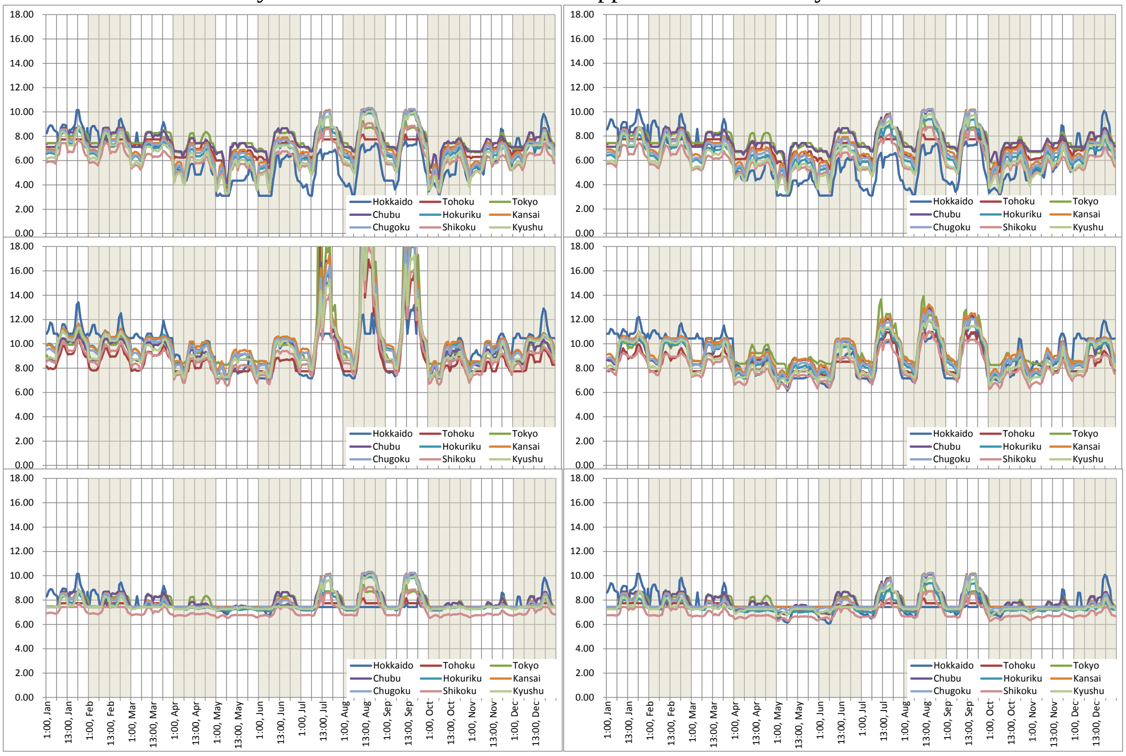
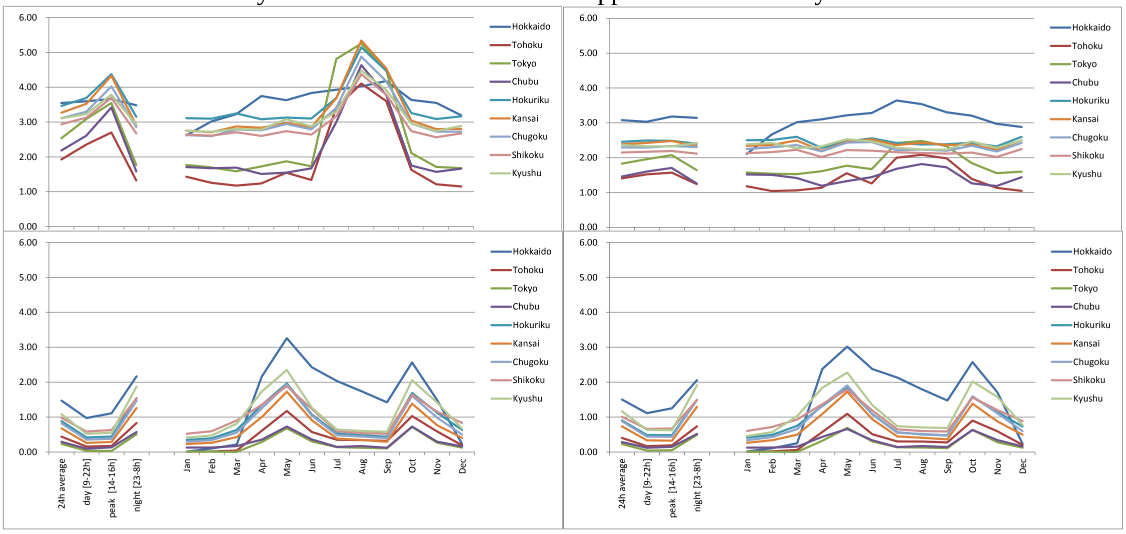


Figure A.2: Average Price Rises by All Nuclear Power Shutdown (Scenario ALL, upper panel), by GTCC Installation (Scenario ALL + GTCC, lower panel)
[Simple Average, yen/kWh]

<Lower-bound Elasticity Case> <Upper-bound Elasticity Case>



While the smaller elasticity would increase the impacts on prices, it would reduce the inter-regional transmission (Figure A.3). Irrespective of the assumed elasticity values, the nuclear power plant shutdown and the GTCC installation would decrease inter-regional transmission as shown in the main text.

Figure A.3: Load Factor of Interregional Transmission Links in the Base Run (upper panel), Nuclear Shutdown Case (Scenario ALL, middle panel), and GTCC Installation Case (Scenario ALL+GTCC, lower panel)
[%, south/westbound > 0, north/eastbound < 0]

<Lower-bound Elasticity Case> <Upper-bound Elasticity Case>