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Estimating the Effect of Nuclear Energy on a Country's Electricity Generation Mix: Fukushima as a Case Study

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ESTIMATING THE EFFECT OF NUCLEAR ENERGY ON A COUNTRY'S ELECTRICITY GENERATION MIX: FUKUSHIMA AS A CASE STUDY

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ABSTRACT

In this paper, I attempt to estimate the true effects of removing nuclear energy on a country's energy portfolio, particularly how the country substitutes to other fuel sources for electricity generation and how it impacts the country's marginal electricity prices. In 2011, anti-nuclear sentiment that arose in Japan following the meltdown of the Fukushima prefecture's nuclear power plant resulted in the country decreasing its nuclear electricity generation from over 30% of its total supply to 0% in under two years. I use the dramatic variation across Japan's electricity supply regions over the denuclearization period to attempt to estimate the true effect of the removal of nuclear energy on Japan's energy mix, total electricity demand and electricity prices. I find that Japan primarily substituted nuclear energy with thermal energy sources but did not significantly increase generation from renewable sources after the change. Additionally, I estimate an about 5% increase in marginal electricity price and a 2-7% total decrease in electricity demand due to the removal of nuclear power as an energy source. However, the highly regulated structure of electricity prices and supply in Japan at the time likely resulted in smaller and delayed price increases than would have occurred in a deregulated electricity market. In addition, the price regulation likely prevented a larger drop in electricity consumption than would have resulted with unregulated prices. The results suggest that regions considering major shifts away from nuclear energy, especially in deregulated electricity markets, should expect almost one for one substitution with fossil fuel generation, increases in electricity prices of at least 2% and decreases in electricity demand of at least 5%.

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SECTION 1 - INTRODUCTION

Even amidst growing concerns over the environmental and public health effects of carbon-based electricity generation, nuclear energy has been increasingly neglected as a viable energy source. Investment in nuclear capacity in many developed countries has been either stagnant or decreasing over the last decade (International Energy Association). In this paper I use the aftermath of the Fukushima nuclear power plant meltdown to analyze the effect of removing nuclear energy from Japan's energy portfolio. I specifically look at the effect on Japan's thermal and renewable energy generation, its electricity prices and its total electricity demand. The Fukushima meltdown occurred in March 2011 and within a year and a half Japan decreased their nuclear energy use from almost 35% to 0% in response to increasing fear over the safety of nuclear power and rising anti-nuclear sentiment. This drastic and unexpected reduction in nuclear generation can be used to analyze the causal effect of a country removing nuclear energy as an energy source.

Several other academic papers have studied this topic previously. Kiso, Chan & Arino (2021) use prefecture level variation in electricity prices after Fukushima to estimate the effect of electricity prices on solar panel installation. They find that the exogenous variation in electricity prices after Fukushima led to increased installation of solar panels by Japanese residents. While their analysis uses marginal electricity prices as the independent variable rather than an outcome variable, much of the intuition behind the energy source substitutions and price effects after Fukushima are similar to this analysis.

Hong, Bradshaw & Brook (2013) conduct a decision-making analysis on Japan's possible energy policy options after the Fukushima crisis. They identify many of the limitations to renewable energy substitution, finding that renewable energy sources do not allow for a substantial backup power supply and are therefore not a sustainable and reliable substitute for nuclear energy in either the short or long term. They also compare capacity and capacity factors across energy types and conclude that the best option for Japan in 2012 would have been to reintegrate nuclear power as a primary energy source as swiftly as possible. However, this paper did not estimate any causal effects of the loss of nuclear energy on Japan's energy mix, it merely analyzed different policy paths for Japan at the time.

Furlan, Guidolin & Guseo (2016) predict the medium and long-run effects of the Fukushima meltdown on the evolution of nuclear power in seven other major countries including the United States. They use a time-series analysis based on data of the countries' short-run behavior that predicted a decline in nuclear power consumption in the United States, France, Germany and South Korea in the aftermath of Fukushima. However, they did predict that China, Russia and Canada's nuclear energy use would increase. Overall, they predicted a decline in nuclear power generation across the world as a result of the Fukushima accident. This paper extends the relevance of my analysis to other major countries, including the United States, but does not directly look at Japan's response to the crisis.

While these papers all analyze the post-Fukushima period, there has been no direct econometric analysis of the pre-to-post Fukushima time period in Japan. These papers did not investigate the causal effect of the removal of nuclear energy on the several major outcome variables relating to electricity generation that I analyze. Based on these previous works, I expect my results to show a large substitution into fossil fuels in the after period, as well as some increase in total thermal plant capacity or the operating capacity factors of existing thermal plants in order to meet the increased demand for these energy sources. In addition, I expect to find significant electricity price increases across Japan, but particularly in regions with high pre-

Fukushima nuclear power generation, due to the larger increases in generation and fuel costs incurred by switching from nuclear to thermal energy generation.

Japan's electricity during the period of analysis was provided by ten regional monopolies that were heavily regulated by the government. Prior to Fukushima, Japan generated almost 35% of its total electricity from nuclear power with a stated goal to increase this share to 50% by 2030. As shown in the electric company data, the share of nuclear energy varied significantly by region from over 50% of total generation in some to 0% in others. After the Fukushima meltdown, Japan decreased its nuclear generation in all regions until it reached zero across the country.

This paper will use the sharp, unanticipated changes in nuclear electricity generation to predict the true effects of removing nuclear energy. Using variation at a regional level, I estimate this effect on thermal and renewable powered electricity generation, total electricity generation and marginal electricity prices from the pre to post-Fukushima period. Even as more and more countries adopt carbon neutrality and clean energy policy initiatives, investment in nuclear power has been stagnant or decreasing in most developed countries for the last decade. Understanding Japan's energy response to the Fukushima disaster is instructive of the true effect of nuclear energy on a country's energy portfolio.

I find that the regions with over 40% nuclear shares in 2010 (prior to the Fukushima meltdown), were estimated to experience a 58% increase in thermal generation but no significant change in renewable generation. In fact, only two regions, Hokuriku and Shikoku, were predicted to have a significant increase in renewable generation, while two other regions, Tohoku and Kansai were actually predicted to decrease renewable generation in the after period. Total electricity demand was predicted to decrease between 2-7% in all regions after removing nuclear energy except in Okinawa which had no nuclear energy prior to Fukushima. Finally, the regions with over 20% nuclear energy in 2010 were predicted to experience a 5% increase in marginal electricity price after Fukushima while the regions with less than 20% nuclear shares were not predicted to have any significant change in marginal electricity prices.

This paper primarily illustrates the short-run effects of removing nuclear energy. Because this analysis only analyzes a period of five years, the true long-run substitutions and changes may be different than what is found here. However, this paper does show that in the short-run, nuclear energy is substituted with fossil fuels rather than renewable energy. Even though renewable energy capacity can be increased in the long run, these energy sources do not provide the flexibility required to match seasonal and fluctuating electricity demand and therefore can never be the sole energy source for electricity generation. Because generation by fuel based energy sources can be adjusted to match demand, but solar, wind or hydro power cannot, renewable sources do not provide efficient electricity production to meet fluctuating demand. In order to achieve net-zero emissions, policymakers must recognize that renewable energy sources are not a complete substitute for nuclear energy.

I begin this paper with an overview of nuclear energy and electricity generation in Japan. In section three I summarize and describe the data I use in the analysis. I explain my empirical strategy in section four and I present the results in section five. In section six I discuss limitations of the paper followed by a conclusion in section seven.

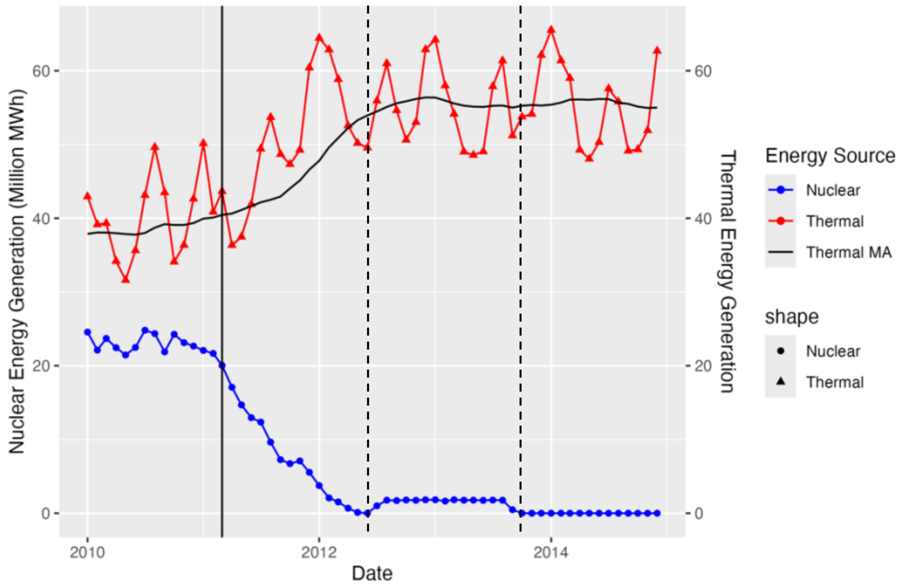
SECTION 2 - NUCLEAR ENERGY IN JAPAN

2.1 The Great East Japan Earthquake

On March 11th, 2011, the Tohoku Region of Japan, located on the nation's eastern coast, experienced the fourth largest recorded earthquake in history. The shocks caused a tsunami with waves reaching heights of 133 feet to hit the coast of the Fukushima prefecture where a large nuclear power plant with four active reactors used the coastal waters as its cooling source. The earthquake and subsequent waves caused a failure in the plant's cooling system that resulted in radioactive material being released into the surrounding areas. About 50,000 residents of the Fukushima prefecture were displaced after the accident and Japanese faith in nuclear energy was severely degraded (Britannica). Following the crisis, all nuclear power plants in Japan shut down for maintenance, renovations or inspections for varying lengths of time. In the summer of 2012, Japan reached zero nuclear power generation for the first time in decades. Though one nuclear reactor was restarted at the end of 2012 and operated through the beginning of the following year, by July 2013, nuclear generation was persistently zero. Figure 1 shows Japan's nuclear electricity generation over time. The sharp decrease in nuclear generation after Fukushima (denoted by the solid black line) is very clear. The dashed lines indicate the first month of zero nuclear generation (June 2012) and when the country officially went to no nuclear generation (October 2013).

Prior to the Fukushima meltdown, investment in nuclear energy was a strategic policy objective for Japan. At the beginning of 2011, over 30% of the nation's electricity was generated by 54 nuclear reactors across the country, with a stated objective to increase this share to 50% by

Figure 1: Thermal and Nuclear Power Generation in Japan



Note: Data from FEPC Section II. Demand and Supply. Jan. 2009 to Dec. 2014.

2030 (World Nuclear Association). Nuclear energy is particularly important to Japan's electricity portfolio because the country has no domestic thermal energy resources. This paper will refer to all combustion fuel sources including coal, natural gas and geothermal fuel sources as thermal energy. Japan's Ministry of Economy, Trade and Industry (METI) reports that Japan's energy self-sufficiency ratio dropped from 20.2% in 2010 to 6.3% in 2013 due to the shutdown of nuclear plants. This resulted in Japan relying on foreign imported fuel sources for close to 90% of their energy generation (World Nuclear Association). Additionally, a METI Power Generation Cost Verification Working Group in 2015 found that fuel and operation costs for coal, natural gas and oil powered electricity generation were significantly higher than for nuclear (Matsuo). Thus, when Japan dropped to zero or near zero nuclear power in a very short time period, they substituted it with higher cost, foreign imported fuel sources. This dramatic drop, caused by a new fear over other potential nuclear disasters after Fukushima, was unanticipated and therefore can be considered independent from other demand factors for electricity.

Figure 1 also shows the corresponding increase in thermal energy generation in the period following Fukushima. The increase aligns very closely with the drop in nuclear generation. Seasonal changes in electricity generation are clearly shown by the red line in Figure 1. Even prior to Fukushima, thermal generation had much larger seasonal fluctuations than nuclear. To account for these fluctuations the figure also plots the twelve-month moving average of thermal generation on the black line. The lack of fluctuations in nuclear generation, even prior to Fukushima, show that Japan was likely running their nuclear reactors at much higher average capacities throughout the year than their thermal generators. Nuclear fuel was cheaper than thermal fuel, so Japan relied on their nuclear plants for generation first then used their thermal plants to make up the difference to meet demand, especially during peak electricity seasons. This explains why thermal generation fluctuates so much more than nuclear in the pre-Fukushima period and why the fluctuations stay around the same magnitude after, even as the overall thermal share of generation increases.

In 2015, Japan began to restart nuclear reactors, likely in response to cost pressures and supply constraints on thermal energy plants, which marks the end of the immediate, short-run, post-Fukushima period.

2.2 Japan's Regulated Regional Electricity Market

Prior to 2016 Japan's electricity was supplied by regional, regulated monopolies. These companies divided Japan into 10 regions based on their allocated service areas and residents in each region had to source electricity from their designated supplier. Both before and after Fukushima, these regions varied drastically in their electricity generation mix by energy source.

Table 1: Region Data for Energy Shares by Type - 2010 & 2014

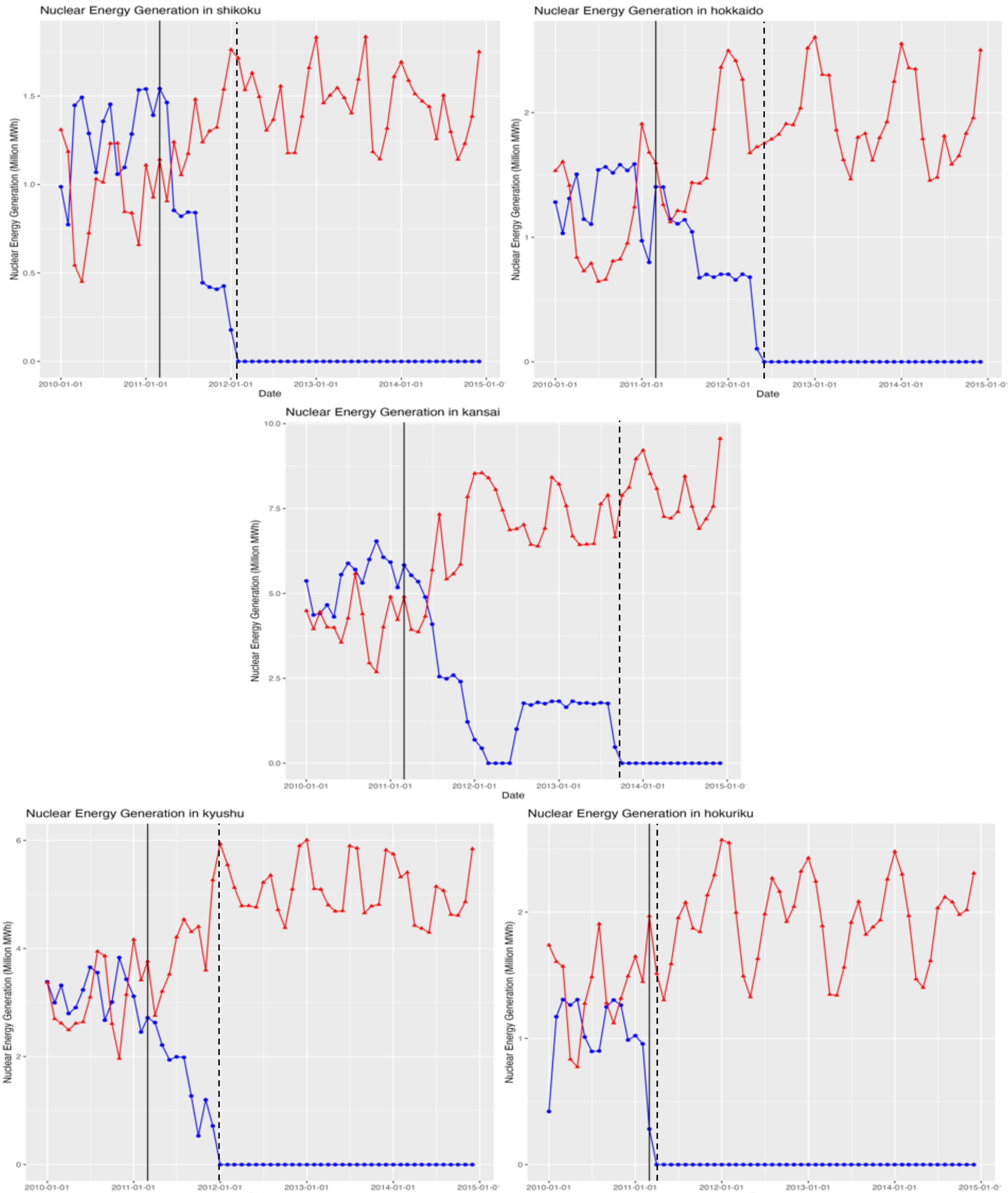
Region	Nuclear Share 2010	Thermal Share 2010	Renewables Share 2010	Δ Thermal Share (Percentage Points)	Δ Renewables Share (Percentage Points)
Shikoku	0.53	0.39	0.08	49.34	3.00
Hokkaido	0.51	0.37	0.12	49.79	1.00
Kansai	0.50	0.38	0.12	50.02	0.00
Kyushu	0.49	0.44	0.07	47.78	1.00
Hokuriku	0.36	0.46	0.18	33.49	3.00
Tokyo	0.33	0.63	0.04	32.35	1.00
Tohoku	0.32	0.55	0.12	31.54	1.00
Chubu	0.14	0.79	0.07	14.71	0.00
Chugoku	0.07	0.85	0.08	6.64	0.30
Okinawa	0.00	1.00	0.15	-0.01	-15.00
Japan	0.35	0.59	0.08	32.6	1.00

Note: Data from FEPC Section II. Demand and Supply. Jan. 2010 to Dec. 2014. Regions are listed in descending order by nuclear share in 2010

An overview of this variation is found in Table 1 which shows energy generation statistics by region in 2010 and 2014. In particular, the 2010 share of electricity generated from nuclear power in each region ranged from 53% in Shikoku to 0% in Okinawa. This variation caused the nuclear power plant shutdowns following Fukushima to affect each of the regions very differently. Additionally, each region responded to the crisis at different speeds. The regions closest to Tohoku, where the tsunami hit, generally shut down their reactors the fastest. This includes Tohoku, Hokuriku and Chubu which all reached a 0% share of nuclear generation by June 2011, just three months after Fukushima. Notably, the Tokyo region did not immediately shut down its reactors even though it borders Tohoku. This may because it is home to the Japan's capital, or that it had fewer or less accessible short run substitutes to nuclear energy.

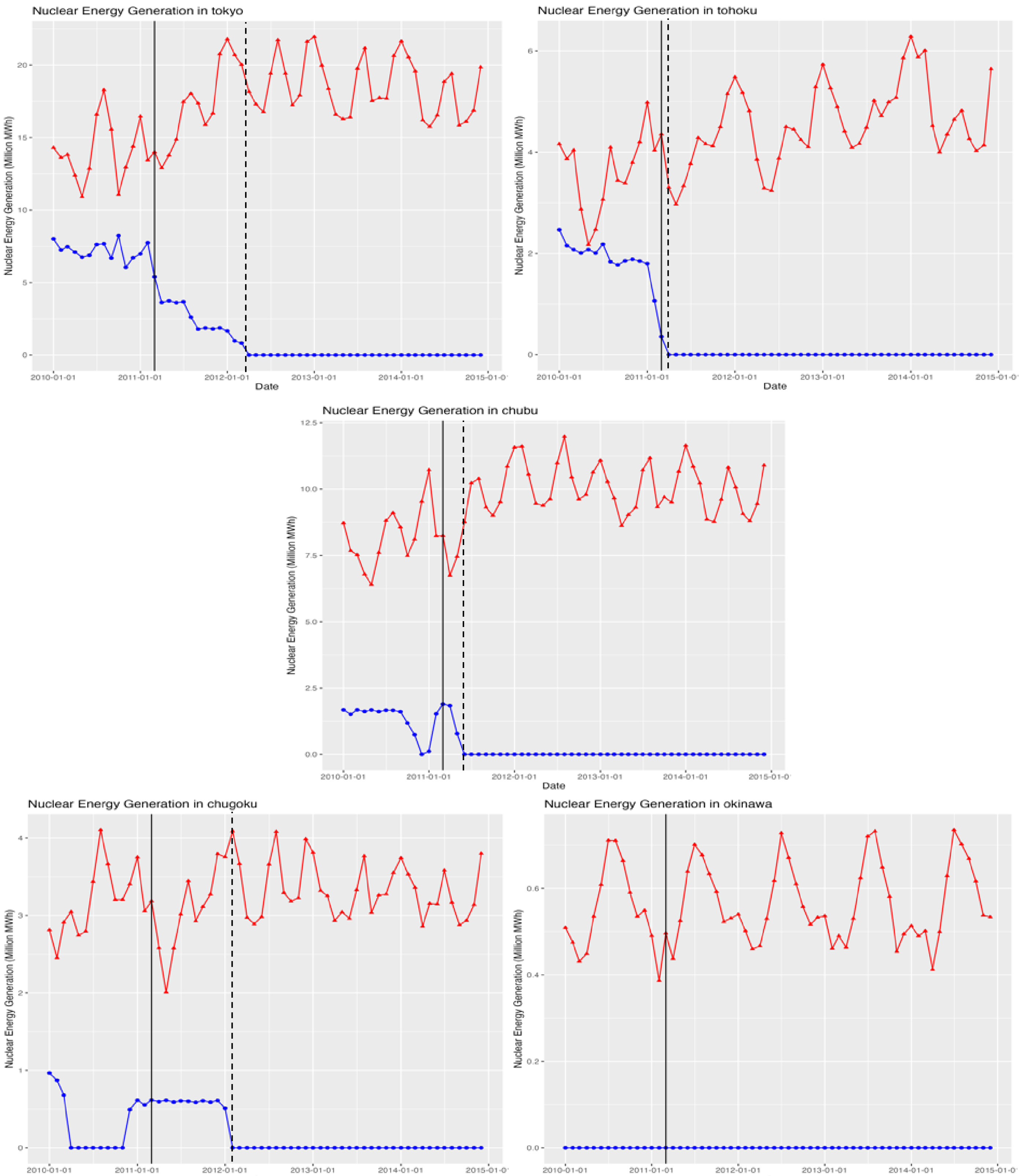
Figure 2 shows graphs of nuclear and thermal generation (in MWh) in each region. The regions are ordered from the greatest 2010 nuclear share of electricity generation to the lowest. The solid black line indicates March 2011, the month the earthquake occurred, and the dashed line indicates when the region reached zero nuclear generation for the duration of the post-Fukushima period. The intermediate period represents the region's transition from nuclear power to other fuel sources. The slowest region to completely shut down nuclear generation was Kansai. Kansai temporarily shut down all its reactors from March 2012 to June 2012 but restarted one reactor which then operated until October 2013. Kansai was the third most nuclear reliant region, generating over 50% of its electricity from nuclear power at the beginning of 2011 and also the second largest industrial region in Japan. Both of these characteristics would have slowed the region's ability to completely denuclearize.

Figure 2: Nuclear and Thermal Generation Regions 1-5



Note: For all graphs, nuclear generation is represented by the blue dotted line, thermal generation by the red triangle line. The regions are listed in order by their nuclear share of generation in 2010. Shikoku had the highest with 53% nuclear and Okinawa the least with 0%. Data from FEPC Section II. Demand and Supply Jan. 2010 to Dec. 2014.

Figure 3 Continued: Nuclear and Thermal Generation Regions 6-10



SECTION 3 – DATA

3.1 Data Sources

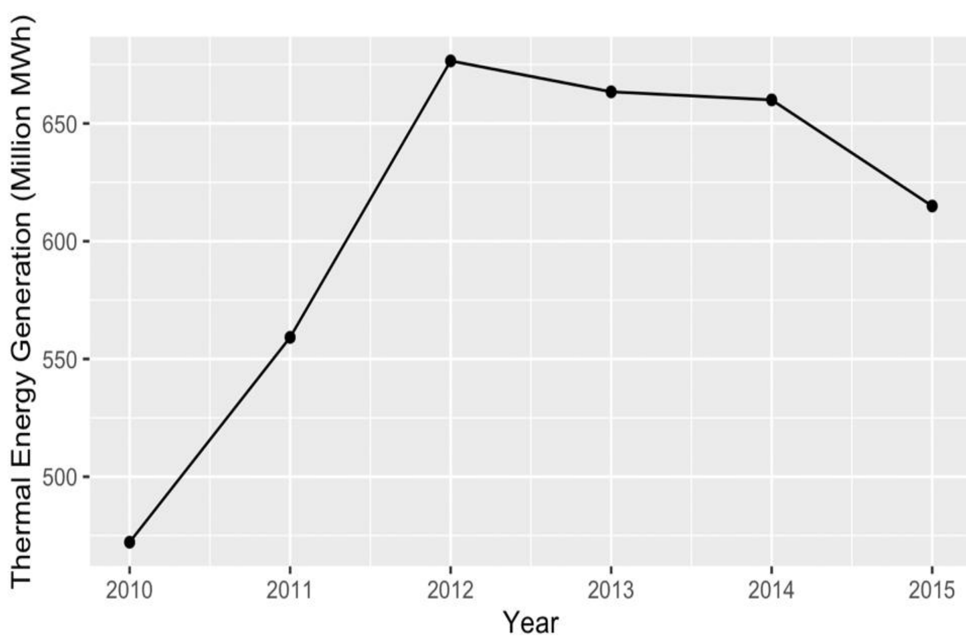
In this analysis I use monthly, regional data on electricity generation published by the Federation of Electric Power Companies of Japan (FEPC, Section II). These data are available monthly up to March 2016. I also use regional capacity and facility count data from the FEPC; however, these data are only published annually (FEPC, Section I). Finally, I use monthly electricity price data from the Japanese Statistics Bureau's Retail Price Survey. These data were only available at the monthly prefecture level. To aggregate this to the electric companies' regional level, I matched each prefecture with its electrical region and found the average price for each month in each region. The prices are measured in yen (¥). In 2010, $1 = ¥87.57.

Access to data was a primary limiting factor in this analysis. The regional divisions in the electricity and power data are the designated service areas of the 10 electric companies, and therefore are not official administrative areas. Because of this, GDP, production, manufacturing and other control data are not available at this region level. Further, the Japanese government statistics database only publicly archives monthly data at a prefecture level (which could then be aggregated to the electrical region level) up to 10 years from the latest release. At the time of this analysis, only data back to 2013 was publicly accessible which would not include the time of the earthquake or any data from before the Fukushima meltdown to act as a control period. Because of these limitations, the models do not include regional controls outside of region level fixed effects, though other controls would make the analysis more precise and robust.

3.2 Data Structure and Period of Analysis

The generation and demand data are panel data with 600 total observations, with an observation as each electric region in each month from January 2010 to December 2014. The dataset has total electricity generation for each region and generation by fuel type: nuclear, thermal, hydroelectric and other renewable energy sources (primarily solar and wind). However, for this analysis I combined hydroelectric power and other renewable energy sources, which are what I will refer to as renewable energy sources moving forward. The analysis starts in 2010 to capture the pre-Fukushima electricity environment as a control, though not extending too far back as to introduce significant variation within region demographics. The period ends in 2014 for multiple reasons. Japan began to permanently restart some nuclear reactors during 2015, beginning the country's slow reintegration of nuclear power to their energy portfolio. Additionally, foreign oil and natural gas prices decreased around this time lessening the supply side pressure on electricity prices. Figure 3 shows that by 2015 total yearly thermal energy

Figure 3: Total Yearly Thermal Energy Generation in Japan



Note: Data from FEPC Section II. Demand and Supply. Jan. 2010 to Dec. 2014.

generation begins to decrease sharply for the first time since 2011, at the same time that Japan begins to restart its nuclear reactors. This indicates that the strongest and most direct effects of the Fukushima disaster on energy generation and consumption patterns occur before 2015.

Further, in 2016 Japan began to deregulate the electricity market which majorly changed the electric companies' operations and competition strategies, as well as introduced new, smaller companies into the market. It also marked the end of the strict regional divisions in electricity generation and consumption. If this change was anticipated by the electricity companies then they may have begun to make some adjustments during 2015 to prepare for the coming deregulation. This time period is also the same as used in Chan, Kiso & Arino (2021) who use prefecture level variation in the post Fukushima period to analyze on the effect of electricity prices on solar panel installation.

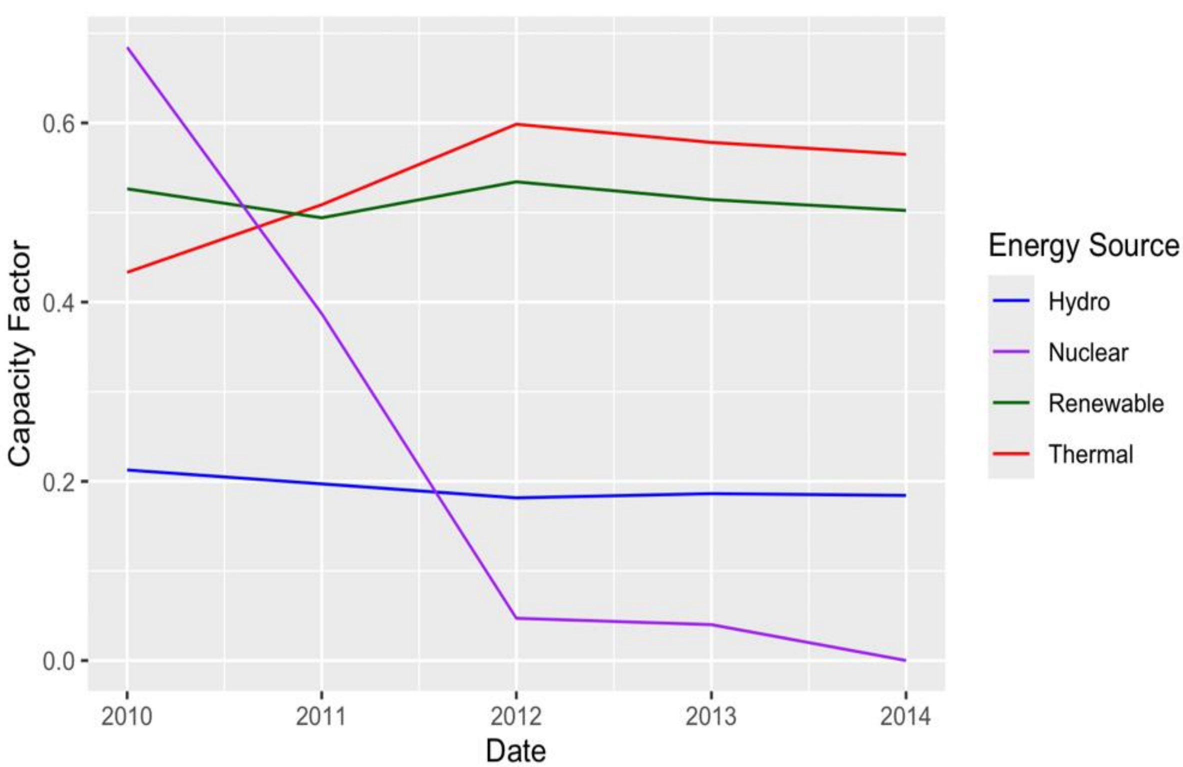
3.3 Electricity Generation and Plant Capacity Data

The facility data, which include capacity by energy type and total capacity for each region is a panel dataset with 130 observations over 13 years, from 2010 to the most recent release in 2022. This data will be used to analyze how Japan substituted for nuclear energy after Fukushima and to look at capacity and capacity factors by energy type.

Electricity generation is recorded in megawatt hours (MWh). Every electricity generator has a stated capacity based on its characteristics including fuel type, age, size and efficiency. Generator capacity, according to the U.S. Department of Energy, is "the amount of electricity a generator can produce when it's running at full blast." This capacity is measured in kilowatts (kW) and indicates the absolute maximum amount of electricity that generator can produce at any given time. However, power plants do not operate at full capacity all the time due to maintenance requirements, fuel availability and electricity demand, and therefore capacity over a period is not the same as actual energy generation. In 2010, nuclear reactor capacity only made up 22.4% of Japan's total electricity *capacity* while thermal generators made up 60%, however, nuclear energy's share of electricity *generation* was 34% and thermal's was only 58%. By 2014, nuclear energy's share of generation capacity had only dropped to 19.6% but its share of total electricity generation had dropped to 0%. So, while the nuclear plants were not running over the period following Fukushima they were not actually dismantled and could be restarted relatively quickly when Japan decided to in 2015.

The ratio of actual generation to maximum possible generation is measured by a plant's capacity factor. The capacity factor is the percent of time the plant runs at maximum power (U.S. Department of Energy) and can explain much of how Japan was able to prevent electricity

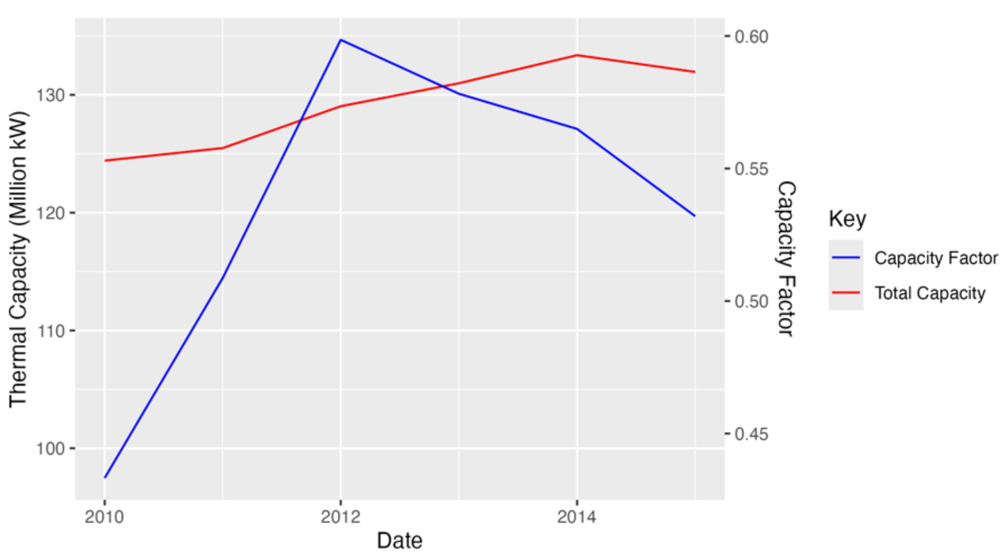
Figure 4: Capacity Factor by Energy Source



Note: Data from FEPC Section I Facility Data. 2010 to 2014.

shortages immediately after the earthquake. Figure 4 shows the capacity factor of each energy source from 2010 to 2014. As shown in the graph, nuclear has the highest capacity factor prior to 2011 and then drops rapidly to nearly zero by 2012 as regions transition away from nuclear energy. Since new powerplants take years to build and begin operation, and renovations and expansions to existing plants take nearly as long, to make up for the loss of nuclear energy, Japan began operating their thermal plants at a much higher capacity factor during the short term after Fukushima. There is not much change in the capacity factors of hydroelectric and renewable plants. This is likely because Japan could begin importing more fossil fuels to increase electricity generation from thermal plants, but could do little to increase wind, solar, or hydroelectric power generation on demand. Figure 5 shows a closer look at thermal energy capacity against its capacity factor over the time period. The capacity factor peaks in 2012 but then decreases through 2015 (by about 7 percentage points) as total thermal capacity begins to increase to match demand.

Figure 5: Thermal Capacity Overview

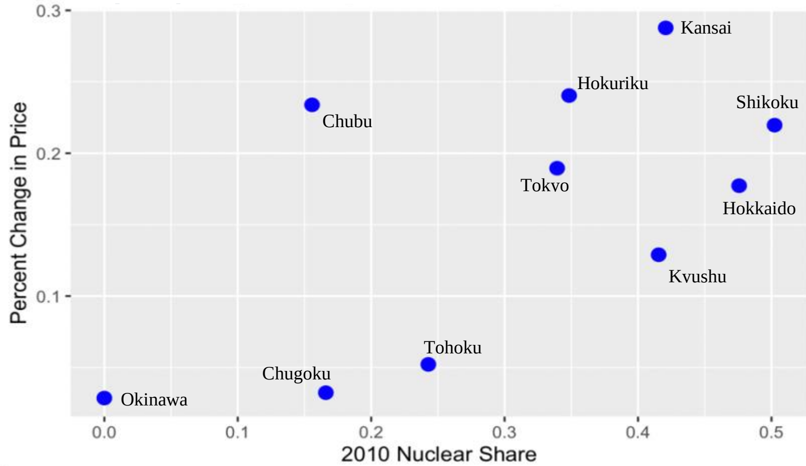


Note: Data from FEPC Section I Facility Data and Section II Supply and Demand. 2010 to 2014.

3.4 Electricity Price Data

The electricity price data include the base price and three levels of marginal prices. In Japan, electricity is charged in two parts: a base fee per month plus a per kilowatt hour price according to the three-increment marginal pricing scale. The lowest marginal price is charged for use up to 120 kWh, the second price is charged up to 300 kWh and the highest price is charged on use above 300 kWh. Households in Japan on average use more than 300 kWh of electricity a month (Lindner), so it would be expected that marginal changes to electricity consumption would be most sensitive to changes in the highest marginal electricity price. Similarly, it would be expected that the marginal prices would be more responsive to changes in energy supply and demand that the base price. In the data, the highest marginal price fluctuates the most over the time period and correlates more strongly with the regions' actual transitions away from nuclear energy. Additionally, since electricity supply in Japan during this time period was heavily regulated, the electricity companies could not change the base electricity fee without government approval. This means that companies could not immediately respond to the increased generation costs after Fukushima by raising prices. The base prices did not begin to rise until 2013, however marginal prices began to increase early in 2012 and have more variation based on region in both magnitude of change and timing. Figure 6 shows the percent change in marginal electricity prices in each region from January 2010 to December 2014. These changes are plotted against the regions' nuclear shares in 2010. The figure shows that regions with a higher initial share of nuclear energy experienced larger price increases than regions with lower shares of nuclear energy. In contrast, the eventual increase in electricity base prices that occurred in 2013 is very uniform across all regions and not strongly correlated in magnitude or timing with the regions' pre-Fukushima nuclear shares.

Figure 6: Percent Change in Marginal Electricity Price by 2010



Note: Data from FEPC Section I Facility Data and JBS Retail Price Survey Data Jan. 2010 and Dec. 2014.

SECTION 4 – EMPIRICAL METHODOLOGY

Because the regions differed drastically prior to Fukushima and they also differed in their response to the disaster, this variation can be leveraged in both a difference-in-differences (DID) and fixed effects (FE) approach to estimate the causal effect of the removal of nuclear energy on Japan's electricity situation. As discussed earlier, there is a lack of public data for control variables such as demographic characteristics, manufacturing and production measures, or income and GDP. Therefore, these models rely on the assumption that within each region these variables remained relatively stable over the period of analysis. Because the period is only five years and Japan has a well-developed economy, it is likely that the regions' populations and other demographic characteristics did not change substantially over the period. Manufacturing and production are more likely to have varied over the time period within regions. However, this model will assume that any major shifts in manufacturing, regional income or production occurred uniformly across the country, such as nation-wide inflation or periods of recession. If this is true, then these effects will be controlled for through the time fixed effects. Seasonal changes in demand for electricity will be controlled for in this way, as will nation-wide increases in electricity demand.

In this section I will describe my empirical strategy for the following models: a fixed effects model, a grouped difference-in-differences model and a fixed effects model with region period interactions.

4.1 Fixed Effects Model

In order to estimate the average effect of the removal of nuclear energy I use the "event" of the Fukushima meltdown as a treatment for removing nuclear energy. Because certain regions like Okinawa and Chugoku had very little reliance on nuclear energy before Fukushima, they act as controls, as they never experience a large drop in nuclear energy generation. The first regression I estimate is the fixed effects model shown in Equation 1. For all of my models γ_t represents month fixed effects and η_i represents region fixed effects.

$$(1) \quad \log(thermal\_gen_{it}) = \beta_0 + \beta_1 after_{it} + \gamma_t + \eta_i + \varepsilon_{it}$$

I use this model to estimate the average percent change in thermal electricity generation caused by the loss of nuclear power. The first model I estimate uses a staggered treatment assignment based on when each different region reached a persistent zero share of nuclear energy. This variable follows the start dates indicated by the dotted lines on the region graphs in Figure 2 where after is set to 1 for each region in months after the line and zero before. Using this approach to assign the treatment start allows any region in a month prior to its respective start date to be treated as part of the control group.

For robustness I estimated the above equation using three other model specifications. As shown in Figure 1, there is a transition period during which Japan's nuclear generation is decreasing as it begins adopting other fuel types. As noted in the figure, nuclear generation reaches zero for the first time in June 2012, but then a nuclear plant is restarted which runs until October 2013. Because Japan is still generating some nuclear energy during this time period, the treatment, as the absence of nuclear energy, has not been fully triggered. In the second regression I remove all observations from during the first part of the transition period, April 2011 to May 2012 and re-estimate Equation 1. This estimation only has 450 observations and the after dummy is set to 1 for any observations past April 2011, zero before. I repeat this in the third regression but further remove all observations up to October 2013. This estimation only has 290 observations and after is set to 1 for any observations after October 2013. Finally, I estimate the model one last time with the all observations and set the treatment to start immediately after the earthquake in March 2011. In this the after variable is zero before March 2011 and one after for all regions. The coefficient for the after variable in each of these regressions estimates the average true effect of nuclear energy (in terms of a percent change) on thermal powered electricity generation across all regions.

I cannot use Equation 1 to estimate the percent change in renewable generation because some regions had zero renewable generation prior to the earthquake and the log of zero is undefined. Running this regression would require these observations to be dropped which would heavily bias the estimate on after downward. Removing observations for regions in months with 0 MWh of renewable generation, which are all before the treatment start, but then still including these regions in the after group when they begin to generate some renewable energy, brings down the average estimate for after. Additionally, even if I replace these zero observations with 1 (so the logged value would be zero and the observations would not have to be dropped), since most regions produce little renewable energy, small changes in generation result in very large estimates for the percent change that are not precise or statistically significant. To account for this, I estimated Equation 1 with the same four variants of the after variable but without logging the dependent variable. This is shown in Equation 2.

$$(2) \quad renewable\_gen_{it} = \beta_0 + \beta_1 after_{it} + \gamma_t + \eta_i + \varepsilon_{it}$$

The results for estimations of Equations 1 and 2 for log thermal generation and renewable generation (MWh), are reported in Tables 2 & 3 respectively.

Table 2: Fixed Effects Estimation of Log Thermal Generation

	Dependent variable:			
	Log Thermal Generation			
	(1) Staggered After	(2) After 06/12	(3) After 10/13	(4) After 03/11
Staggered After	0.578***			
	(0.078)			
After		0.338***	0.340***	0.306***
		(0.099)	(0.117)	(0.093)
Constant	14.674***	14.751***	14.751***	14.751***
	(0.057)	(0.081)	(0.081)	(0.081)
Observations	600	450	290	600
R^2	0.084	0.025	0.029	0.018
Adjusted R^2	0.083	0.023	0.025	0.016

*p<0.1; **p<0.05; ***p<0.01

Table 3: Fixed Effects Estimation of Renewable Generation

	Dependent variable:			
	Renewable Generation			
	(1) Staggered After	(2) After 06/12	(3) After 10/13	(4) After 03/11
Staggered After	33,700.960			
	(31,240.520)			
After		-26,184.590	-30,972.870	-8,123.669
		(37,419.080)	(44,525.290)	(36,041.940)
Constant	508,114.400***	532,068.700***	532,068.700***	532,068.700***
	(22,743.440)	(30,552.560)	(30,936.540)	(31,213.240)
Observations	600	450	290	600
R^2	0.002	0.001	0.002	0.0001
Adjusted R^2	0.0003	-0.001	-0.002	-0.002
F Statistic	1.164	0.490	0.484	0.051

*p<0.1; **p<0.05; ***p<0.01

*All regression output tables are formatted using the Stargazer.R package as cited in the References Section

4.2 Grouped Difference-in-Differences Model

The previous model only reports an average effect of removing nuclear generation across all regions. However, given the vast differences in energy situations across regions, it is likely that there is a heterogenous effect of the treatment, the Fukushima meltdown, across regions based on their pre-Fukushima energy mixes. To analyze how Fukushima impacted the regions differently I use a multiple group difference-in-differences model as shown in Equation 3:

$$(3) \quad \log(\widehat{outcome}_{it}) = \hat{\beta}_0 + \hat{\beta}_2 group2_{it} + \hat{\beta}_2 group3_{it} + \hat{\beta}_3 after_{it} + \hat{\beta}_3 group2\_after_{it} + \hat{\beta}_4 group3\_after_{it} + \gamma_t + \eta_i + \varepsilon_{it}$$

The regions are grouped by their share electricity generation from nuclear power in 2010. Group 1 is the low nuclear group and includes regions that generated less than 20% of their electricity from nuclear power in 2010. Group 2 represents regions with 20 - 40% nuclear, and Group 3, the nuclear reliant group, includes regions with more than 40% nuclear shares of their pre-Fukushima electricity. There are two regions in Group 1, four regions in Group 2 and four regions in Group 3. Summary statistics for the groups are presented in Table 4. This grouping allows the effect of the treatment to vary based on the group's initial nuclear reliance. The model still includes month and region fixed effects for controls. The after variable equals 1 after March 2011 for all regions.

Table 4: Summary Statistics for Generation by Group in 2010 and 2014

Group	Nuclear Gen	Thermal Gen	Renewable Gen	Total Gen
Group 1 2010	3.01	44.56	3.40	50.97
Group 2 2010	140.35	321.08	36.59	498.02
Group 3 2010	134.50	106.54	28.19	269.23
Japan 2010	277.86	472.18	68.18	818.22
Group 1 2014	0.00	46.14	3.36	49.50
Group 2 2014	0.00	418.60	33.99	452.58
Group 3 2014	0.00	195.28	24.59	219.87
Japan 2014	0.00	660.01	61.94	721.95

Note: Data is in million megawatt hours

I estimate this model for log thermal electricity generation, the log marginal price of electricity and renewable generation in MWh. Group 1 is excluded as the baseline group. The effect of the change on Group 1 is captured by $\hat{\beta}_3$ on the after variable. This model can also be used to analyze the direct versus indirect effect of nuclear energy. The estimates for Groups 2 and 3 can be considered the direct effect of nuclear energy's removal as they include regions that went from large shares of nuclear energy to zero, while the regions in Group 1 had little to no nuclear adjustment. Conversely, any estimated changes for Group 1 represent the indirect effects of the substitution of other groups into non-nuclear energy sources. For this reason, it might be possible that Group 1 actually has an estimated negative percent change in thermal electricity generation, because if the increased demand for thermal fuel sources drives up fossil fuel costs it likely that the regions in Group 1 might either decrease total electricity generation or substitute some of their generation into renewables sources. The results for Equation 2 are reported in Table 5.

Table 5: DID Model with Treatment as Group Assignment and Fixed Effects

	Dependent variable:		
	Log Thermal Generation	Renewnable Gen. (MWh)	Log Marginal Price
	(1)	(2)	(3)
Group 2	1.322***	581,217.700***	-0.181***
	(0.181)	(72,251.130)	(0.019)
Group 3	0.362**	402,088.400***	-0.128***
	(0.181)	(72,251.130)	(0.019)
After	0.038	6,588.633	0.010
	(0.171)	(68,119.020)	(0.018)
Group 2 After	0.211	-24,871.030	0.050**
	(0.210)	(83,428.420)	(0.022)
Group 3 After	0.458**	-11,909.720	0.048**
	(0.210)	(83,428.420)	(0.022)
Constant	14.078***	138,746.300**	3.332***
	(0.148)	(58,992.800)	(0.015)
Observations	600	600	600
R^2	0.339	0.290	0.316
Adjusted R^2	0.333	0.284	0.310
F Statistic	60.928***	48.624***	54.892***

*p<0.1; **p<0.05; ***p<0.01

4.3 Fixed Effects Model with Region Interactions

Finally, I wanted to allow this effect to vary even more heterogeneously by region. Given the previous reasoning, I ran a similar model but substituted the group assignments for only region fixed effects and interacted each region with the after-treatment dummy. The after dummy was set to one for all regions in months after March 2011 and zero prior. This allows the after-treatment effect to vary for each region. Okinawa is dropped as the base group. This model is shown in Equation 4.

$$(4) \quad \log(\widehat{outcome_{it}}) = \widehat{\beta_1} + \widehat{\beta_2} after_{it} + \hat{\pi}_i region\_after_{it} + \gamma_t + \eta_i + \varepsilon_{it}$$

The model will estimate nine coefficients for each region's after treatment period and a coefficient on after which represents the effects of post-Fukushima energy landscape on Okinawa. The fixed effects estimates are not reported. These estimates show the difference in the effect on that region compared to the estimate for the control, Okinawa. The model still includes month and region fixed effects and the results are reported in Table 6 for log thermal electricity generation, renewable electricity generation and marginal price respectively.

I also estimated this model for the log of total demand for electricity. This will show how Japanese citizens changed their overall electricity usage in response to the disaster. This is particularly interesting at the regional level because it is expected that the regions closest to the disaster and the ones with the highest pre-Fukushima nuclear shares would have the largest change in electricity demand as a direct effect of losing their primary energy source. Conversely, the estimated change in the other regions represents the indirect effect of the nuclear shut down through its impacts on the supply and demand of thermal energy sources for non-nuclear dependent regions. As demand for other energy types increases, the initial high thermal energy regions are affected even though they initially had little to no nuclear generation. The results for this estimation are reported in Table 6.

Table 6: Fixed Effects Estimation with Region Interactions

	Dependent variable:		
	Log Thermal Gen.	Renewable Gen. (MWh)	Log Marginal Price
	(1)	(2)	(3)
After	0.049	45.044	0.005
	(0.055)	(55,092.980)	(0.017)
Chugoku After	-0.021	13,087.180	0.010
	(0.078)	(77,913.240)	(0.024)
Chubu After	0.138*	-870.422	0.050**
	(0.078)	(77,913.240)	(0.024)
Tohoku After	0.178**	-94,789.690	0.052**
	(0.078)	(77,913.240)	(0.024)
Tokyo After	0.215***	575.600	0.117***
	(0.078)	(77,913.240)	(0.024)
Hokuriku After	0.271***	21,774.730	0.001
	(0.078)	(77,913.240)	(0.024)
Kyushu After	0.415***	30,245.400	0.060**
	(0.078)	(77,913.240)	(0.024)
Kansai After	0.497***	-78,810.040	0.070***
	(0.078)	(77,913.240)	(0.024)
Hokkaido After	0.486***	11,484.070	0.048**
	(0.078)	(77,913.240)	(0.024)
Shikoku After	0.390***	15,616.040	0.033
	(0.078)	(77,913.240)	(0.024)
Constant	13.190***	6.933	3.369***
	(0.048)	(47,711.920)	(0.015)
Observations	600	600	600
R^2	0.967	0.773	0.693
Adjusted R^2	0.966	0.766	0.683
F Statistic (df = 19; 580)	888.460***	104.186***	68.910***

*p<0.1; **p<0.05; ***p<0.01

*Regions are listed in descending order by 2010 nuclear share. Okinawa is the base region and is not included in the regression.

SECTION 5 - RESULTS

The results show that losing nuclear power as an energy source resulted in a significant and large increase in thermal energy generation both on average and across groups, but with the largest increase estimated for group 3. However, in the region interaction model the two regions with the lowest nuclear shares prior to Fukushima were not predicted to have any significant change in thermal energy generation after Fukushima, while all other regions were predicted to have a significant increase in thermal generation.

The estimates in Tables 2 and 3 represent the average effect on all regions of removing nuclear energy as a power source on the regions' percent increase in thermal energy generation. The estimates range from .578 (using the staggered treatment start) to.306 (when using March 2011 as the treatment start for all regions). This means that the estimated minimum effect of losing nuclear energy is an almost 36% (when exponentiated) average increase in fossil fuel powered electricity generation, but the true effect could be as high as 78%. It is also interesting that the general fixed effects model with staggered treatment start did not report any significant changes in renewable energy generation. This means there was not a significant increase in renewables across regions after they reached zero nuclear generation. Moreover, none of the model specifications for Equation 1 estimated a significant positive change in renewable generation.

According to the estimates of Equation 1, Japan did not significantly change its renewable generation because of the loss of nuclear. This indicates that renewable energy sources, including hydroelectric, are not good substitutes for nuclear energy. Renewable energy sources have lower capacity factors than other energy sources, especially nuclear, and more importantly renewable power plant output cannot be changed quickly in the short run to meet demand needs. Additional electricity cannot be generated from solar power or wind without the addition of new infrastructure while more fossil fuels can be imported in the short run to fuel thermal power plants to run for greater amounts of time even without any changes to the plants' capacities. The increases in the operating capacity factors for thermal plants immediately after Fukushima that were observed earlier indicates that this is how Japan prevented electricity outages while taking nuclear power plants offline. Since electricity cannot be stored, power plants must be able to respond quickly to make sure that electricity supplied matches electricity demanded. Excess electricity is wasted, and not being able to handle peak demand loads results in blackouts. Renewable energy sources were inefficient substitutes because the amount of generation cannot be easily adjusted to match demand at a given time as it instead depends on uncontrollable variables such as weather condition.

The results of the difference-in-differences model reported in in Table 5 show the heterogenous effects of the removal of nuclear energy by pre-Fukushima nuclear share groups. No significant change in thermal generation for Group 1, the low nuclear share group was estimated by this model. Additionally, there was predicted to be no significant difference in the effects for Groups 1 and 2. The lack of significance for the Group 2 coefficient may be because Group 2 had the largest variation in shares of pre-Fukushima nuclear energy generation, from less than 14% in one region to 36% in another. This variation may have made the estimate for this group less precise than the estimates for the others. However, as expected, Group 3 is found to have the largest effect, with an estimated 60% increase in thermal generation after treatment, significant at a 5% level.

The results from Model 3 with region level interactions are very similar. This model reports that Okinawa and Chugoku, the regions with the lowest pre-Fukushima nuclear shares had no significant change in thermal generation. All other regions showed significant positive increases in thermal generation after Fukushima ranging from 15% to 64%. The estimates to correlate strongly with the group designations from Model 2, however, the regions with the two highest estimates, Kansai and Hokkaido, did not have the highest pre-Fukushima nuclear share. This indicates that region characteristics such as location, industry or urbanization may have impacted the effects of the treatment. A more region-specific analysis of these characteristics would be interesting but is not within the scope of this paper.

The marginal price estimations also reflect the regional differences. Groups 2 and 3 who had higher initial shares of nuclear generation had lower electricity prices in the before period. This reflects that electricity generation from nuclear power was significantly cheaper than from fossil fuels. Much of this cost difference comes from the differences in fuel costs by energy source, which was exasperated for fossil fuels after the sudden and sharp increase in thermal energy generation. We see this in the data as Groups 2 and 3 are estimated to experience about a 5% price increase in the after period, while Group 1 is not estimated to have a significant increase in marginal electricity price. In the region level estimation, Kansai and Kyushu (from Group 3) and Tokyo and Tohoku (from Group 2) were estimated to have a significant increase in price.

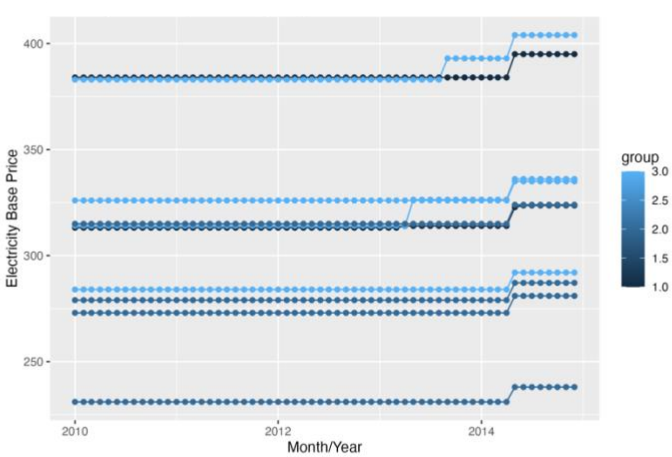
Notably, Shikoku from Group 3, with the highest pre-Fukushima nuclear share, was not estimated to have a significant change in price due to the treatment. This may be because this regions did not really increase their thermal capacity after the earthquake while Kansai, Tohoku and Tokyo immediately did. Since investment in new capacity is very expensive, this may explain why these regions experience larger price increases than other regions in their groups. It may also be that Hokkaido and Shikoku’s locations in terms of ports or fuel importation allowed for quicker or cheaper increase in the transportation of fossil fuels to their power plants. This would have mitigated some of the increased costs of shifting to thermal electricity generation in these regions. They also had the slowest transition to zero nuclear power (aside from Kansai which reach zero nuclear generation but then restarted a reactor). The longer transition period may have allowed these regions to have a smoother transition and lessen some of the costs of substitution

Finally, it is important to note that overall, all regions decreased their total electricity generation over this period. These drops were likely caused by the calls to ration electricity by the government to prevent blackouts. The increased cost of electricity generation, the increases in electricity prices and the growing fear over nuclear energy use may all be reasons why total generation dropped during the after period. From these results, it can be concluded that nuclear energy is a relatively cheaper, cleaner and reliable energy source that can sustain higher levels of electricity demand than if nuclear energy is not utilized.

SECTION 6 - LIMITS OF THE MODEL & FURTHER RESEARCH

This model has several limitations. The primary one is access to data which was briefly discussed earlier. Though the models include region fixed effects, within region changes over time, especially to manufacturing or other electricity intensive variables, are not controlled for in this analysis and could have biased the estimations. Additionally, the regulation of electricity prices likely biased the estimates of the effect on prices down. Because electricity and utility prices in Japan were regulated at the time, electricity price increases had to be shown to be caused by cost increases and approved by the government. Figure 7 shows the electricity base price over time by region. Though two regions adjusted prices in 2013, most regions did not adjust their electricity base price until 2014 after the electricity companies reported a cost analysis to the Japanese government of the increased costs caused by the aftermath of Fukushima. Because of this regulation, price increases did not correlate in either magnitude or timing to changes in electricity generation. In addition, all regions experienced the same increase in base price regardless of the actual heterogenous effect of the nuclear shutdown on their individual costs. In an unregulated environment prices shift to reflect supply and demand pressures, but this could not occur here, so the estimations of price changes do not capture the entire effect of the after nuclear energy period on prices.

Figure 7: Electricity Base Price by Region



There is much more research that can be done on this subject. It would be interesting to analyze the electricity company accounting data over this same period to attempt to estimate the true cost of the nuclear shut down. Though the companies avoided major electricity shortages, the regulation of prices resulted in large losses for the electric companies. Forbes reports that the disaster cost the companies over $110 billion even while residential electricity expenditures rose by 20% (Forbes).

Since this is a short-term analysis, it would also be interesting to look at data past 2016 to see how Japan has responded to the crisis in the long term. Generation capacity and number of sites would be interesting to analyze through 2024 as Japan has slowly begun to turn back to nuclear energy. In 2022, nuclear energy still only made up about 8% of its electricity generation, however, Japan has maintained much of its previous nuclear infrastructure and the country is predicted to again reach a 20% nuclear share by 2030 (East Asian Forum). For this reason, the capacity and site data over this period do not tell the whole story of how Japan adapted after Fukushima. But, looking more closely about how and when nuclear reactors were shut off or turned back on and when Japan was able to actually get new thermal capacity operational after Fukushima may show an even richer story of their nuclear transition.

Additionally, Japan deregulated its electricity market in 2016, allowing new entrants in both the electricity generation and retail markets. The nuclear shutdown after Fukushima highlighted inefficiencies in the regionally monopolized market and illustrated the need for competition to lower costs and modernize Japan’s electricity supply infrastructure. It would be interesting to analyze the transition into a competitive market and to compare the electricity situation before and after this regulation occurred, especially if there is variation in how fast the regions deregulated.

SECTION 7 - CONCLUSION

Nuclear energy is important in Japan not only for public health and environmental reasons, but also due to Japan's lack of fossil fuel resources within its borders. Without nuclear energy, Japan is reliant on energy imports from foreign nations to meet its energy needs. This has large economic and political consequences for the nation and Japan is unlikely to ever be energy independent without nuclear power. Additionally, at the time of the Fukushima disaster generation costs for fossil fuel and renewable powered electricity were significantly higher than nuclear, especially when excluding fixed costs of power plant construction.

This paper shows the true effect of removing nuclear power on Japan's energy situation. After the disaster, Japan had to turn to fossil fuels in the short run to continue to meet electricity demand. It highlights that when nuclear energy is removed, electricity generation is substituted by high cost, high emissions fossil fuels rather than renewable energy sources. Additionally, it shows that though total electricity demand in Japan decreased by about 8% over the period of analysis, this change was not uniform across the country and depended heavily on a region's initial energy portfolio, including how much thermal infrastructure the region had initially and how easily it could begin to increase its thermal electricity output after the disaster.

While this analysis is short-term, looking at only a period of four years after the earthquake, the results may be generalized to some extent to the long run. Increases in thermal capacity, rather than renewable capacity already began within this period. This shows that even when looking for long run solutions, policymakers and companies were still primarily planning to use thermal power to replace nuclear rather than renewables. In addition, it can be seen by the capacity factors that renewable energy generation is not flexible enough to meet seasonal and other fluctuations in electricity generation. Because electricity cannot be stored, electricity companies need to be able to quickly increase or decrease supply to match current demand. Even with added renewable infrastructure, the sun, wind or bodies of water cannot be turned on and off to meet demand. These inefficiencies in capacity factors prevent renewables from ever being a true substitute for nuclear, even in the long run.

This analysis should also advise other jurisdictions against slowing investment in nuclear energy or shutting down existing plants. Though there has been much improvement in renewable energy generation since 2011, these energy sources still have many disadvantages, particularly their low capacity factors, that prevent them from being an adequate substitute for nuclear energy. In the United States, nuclear reactors have steadily been shut down since the early 2000s. However, there is a growing discussion about the true cost of removing nuclear energy as a clean, reliable energy source. As recently as December 2023, California voted to extend the license of its last remaining nuclear power plant through 2030 when the plant was previously scheduled to shut down in 2024. Discussions about how to guide the future of nuclear power should consider Japan's energy situation in aftermath of the Fukushima disaster. While health and safety concerns around nuclear energy should be heavily considered, the true costs of removing nuclear energy, both directly from higher fuel and generation costs, but also in the costs to public health and the environment from the increase in fossil fuel generation, are significant. Environmental advocates cannot rely on nuclear energy to be substituted by other renewable energy sources in the short run and should expect that the removal of nuclear energy will result in large increases in the use of fossil fuels for electricity generation. In the long run there may be more room for increased renewable capacity to make up for some loss of nuclear energy, but the inflexibility of renewable energy generation means that it can never be a complete substitute for nuclear energy.

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