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Discussion Papers in Economics and Finance

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Discussion Paper No 21-5

September 2021

ISSN 0143-4543

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September 2021

Abstract

This study investigates how adoption of residential solar PV systems responds to changes in the economic value of adoption caused particularly by electricity price fluctuations. We shed light on the importance of a house(hold) characteristic that has been largely overlooked in the literature: the distinction between retrofit installations and new-build installations. To identify the effect of electricity prices on solar PV adoption, we regard the 2011 Fukushima nuclear accident and subsequent shutdown of nuclear power plants in Japan as a natural experiment that resulted in large (temporal and regional) exogenous variations in electricity generation costs. Using Japanese data for 2009–2014, we find a downward bias of 40–50% in the estimated effect of electricity prices if they are not instrumented with the cost variations. Our estimation shows that retrofit installations are 2–2.5 times more responsive to changes in electricity prices than new-build installations. An important policy implication of these contrasting responses is that financial incentive programs such as feed-in tariffs can be more cost-effective if they target more at owners of existing homes than at owners of new-build homes because retrofitting decisions are more likely to be induced by such incentives.

Keywords: solar PV; retrofit installation; new-build installation; electricity price; Fukushima

JEL Classification: L94, Q41, Q42, Q48

*Earlier versions of this paper were entitled "The Effect of Electricity Prices on Residential Solar PV Adoption: Fukushima as a Natural Experiment" (Discussion Papers in Economics and Finance, 18(10), University of Aberdeen) and "The Effect of Electricity Prices on Residential Solar Photovoltaic Panel Adoption: Fukushima as a Natural Experiment."

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1 Introduction

Buildings account for about 30% of global final energy consumption (International Energy Agency, 2019). Reducing the use of non-renewable energy in buildings is therefore a priority to achieve a low-carbon economy. Indeed, there are many government programs (e.g., subsidies) that are designed to stimulate the diffusion of energy-efficient or renewable-energy technologies for buildings, such as energy-efficient heating or cooling and rooftop solar PV electricity generation. Understanding the factors that influence adoption decisions of these technologies is essential for a faster transition and more effective policy design.

Many previous studies econometrically examine the determinants of energy-efficient or renewable-energy investments for buildings (e.g., Hassett and Metcalf, 1995; Gillingham, Harding and Rapson, 2012; Michelsen and Madlener, 2012; De Groote and Verboven, 2019). Broadly, these determinants relate to the economic costs and benefits of adoption (e.g., installation costs, subsidies, and electricity prices), demographic, socio-economic, and political heterogeneity across adopting households and firms (e.g., size, homeownership, and environmental preferences), and building characteristics (e.g., building age).

In this context, this paper sheds light on the importance of a house(hold) characteristic that has been largely overlooked in the previous literature: the distinction between retrofit installations (i.e., installations on existing buildings) and new-build installations (i.e., installations on new buildings). Although retrofitting existing buildings with energy-efficient or renewable-energy technologies has a huge potential for carbon emissions reductions at relatively inexpensive costs (e.g., Bardhan et al., 2014), the previous studies on the adoption behavior of these technologies rarely account for this distinction. As a notable exception, Michelsen and Madlener (2012) conduct a survey on the adoption decisions of residential heating systems in Germany, finding that demographic, socio-economic, building, and location characteristics are more influential for retrofit installations of residential heating systems than for new-build installations.

This paper considers important factors that are not covered in Michelsen and Madlener (2012): financial incentives that increase the economic benefits of adoption, such as electricity prices and installation subsidies. We find empirical evidence of a phenomenon unattended in the literature: the two types of adoption react very differently to changes in these incentives.

Specifically, we examine how residential solar PV diffusion in Japan during 2009–2014 responded to changes in the financial incentives, particularly electricity prices. Note that electricity prices (i.e., the prices of electricity purchased from the grid) affect solar PV adoption by changing the monetary value of replacing grid electricity with self-generated solar electricity. A distinctive feature of the prefecture-level panel data set we use is that the number of residential solar PV installations is reported separately for existing homes and new-build homes. We estimate a two-way fixed effects model, where the number of retrofit or new-build installations is explained by the price of electricity, other regressors such as local government incentives on PV adoption, and time/location fixed effects. Separately analyzing retrofit and new-build installations in this framework reveals the difference in the marginal effect of electricity prices or installation subsidies between the two categories.

Our estimation results show a clear contrast between retrofit and new-build installations. Retrofit installations are substantially more responsive to changes in electricity prices and subsidies than new-build installations are. For example, averaged across our preferred specifications, the estimated elasticity of solar PV adoption with respect to electricity prices is 1.94 for existing homes (highly statistically significant) and 0.84 for new-build homes (insignificant or marginally significant). In other words, owners of existing homes are much more likely to be marginal adopters whose decisions are affected by changes in these financial incentives.

Our results provide an important policy implication for the policy design of financial incentives (e.g., feed-in tariffs (FITs) and installation subsidies) to promote solar PV systems (and, potentially, other technologies). Given the policy goal of speeding up technology diffusion to reduce carbon emissions, providing larger support to owners of existing homes, who are more likely to be marginal adopters, than to buyers of new-build homes can be a simple yet underutilized way of improving the cost-effectiveness of these programs, as is consistent with the theory of tagging and targeting (e.g., Akerlof, 1978; Allcott, Knittel and Taubinsky, 2015). As an illustrative example based on the estimation results and the actual statistics from our data, we simulate the impact of marginally increasing the FIT rate for selling self-generated solar electricity to the grid. FITs are parallel to electricity prices in that higher tariffs and prices increase recurring future benefits of PV adoption. We find that the marginal effect of FIT spending (as measured by additional solar PV capacity per additional FIT spending) is 17% higher when the FIT rate is increased for retrofit installations than when it is increased for new-build installations. The disparity suggests that setting a higher FIT rate for retrofitting than for new-build fitting is a more cost-effective way of policy targeting.

The estimation results mentioned above reflect another contribution of the paper. That is, we pay close attention to the effect of electricity prices, which has been understudied in the PV adoption literature, and use an instrumental variable (IV) to overcome the potential endogeneity of electricity prices. Self-generated solar electricity can replace a sizable portion (typically, 30–40%) of an adopter's consumption of grid electricity. This reduction in grid electricity consumption is greater than what is achieved by other energy-efficient home appliances (e.g., air conditioners and refrigerators) for which previous studies find positive effects of electricity prices on adoption (Rapson, 2014; Houde, 2018). Higher prices of grid electricity obviously increase the private monetary benefit of reducing grid electricity consumption, thus affecting solar PV adoption decisions.[1] Borenstein (2017) argues that California's tiered residential electricity prices likely contribute to a surge in residential PV adoption, pointing out an important role of electricity prices. Although electricity prices are typically not the focus of the previous literature on the determinants of PV adoption, there are studies that include electricity prices as an exogenous covariate regressor and estimate their impact (e.g., Durham, Colby and Longstreth (1988) and Kwan (2012) for cross-sectional analyses, and Hughes and Podolefsky (2015), Matisoff and Johnson (2017), and Crago and Chernyakhovskiy (2017) for panel-based analyses). These studies often report positive (and statistically significant) effects of electricity prices but at other times find insignificant or even negative effects.

There are two challenges in estimating the effect of electricity prices (or other financial incentives for that matter) on technology adoption. First, there is often little variation in electricity prices

[1] Solar PV adoption is unlikely to be affected by electricity prices if adopters can sell all self-generated electricity to the grid at a FIT rate that is higher than the marginal electricity price they face.

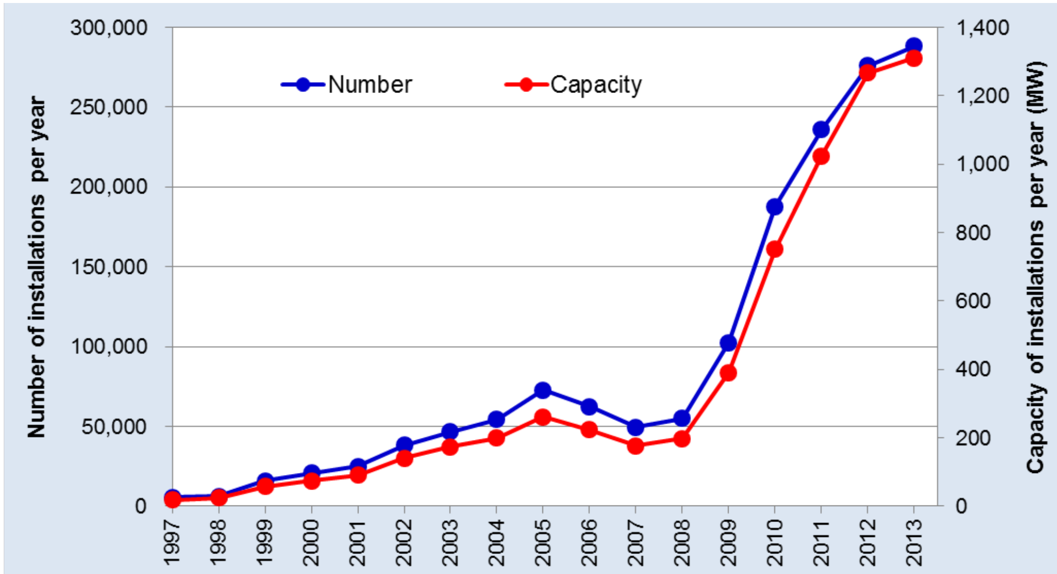
once location and/or time fixed effects are controlled for, making precise estimation of the effect difficult (De Groote, Pepermans and Verboven, 2016). Second, while electricity prices are mostly assumed exogenous in the previous studies on PV adoption, there may be area characteristics and trends that affect both PV adoption and electricity prices.[2] If such factors are not included in the estimation model, electricity prices become endogenous. This is obviously a serious concern in cross-sectional settings. Even panel settings with location and time fixed effects are not free from this possibility if, for example, electricity prices contain a component that funds FITs for renewable energy and cannot be controlled for by location or time fixed effects. For these reasons, previous studies often drop electricity prices from their estimation.

We overcome these challenges by exploiting substantial temporal and regional variations in electricity prices and generation costs caused by the 2011 Fukushima nuclear accident. The nuclear accident caused by an earthquake of magnitude 9.0 and the subsequent tsunami led to shutdown of all nuclear power plants in Japan, which did not resume power generation before the end of our sample period (2014) and most of which still remain shut down as of 2019. Nuclear power has been replaced by more expensive fossil fuels (crude oil, liquefied natural gas (LNG), and coal), raising electricity prices by up to 30% within a few years. Importantly, the extent of the price hike due to this cost-increasing substitution differs substantially across regions, depending on each region's pre-earthquake share of nuclear power and pattern of fuel substitution.[3]

With this observation in mind, we construct a time series of the average fossil fuel costs for each region based on the import prices of the three substitute fossil fuels (Japan's domestic production of these fuels is negligible) and a formula officially used by electricity companies to set a component of the electricity price. This cost shifter is used as an instrument for electricity prices, and its substantial exogenous variation (both over time and across regions) triggered by the natural disaster allows us to identify the effect of electricity prices on solar PV adoption. We find that not instrumenting electricity prices, as in the previous studies above, leads to a large downward bias (about 40–50% across different specifications). This is likely due to unobserved factors, such

[2]For example, a Renewable Portfolio Standard (RPS), which has been introduced in more than a half of the states in the US to increase the share of renewable sources, can boost the adoption of solar PV, while prior studies suggest the possibility that an RPS increases electricity prices (Palmer and Burtraw, 2005; Fischer and Newell, 2008; Tra, 2016).

[3]Neidell, Uchida and Veronesi (2021) uses this variation in electricity prices to identify the effect of electricity use in preventing death due to cold weather.



[Sources: New Energy Foundation; New Energy Promotion Council; Japan Photovoltaic Energy Association]

Figure 1: Residential Solar PV in Japan (1997-2013)

as pro-environmental preferences of residents, that cause regionally varying trends in not only residential solar PV diffusion but also in other types of energy-efficiency and renewable-energy investment by residents and firms that affect electricity demand and supply and thus electricity prices. Our results indicate that we should care about the endogeneity of electricity prices when analyzing their effect on the diffusion of solar PV and other low-carbon technologies.

The rest of the paper is organized as follows. Section 2 provides the background on residential solar PV diffusion and the electricity market in Japan. Section 3 describes the empirical framework and data. Section 4 presents the estimation results, and Section 5 discusses their implications. Section 6 concludes.

2 Background

2.1 Residential Solar PV in Japan

Residential solar PV electricity generation has been expanding in Japan since the 1990s mainly due to decreasing PV panel costs, public support such as one-time subsidies on installation and FITs for generated electricity. Figure 1 shows the number and capacity of annual residential solar PV installations between 1994 and 2014, indicating a gradual increase until the mid-2000s and a

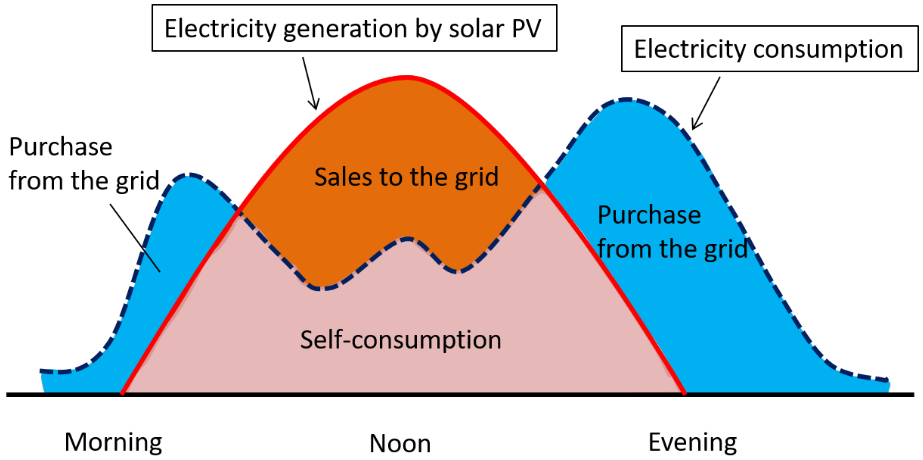


Figure 2: Self-consumption and Sales of Self-generated Solar Electricity

rapid expansion after 2009.[4] The surge after 2009 is mainly due to two national programs which both started in 2009: a subsidy on residential solar PV installation and a FIT for solar electricity. The increase after the 2011 earthquake and Fukushima accident may also be attributable to rising electricity prices, a hypothesis that we aim to examine.

This national subsidy program was in place from January 2009 to March 2014, providing a one-time subsidy to households after solar PV installation. Our estimation uses the number of applications for this subsidy. The subsidy rate was ¥70,000/kW in 2009, covering roughly 10% of the average solar PV system cost per kW at that time, and gradually decreased over time to become ¥20,000/kW for the final year (about 5% of the per-kW cost at that time). Households in all of the 47 prefectures could apply for this subsidy, with no quota given to each prefecture.

Under the Japanese FIT scheme for residential solar PV, which started in November 2009, the price of electricity from the grid influences the economic benefit of adoption. The scheme legally requires electricity companies to purchase solar electricity from households at a fixed rate for 10 years. An important characteristic of the scheme is that residential solar PV owners, defined as owners of less than 10 kW of solar PV capacity, can sell only surplus electricity. That is, the solar PV system first supplies electricity for domestic consumption ("Self-consumption" in Figure 2) and sells only the surplus after domestic consumption to the electricity grid at a fixed FIT rate

[4]There were about 288,000 residential installations in 2013 only and cumulatively about 1,547,000 installations until 2013, which are estimated to account for 0.15% and 0.82% of total electricity consumption in Japan, respectively.

("Sales to the grid" in Figure 2). Therefore, solar PV adoption rewards households in two ways: first, by reducing the electricity purchase from the grid and, second, by selling surplus electricity to the grid. A higher electricity price (for the purchase from the grid) therefore provides a larger incentive for solar PV adoption because households can expect greater electricity-cost savings by using self-generated electricity.

The FIT rate was set high to stimulate solar PV diffusion, and the scheme was financed by extra charges on electricity users. The FIT rate was originally ¥48/kWh for solar PV systems installed in 2009 and 2010, and it has been reduced gradually (e.g., ¥37/kWh for solar PV systems installed in 2014). During our study period (2009–2014), the FIT rate remained higher than the (average or marginal) electricity price in any region. Mandatory purchase of renewable electricity means additional costs to electricity companies. These additional costs are financed by a "renewable energy surcharge" that is added to each user's electricity bill and has been increased over time (from ¥0.01/kWh in 2011 to ¥0.35/kWh in 2014 Q1).

The FIT scheme is implemented nationwide, and all prefectures follow the same rules. The FIT rate and the renewable energy surcharge described above are set by the central government (the Ministry of Economy, Trade and Industry, or METI) and common to all prefectures. This is important for our study because including time fixed effects can control for the effect of changes in the FIT and the renewable energy surcharge over the years.

2.2 Residential Electricity Market in Japan

2.2.1 Regulated Regional Monopolies

Prior to 2016, Japan's residential electricity market was highly regulated by the central government (METI). The country was divided into 10 regions, each of which was served by a vertically integrated monopoly in charge of electricity generation, transmission, and distribution. Each regional monopoly supplied electricity to all households in the region. For the protection of consumers, electricity prices in each regional market could not be raised without METI's approval.

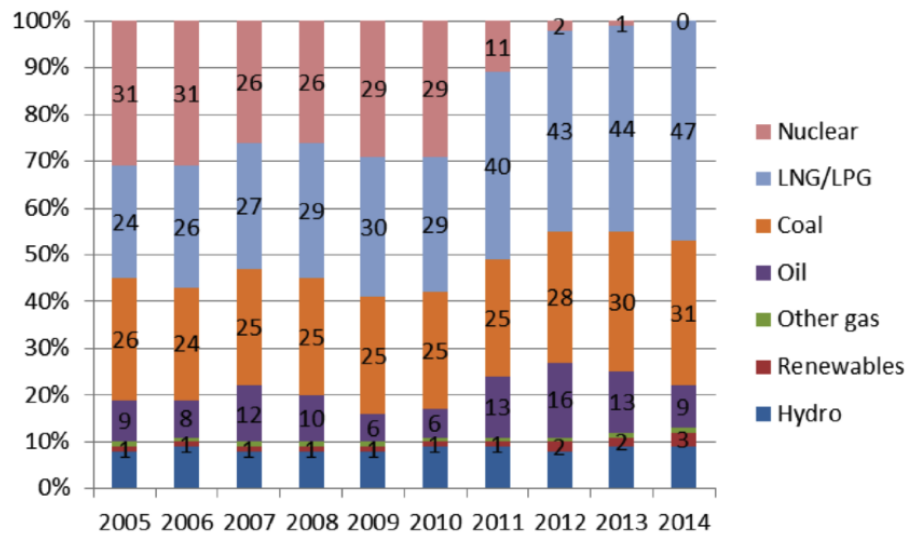


Figure 3: Japan's Electricity Generation by Energy Source

2.2.2 Electricity Price Variation after Fukushima

On March 11, 2011, a massive earthquake of magnitude 9.0 and subsequent tsunami hit the east coast of Japan. This earthquake and tsunami caused devastating meltdowns at Tokyo Electric Power Corporation's Fukushima No.1 Nuclear Power Plant, triggering severe radioactive contamination of the environment. At the time of the accident, the country had 54 nuclear reactors in total, 37 of which were in operation (IIC, 2014). Safety concerns on nuclear power led all operating reactors to shut down successively by May 2012, and they were not allowed to resume operation. Although two reactors were permitted to restart in July 2012, their periodic inspections in September 2013 resulted in another complete nuclear shutdown, which continued until August 2015 when a reactor resumed operation under stricter regulations. Figure 3 shows the effect of the shutdown on Japan's electricity generation mix. The share of nuclear power was about 30% before the March 2011 earthquake but dropped to 11% in 2011, 2% in 2012, 1% in 2013, and eventually 0% in 2014.

Nuclear power was mostly replaced by fossil fuels (coal, liquefied natural gas (LNG), and oil). In Figure 3, fossil fuels' share increased from 60% in 2010 to 87% in 2013 and 2014, taking over most of nuclear power's share in 2010 (29%). Facing the nuclear shutdown, electricity companies urgently expanded the use of fossil fuels by, primarily, reactivating old, idle fossil-fuel-based

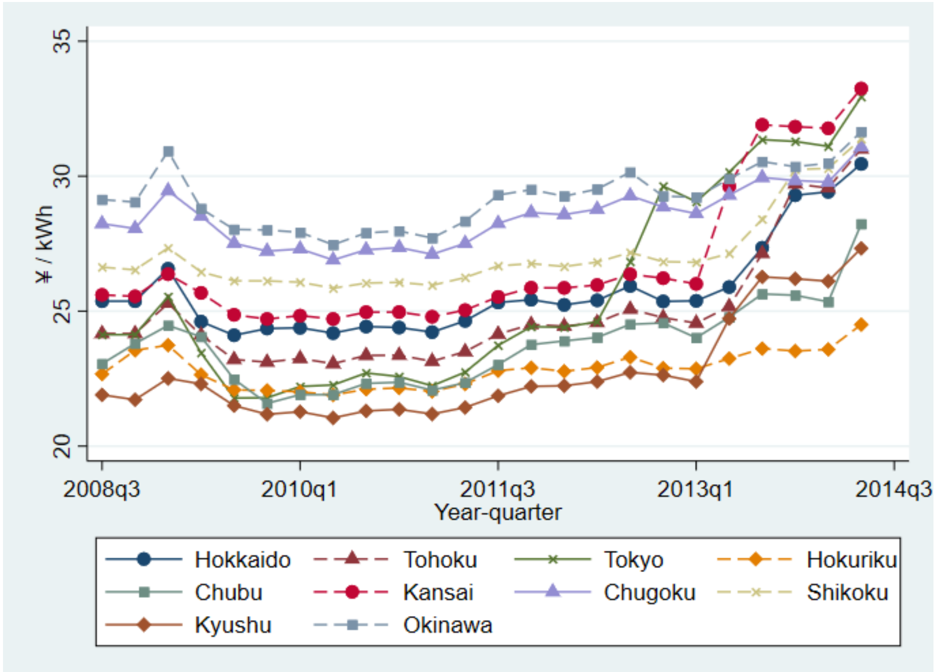


Figure 4: Marginal Electricity Price per kWh by Region

generators, which were typically small-sized and less efficient, and, additionally, building a small number of new ones.

The shutdown of nuclear power plants and substitution by fossil fuels resulted in a sharp increase in electricity prices because fossil fuels were more expensive sources of electricity generation than nuclear power.[5] The average electricity price per kWh increased by 37% within four years of the earthquake, from ¥19.8/kWh to ¥27.3/kWh. During the period of our analysis (2009 Q1 to 2014 Q1), six electricity companies (regions) raised base electricity prices, with all the cases occurring after 2012. When requesting METI's permission for price increases, they listed the increased fuel costs due to fuel substitution as the primary reason, with some companies also referring to higher safety and security costs for nuclear power plants under the tightened regulations.

Whereas electricity prices soared in all regions of Japan following the Fukushima accident, the magnitude of the increase varied substantially across regions. Figure 4 shows the average residential electricity price per kWh by region before and after Fukushima. Some regions (e.g.,

[5] METI (2015) estimates the fuel cost in 2014 to be ¥1.5/kWh for nuclear power, ¥5.5/kWh for coal, ¥10.8/kWh for LNG, and ¥21.7/kWh for oil. The order remains the same in terms of the sum of the operation, maintenance, and fuel costs: ¥4.8/kWh for nuclear power, ¥7.2/kWh for coal, ¥11.4/kWh for LNG, and ¥24.3-29.4/kWh for oil.

Hokkaido, Tokyo, and Kansai) suffered significant price hikes starting in the second quarter of 2011 (about 20–30% within three years), while other regions (e.g., Hokuriku, Chugoku, and Okinawa) experienced milder hikes (7–11% within the same period).

Figures 5 and 6 indicate two major factors that affected the magnitude of each region's electricity price hike after Fukushima: the share of nuclear power in the region's electricity generation before Fukushima and the increase in the share of natural gas or oil (as opposed to coal) after Fukushima to substitute for nuclear power. Figure 5 shows a substantial regional variation in the share of nuclear power before Fukushima (in 2010). The share was over 40% in the regions most dependent on nuclear power (Hokkaido, Kansai, Shikoku, and Kyushu), whereas it was less than 5% in Chugoku and Okinawa. Figure 6a plots the increase in fossil fuel's share between 2010 and 2013 against the decrease in nuclear power's share in the same period, showing that nuclear power was mostly replaced by fossil fuels (coal, LNG, and oil) in all 10 regions. Figure 6b plots the percentage increase in electricity prices between 2010 Q1 and 2013 Q1 against the increase in the aggregate share of LNG and oil in the generation mix between 2010 and 2013. Figure 6b suggests that substitution by LNG and oil is positively correlated with the magnitude of the electricity price hike.[6] Figures 5 and 6 suggest that regional electricity prices, which exhibit regionally varying post-Fukushima trends (Figure 4), tended to increase substantially if a region (i.e., a regional monopoly) depended heavily on nuclear power before Fukushima and needed to significantly increase the use of LNG and oil (rather than coal) after Fukushima to replace nuclear power.

3 Empirical Framework and Data

We investigate the impact of electricity prices on residential rooftop solar PV adoption by means of the following two-way fixed effects model:

$$\ln y_{it} = \beta p_{i,t-1} + \mathbf{X}'_{it}\gamma + \eta_t + \mu_i + \varepsilon_{it}, \tag{1}$$

[6] It is notable that Hokuriku had a relatively high pre-Fukushima share of nuclear power (28%) but did not suffer a large increase in electricity prices. Nuclear power was mainly replaced by coal in the region.

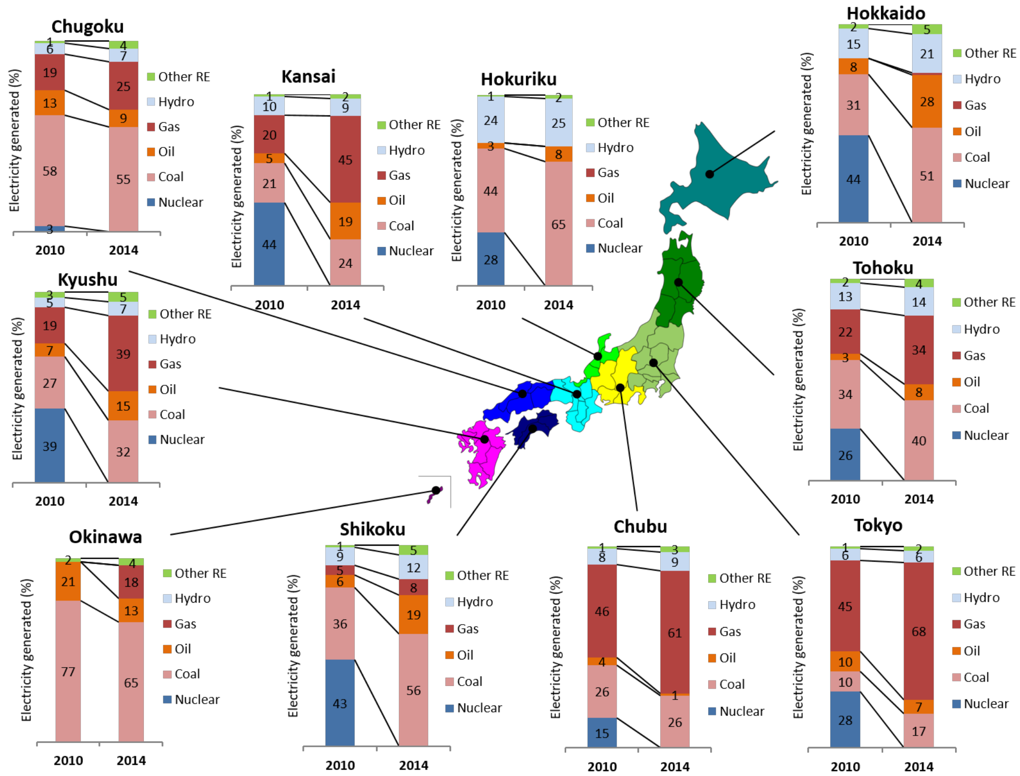
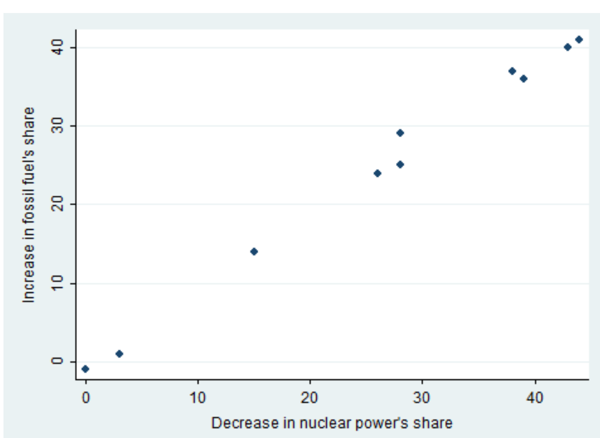
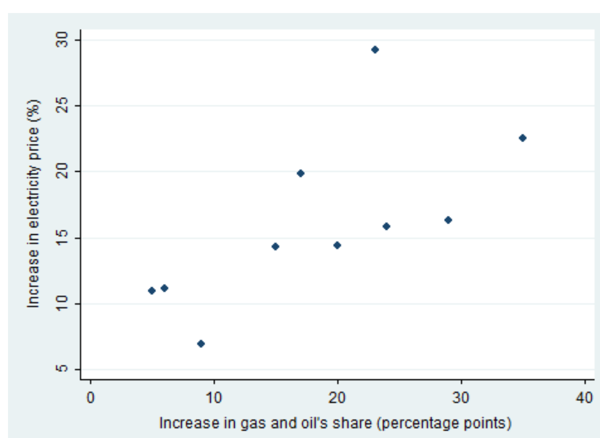


Figure 5: Electricity Mix by Region in 2010 and 2014



(a) Increase in Fossil Fuel's Share vs. Decrease in Nuclear Power's Share



(b) Percentage Increase in Electricity Prices vs. Increase in LNG and Oil's Share

Figure 6: Regional Changes in the Energy Mix and Electricity Prices Between 2010 and 2013

where i stands for prefecture i and t for period (year-quarter) t. This model is estimated separately for retrofit installations and new-build installations as well as for both types altogether. On the left-hand side, y_{it}, is the number of applications to the national subsidy program for residential solar PV installation in prefecture i during period t. For the independent variables, $p_{i,t-1}$ is the one-quarter lagged (marginal or average) electricity price, and X_{it} is a vector of covariates, such as the installation subsidy from the prefectural government. We also consider different definitions for the electricity price variable: the logarithmic form and the two-quarter lagged price. Table 1 reports the summary statistics for these variables. The time fixed effect η_t captures various factors that are common to all prefectures in period t, such as PV system costs and nationwide policies (e.g., the FIT scheme, the central government's installation subsidy, and the "renewable energy surcharge" that is added to each user's electricity bill to finance the FIT scheme). The prefecture fixed effect μ_i controls for prefecture characteristics that are time-invariant over the sample period, such as weather conditions and demographics. The idiosyncratic error ε_{it} is clustered at the prefecture level (there are 47 prefectures).[7]

We also consider a semi-parametric version of Eq. (1) in which the effect of $p_{i,t-1}$ is estimated non-parametrically after partialling out the fixed effects and covariates (Baltagi and Li, 2002; Li and Racine, 2007). It shows that the relationship between $\ln y_{it}$ and $p_{i,t-1}$ is fairly linear, albeit unstable at the ends of the distribution, thus supporting the specification in Eq. (1).

First, we describe more details of the dependent variable $\ln y_{it}$, (the log of) the number of applications to the national subsidy program. The data on y_{it} are available from the Japan Photovoltaic Energy Association, the operating body of the program. Households applied for the subsidy before installation, and over 96% of the applications were successfully approved and resulted in actual installations. We use subsidy applications as our dependent variable rather than subsidy approvals. This is because the time gap between an application and its approval is typically several months but varies case by case, and thus applications better capture the timing of household adoption decisions than approvals.

[7] As described in Section 2.2, prefectures in a region were served by a regional monopoly and faced a common electricity price schedule set by the monopoly. For this reason, we also estimate our model with the error term ε_{it} clustered at the region (rather than prefecture) level, and the results are essentially unaffected.

Table 1: Summary Statistics

Variable	Obs	Mean	SD	Min	Max
National subsidy applications (all)	987	1,285	1,157	40	8,313
National subsidy applications (retrofit)	987	843	710	27	4,655
National subsidy applications (new build)	987	443	485	6	4,038
Marginal electricity price (¥/kWh)	987	25.20	2.79	21.05	31.90
Average electricity price (¥/kWh)	987	24.61	1.83	22.05	29.95
Fossil fuel cost (¥1,000/kl of oil equivalent)	987	31.00	7.94	19.59	54.09
Prefectural subsidy dummy (retrofit)[a]	987	0.52	0.50	0	1
Prefectural subsidy (¥1,000/case; retrofit)[b]	511	103.73	74.69	14	434
Prefectural subsidy dummy (new build)[a]	987	0.48	0.50	0	1
Prefectural subsidy (¥1,000/case; new build)[b]	478	98.48	71.60	14	377
Cumulative solar PV installations	987	19,352	16,700	966	107,961
Housing starts (owned properties)	987	1,653	1,323	222	7,108
Population over age 15 (1,000 people)	987	2,361	2,326	501	11,798
Average worker age	987	41.83	0.62	40.0	43.5
Average wage (¥1,000/month)	987	269.91	28.12	222.2	377.4

[a] This variable equals 1 if a prefectural subsidy is present and 0 if it is absent.

[b] Conditional on the presence of a prefectural subsidy.

For the most part, the data directly reflect each household's independent decision to adopt solar PV. Less than 1% of applications were from new detached houses that had solar PV panels pre-installed by the developers in advance of house sales. Even fewer were applications from (new or existing) non-detached houses for which collective decisions by multiple households might be necessary. Additionally, rental or leased solar PV systems (such as those provided by SolarCity in California) were rare in Japan.

Aggregated across prefectures over 2009 Q2–2014 Q1, there were 831,637 applications for retrofit installations and 436,852 applications for new-build installations. To show the relative magnitude of these numbers, there were 28.6 million detached homes in Japan in 2013, and housing starts for detached homes between 2009 and 2013 amount to 2.1 million. In other words, during the period of our analysis, about 20% of new-build homes installed solar PV, while about 3% of the stock of existing homes installed solar PV (excluding those that did so when they were new).

Next, we discuss more details of the electricity price p_{it}, including its potential endogeneity in the above fixed effects framework. We construct the quarterly data on residential electricity prices by averaging the monthly data from the Retail Price Survey published by the Statistics Bureau of Japan. We use the marginal price for households that consume over 300 kWh a month (or 280 kWh for the Hokkaido region). Because the standard household's monthly electricity consumption is assumed to be 441 kWh by METI, almost all households adopting solar PV, which likely reside in relatively large, detached homes, face this marginal price. We also use the average price for the standard household to test the robustness of the results. As discussed in Section 2.2, these electricity prices exhibit substantial variations over time and across prefectures in the wake of the Fukushima accident.

A concern in estimating Eq. (1) with the simple fixed effects estimator is the potential endogeneity of $p_{i,t-1}$. Because the time and location fixed effects are both included, this problem arises if the spatial and temporal variations in electricity prices that are captured by neither η_t nor μ_i are correlated with unobservable factors that affect residential solar PV adoption and are absorbed by neither η_t nor μ_i. For example, some unobserved factors that vary both over time and across prefectures (e.g., pro-environmental preferences of residents) may have regionally varying impacts on the pace of not only residential solar PV investment but also other types of energy-efficiency and renewable-energy investment. Diffusion of these technologies likely reduces a region's dependence on expensive fossil fuels (by reducing electricity consumption on the demand side and substituting fossil fuels with renewables on the supply side) and thus keeps the electricity price trend lower than would otherwise be the case.

To deal with the potential endogeneity of electricity prices, we construct an IV based on a formula that is used by electricity companies to set a component of actual electricity prices. Note that the IV should be correlated with electricity prices but uncorrelated with unobservable factors that affect residential solar PV adoption, *after controlling for the time and prefecture fixed effects and other covariates*. For region (regional monopoly) i in period (year-month) m, the weighted average fossil fuel cost $f_{i,m}$ is calculated as follows:

$$f_{i,m} = a_i r^o_{m-3} + b_i r^g_{m-3} + c_i r^c_{m-3}, \tag{2}$$

where r^o_{m-3}, r^g_{m-3}, and r^c_{m-3} are respectively the (country-level) import prices of crude oil, LNG,

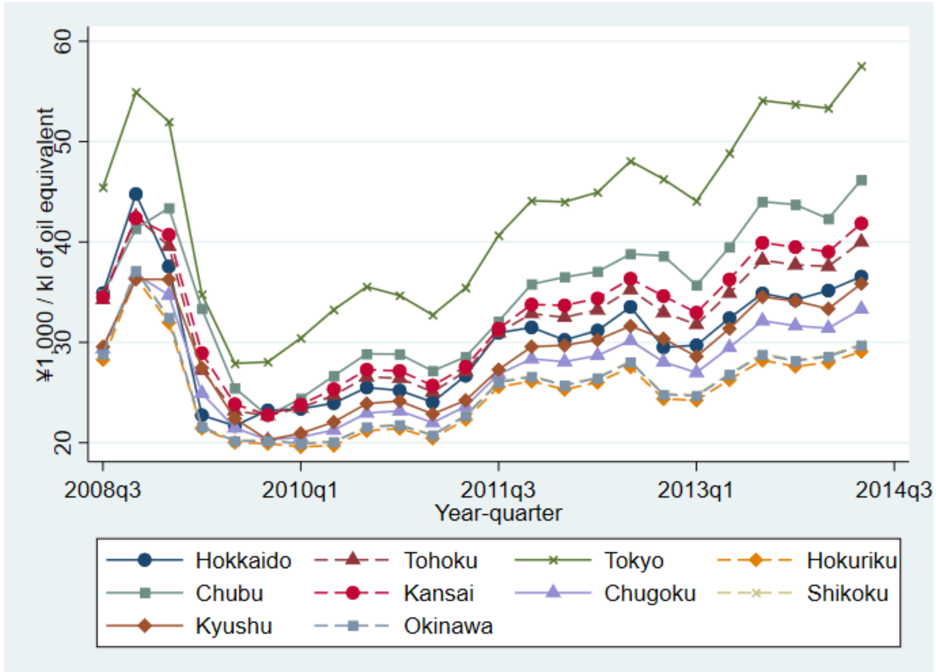


Figure 7: Fossil Fuel Cost by Region

and coal that are averaged over the latest three months (i.e., months $m-3$, $m-4$, and $m-5$),[8,9] and a_i, b_i, and c_i (which equals $1-a_i-b_i$) are the weights that reflect the respective fuels' shares (among the three fuels) in region i's energy mix prior to 2008. In fact, the fuel-cost-dependent component of each region's electricity price for month m is determined by $f_{i,m}$, except that each electricity company might occasionally (e.g., once in several years) update the coefficients a_i, b_i, and c_i to reflect changes in the company's energy mix. Because $p_{i,t-1}$ in Eq. (1) is a quarterly series, $p_{i,t-1}$ is instrumented by the average of $f_{i,m}$ over the three months in period (year-quarter) $t-1$. By construction, this cost shifter is correlated with the (marginal and average) electricity price through fuel price fluctuations. In addition, $f_{i,m}$ can be reasonably considered exogenous (i.e., uncorrelated with unobserved factors that affect residential solar PV adoption and are absorbed by neither η_t nor μ_i) because the coefficients a_i, b_i, and c_i are fixed based on the region's energy mix prior to our study period and the import prices r_m^o, r_m^g, and r_m^c are macroeconomic, country-level statistics that reflect the conditions in the international energy market. Figure 7 plots this cost shifter IV by region over 2008-2014, showing similarities to the trends of regional

[8]The original price data are from the Trade Statistics of Japan, and r_m^o, r_m^g, and r_m^c are obtained by making necessary conversions to account for the different heating values of the three fuels.

[9]Japan's domestic production of these fuels is minimum and ignorable.

electricity prices (Figure 4).

The covariates $\mathbf{X}_{it}$ are included to control for other observable factors that vary both over time and across prefectures and may affect solar PV adoption. First, on top of the national subsidy discussed above, local governments often subsidize households for solar PV installation as well. Referring to prefectural governments' budget information, we construct two variables on such subsidies for each *i*-*t* combination and each installation type (i.e., retrofit or new build): (1) a dummy variable for the presence of a prefectural subsidy and (2) the amount of this subsidy when the average system capacity (kW) for each prefecture in each year is installed.

Following the earlier literature (e.g., Durham, Colby and Longstreth, 1988; Kwan, 2012; Crago and Chernyakhovskiy, 2017), $\mathbf{X}_{it}$ further includes prefecture-level demographic variables (*housing starts*, *population*, *average worker age*, and *average wage*) that are constructed from the database of the Statistics Bureau of Japan. Including these variables is particularly important in cross-sectional analyses. In our panel data setting, most of their effects are likely to be absorbed by the fixed effects (particularly, the prefecture fixed effects) anyway because these variables change little within each prefecture over the study period.

4 Results

Table 2 presents our baseline results of estimating Eq. (1) with only the lagged electricity price, prefecture fixed effects, and time (i.e., year-quarter) fixed effects. The electricity price variable ($p_{i,t-1}$) is either the marginal or average price, or its natural logarithm, and is lagged by a quarter to reflect a delay in the response to electricity price changes (we try other lag structures later). In the even-numbered columns, the electricity price is instrumented with the average fuel cost, as discussed in Section 3. The results are reported separately for retrofit installations (Panel R) and new-build installations (Panel N) as well as for both types altogether (Panel A).

Table 2 Panel A shows that the electricity price has a positive and statistically significant effect on overall residential solar PV diffusion. In columns (1)–(4), the elasticity of solar PV adoption with respect to the marginal electricity price is about 0.75 without the IV and about 1.4 with the

Table 2: Baseline Regression Results

Panel A: All Installations

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Marginal price$_{t-1}$ (¥/kWh)	0.030**	0.054***						
	(0.012)	(0.016)						
ln(Marginal price$_{t-1}$)			0.76**	1.43**				
			(0.32)	(0.56)				
Average price$_{t-1}$ (¥/kWh)					0.046**	0.072***		
					(0.018)	(0.021)		
ln(Average price$_{t-1}$)							1.17**	1.94**
							(0.47)	(0.77)
Electricity price elasticity	0.74	1.35	0.76	1.43	1.13	1.76	1.17	1.94
Instrument	No	Yes	No	Yes	No	Yes	No	Yes
Within R^2	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85

Panel R: Retrofit Installations

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Marginal price$_{t-1}$ (¥/kWh)	0.036*	0.065***						
	(0.018)	(0.022)						
ln(Marginal price$_{t-1}$)			0.93*	1.75**				
			(0.48)	(0.71)				
Average price$_{t-1}$ (¥/kWh)					0.056**	0.087***		
					(0.027)	(0.030)		
ln(Average price$_{t-1}$)							1.44**	2.37**
							(0.69)	(0.97)
Electricity price elasticity	0.89	1.63	0.93	1.75	1.38	2.13	1.44	2.37
Instrument	No	Yes	No	Yes	No	Yes	No	Yes
Within R^2	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77

Panel N: New-Build Installations

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Marginal price$_{t-1}$ (¥/kWh)	0.0055	0.012						
	(0.0072)	(0.010)						
ln(Marginal price$_{t-1}$)			0.12	0.23				
			(0.19)	(0.48)				
Average price$_{t-1}$ (¥/kWh)					0.0081	0.016		
					(0.011)	(0.014)		
ln(Average price$_{t-1}$)							0.19	0.32
							(0.31)	(0.66)
Electricity price elasticity	0.14	0.31	0.12	0.23	0.20	0.40	0.19	0.32
Instrument	No	Yes	No	Yes	No	Yes	No	Yes
Within R^2	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92

Notes: All specifications include prefecture fixed effects and time (year-quarter) fixed effects and have 987 observations (47 prefectures for 21 periods). Cluster-robust standard errors are in parentheses, where the observations are clustered at the prefecture level. Prices (marginal or average) are one-quarter lagged electricity prices. In IV specifications, the electricity price is instrumented by a weighted average of fuel prices. The dependent variable is the log of applications to the national subsidy on residential solar PV installation. Superscripts *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.

IV.[10] Columns (5)–(8) use the average, rather than marginal, price of electricity for a standard household,[11] giving a similar result that higher electricity prices lead to more installations. The estimated effect is somewhat larger with the average price (i.e., about 1.15 without the IV and about 1.85 with the IV) than with the marginal price. In the first stage of each IV specification, our cost shifter instrument is positively and significantly correlated with the electricity price variable with a p-value less than 0.001.

Panels R and N analyze retrofit and new-build installations, respectively, and show that the result in Panel A is essentially driven by retrofitting. For retrofit installations, columns (1)–(8) of Panel R show that the effect of electricity prices is significantly positive and larger than in the corresponding columns in Panel A. On the contrary, Panel N shows that the effect on new-build installations is small and statistically insignificant. Importantly, our result does *not* mean that new-build homes are less likely to be equipped with solar PV systems than existing homes are. In fact, as described in Section 3, we observe a substantially higher rate of solar PV adoption for new-build homes than for existing homes. Instead, our result suggests that when making adoption decisions, owners of new-build homes tend to pay little attention to and, thus, are less responsive to electricity price changes than owners of existing homes.

Comparing the point estimates in Table 2 with and without the IV, we note that not instrumenting the electricity price biases the estimated effect downward by about 40–50%. As discussed in Section 3, an explanation for this bias is that, *after controlling for the time and location fixed effects* (η_t and μ_i), some unobserved factors (e.g., pro-environmental preferences of residents) may result in regionally varying trends in not only residential solar PV investments (our dependent variable) but also other energy-efficiency and renewable-energy investments. These investments lower a region's dependence on expensive fossil fuels (by reducing electricity demand or substituting fossil fuels with renewables), thereby alleviating the post-Fukushima electricity price hikes. Note that our instrument is not affected by this process because it is calculated with fixed parameters (a_i, b_i, and c_i in Eq. (2)) that were determined prior to our sample period (see Section 3).

[10] The elasticity for column (1) or (2) is evaluated at the average of $p_{i,t-1}$ (taken over i and t).

[11] METI assumes that a standard household consumes 441 kWh a month. We acknowledge the possibility that households adopting solar PV tend to consume more electricity, so the average price they face can be different from what the standard household faces.

Table 3 adds other prefecture-level covariates ($\mathbf{X}_{it}$ in Eq. (1)) to the regression. We include the information on prefecture-level solar PV adoption subsidies and the cumulative number of residential solar PV installations (one quarter lagged), along with other demographic variables (each prefecture's housing starts, population, average age, and average wage) considered in the earlier literature (e.g., Durham, Colby and Longstreth, 1988; Kwan, 2012; Crago and Chernyakhovskiy, 2017). Whereas the estimated effects of electricity prices in Table 3 are somewhat larger than the corresponding estimates in Table 2, they show the similar patterns that retrofit installations are more sensitive to electricity price changes than new-build installations are and that not instrumenting the electricity price by the cost shifter leads to a downward bias.

Interestingly, the result about prefectural subsidies also gives a similar contrast between existing and new-build homes. With acknowledging the potential endogeneity of PV adoption subsidies, which Hughes and Podolefsky (2015) investigated for the case of California, we find prefectural subsidies have a significantly positive effect on retrofit installations,[12] but not on new-build installations. Increasing the subsidy rate by ¥10,000 per case (about 10% of the average amount) leads to about 0.9% more retrofit installations, whereas doing so has no statistically significant effect on new-build installations.

Lastly, Table 4 checks the robustness of our results to the number of lags in the electricity price variable. Compared to columns (4) and (6) of Table 3 with one-quarter lagged electricity prices, Table 4 uses two-quarter lagged prices (columns (1) and (3)) and additionally includes the change in the respective electricity prices from $t-2$ to $t-1$ (columns (2) and (4)). The results show very similar patterns to columns (4) and (6) of Table 3.

5 Discussion

Across the different specifications estimated above, we robustly find that the marginal effect of electricity prices is 2–2.5 times larger for retrofit installations than for new-build installations. There is a similar and even stronger contrast with respect to the effect of prefectural subsidies.

[12] If we use the estimates in column (4) of Table 3 Panel R for an illustration, the overall effect of a prefectural subsidy of s per case is given by $0.0085 \times s - 0.0065$, which is positive even for the minimum value of s in the sample. The equivalent pattern holds for the other columns in Panel R.

Table 3: Regression Results with Prefecture-level Policies and Other Controls

Panel R: Retrofit Installations

	(1)	(2)	(3)	(4)	(5)	(6)
Marginal price$_{t-1}$ (¥/kWh)	0.039**	0.077***	0.038**	0.074***		
	(0.018)	(0.023)	(0.017)	(0.023)		
Average price$_{t-1}$ (¥/kWh)					0.060**	0.097***
					(0.027)	(0.031)
Prefec. subsidy (¥1,000/kWh)			0.00088**	0.00085**	0.00087**	0.00085**
			(0.00042)	(0.00043)	(0.00042)	(0.00043)
Prefec. subsidy dummy	0.080*	0.075*	-0.0035	-0.0054	-0.0045	-0.0065
	(0.041)	(0.042)	(0.061)	(0.061)	(0.062)	(0.061)
ln(Cumulative$_{t-1}$)	0.17	0.024	0.27	0.12	0.24	0.12
	(0.27)	(0.28)	(0.27)	(0.27)	(0.27)	(0.28)
ln(Housing starts)	0.27**	0.30**	0.26**	0.29**	0.26**	0.28**
	(0.12)	(0.12)	(0.12)	(0.12)	(0.12)	(0.12)
ln(Population)	-2.38	-4.08	-1.60	-3.24	-1.65	-2.79
	(4.61)	(4.43)	(4.80)	(4.62)	(4.82)	(4.69)
ln(Avg. worker age)	0.46	0.21	0.35	0.12	0.33	0.17
	(1.64)	(1.59)	(1.62)	(1.57)	(1.63)	(1.59)
ln(Avg. income)	0.17	0.36	0.34	0.52	0.34	0.45
	(0.81)	(0.79)	(0.81)	(0.81)	(0.81)	(0.80)
Electricity price elasticity	0.97	1.92	0.95	1.85	1.47	2.37
Instrument	No	Yes	No	Yes	No	Yes
Within R^2	0.78	0.77	0.78	0.78	0.78	0.78

Panel N: New-Build Installations

	(1)	(2)	(3)	(4)	(5)	(6)
Marginal price$_{t-1}$ (¥/kWh)	0.019	0.035*	0.019	0.035**		
	(0.012)	(0.018)	(0.012)	(0.018)		
Average price$_{t-1}$ (¥/kWh)					0.029	0.045*
					(0.020)	(0.024)
Prefec. subsidy (¥1,000/kWh)			0.000027	-0.000022	0.000023	-0.000013
			(0.00026)	(0.00026)	(0.00026)	(0.00026)
Prefec. subsidy dummy	-0.019	-0.019	-0.021	-0.017	-0.022	-0.019
	(0.020)	(0.021)	(0.029)	(0.029)	(0.029)	(0.029)
ln(Cumulative$_{t-1}$)	-0.13	-0.20	-0.13	-0.20	-0.14	-0.20
	(0.23)	(0.24)	(0.23)	(0.24)	(0.24)	(0.24)
ln(Housing starts)	0.43***	0.44***	0.43***	0.44***	0.43***	0.44***
	(0.092)	(0.090)	(0.092)	(0.090)	(0.092)	(0.091)
ln(Population)	-2.46	-3.17	-2.45	-3.19	-2.45	-2.97
	(3.29)	(3.28)	(3.30)	(3.30)	(3.33)	(3.29)
ln(Avg. worker age)	-2.46**	-2.57**	-2.46**	-2.56**	-2.47**	-2.54**
	(1.01)	(1.01)	(1.01)	(1.01)	(1.02)	(1.02)
ln(Avg. income)	0.16	0.24	0.16	0.24	0.16	0.21
	(0.47)	(0.46)	(0.48)	(0.47)	(0.48)	(0.48)
Electricity price elasticity	0.47	0.87	0.47	0.87	0.71	1.10
Instrument	No	Yes	No	Yes	No	Yes
Within R^2	0.93	0.92	0.93	0.92	0.93	0.93

Notes: All specifications include prefecture fixed effects and time (year-quarter) fixed effects and have 987 observations (47 prefectures for 21 periods). Robust standard errors clustered at the prefecture level are reported in parentheses. Prices (marginal or average) are one-quarter lagged electricity prices. In IV specifications, the electricity price is instrumented by a weighted average of fuel prices. The dependent variable is the log of applications to the national subsidy on residential solar PV installation. Superscripts *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.

Table 4: Regression Results with Different Lags

Panel R: Retrofit Installations

	(1)	(2)	(3)	(4)
Marginal price$_{t-1}$ (¥/kWh)		0.066***		
		(0.020)		
Marginal price$_{t-2}$ (¥/kWh)	0.063***			
	(0.020)			
Marg. price$_{t-1}$−Marg. price$_{t-2}$		0.048		
		(0.055)		
Average price$_{t-1}$ (¥/kWh)				0.089***
				(0.027)
Average price$_{t-2}$ (¥/kWh)			0.082***	
			(0.027)	
Avg. price$_{t-1}$−Avg. price$_{t-2}$				0.042
				(0.053)
Prefec. subsidy (¥1,000/case)	0.00096**	0.00078*	0.00093**	0.00081*
	(0.00044)	(0.00042)	(0.00043)	(0.00042)
Electricity price elasticity	1.57	1.65	2.01	2.18
Other regressors in Table 3	Yes	Yes	Yes	Yes
Instrument	Yes	Yes	Yes	Yes
Within R^2	0.78	0.77	0.78	0.78

Panel N: New-Build Installations

	(1)	(2)	(3)	(4)
Marginal price$_{t-1}$ (¥/kWh)		0.028		
		(0.017)		
Marginal price$_{t-2}$ (¥/kWh)	0.026			
	(0.017)			
Marg. price$_{t-1}$−Marg. price$_{t-2}$		0.043		
		(0.033)		
Average price$_{t-1}$ (¥/kWh)				0.037
				(0.023)
Average price$_{t-2}$ (¥/kWh)			0.033	
			(0.023)	
Avg. price$_{t-1}$−Avg. price$_{t-2}$				0.040
				(0.032)
Prefec. subsidy (¥1,000/case)	0.000042	-0.000061	0.000043	-0.000030
	(0.00026)	(0.00026)	(0.00026)	(0.00026)
Electricity price elasticity	0.65	0.70	0.81	0.91
Other regressors in Table 3	Yes	Yes	Yes	Yes
Instrument	Yes	Yes	Yes	Yes
Within R^2	0.92	0.92	0.92	0.92

Notes: All specifications include prefecture fixed effects and time (year-quarter) fixed effects and have 987 observations (47 prefectures for 21 periods). Robust standard errors clustered at the prefecture level are reported in parentheses. The electricity price is instrumented by a weighted average of fuel prices. The dependent variable is the log of applications to the national subsidy on residential solar PV installation. Superscripts *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.

These results imply that owners of existing homes are much more likely to be marginal adopters whose decisions are influenced by these financial incentives than owners of new-build homes are. To the best of our knowledge, this difference between retrofit and new-build installations has not been reported in previous studies on the adoption of energy-efficient or renewable-energy technologies, such as solar PV systems.

It is worth emphasizing that the contrasting responses to financial incentives are observed despite the fact that new-build homes are much more likely to adopt solar PV than existing homes are. During the period of our analysis, the adoption rate is about 20% for new-build homes, whereas it is about 3% for existing homes (excluding those that adopted solar PV when they were new). This highlights the importance of distinguishing the aggregate behavior of each type and the behavior of each type's marginal adopter.

An important policy implication of the contrasting responses is that policies to support residential solar PV adoption (e.g., FITs and installation subsidies) can be made more cost-effective by treating retrofit and new-build installations differently. This implication relates to the theory of tagging and targeting (e.g., Akerlof (1978) and, in the energy efficiency context, Allcott, Knittel and Taubinsky (2015)). Specifically, our findings imply that providing larger support to retrofit installations than to new-build installations improves the cost-effectiveness of solar PV subsidies because retrofit installations are more likely to be the marginal cases that did not take place without these subsidies.[13] Essentially, the distinction between existing and new-build homes is an easily observable characteristic of a house(hold) along which tagging and targeting can be implemented to improve cost-effectiveness. This is parallel to price discrimination whereby a firm makes the price of a good dependent on observable consumer characteristics such as age in order to increase profits.

A numerical example based on Japan's FIT scheme (see Section 2.1 and Figure 2) can give a sense of the impact of such a policy change. The effect of increasing electricity prices is analogous to that of increasing FITs in the sense that both provide recurring financial benefits for solar electricity generation. On average, about 30% of electricity generated by a residential solar PV system in

[13] The same argument can apply to other energy-saving technologies for buildings to the extent that similar contrasts exist in the response to financial benefits between retrofit and new-build installations of those technologies.

Japan is consumed domestically and the rest is sold to the grid. Thus, the financial benefits from a ¥1/kWh increase in the average electricity price are roughly equivalent to those from a ¥0.43($\approx$ 0.3/0.7)/kWh increase in the FIT rate (assuming that both changes last for the same period of time). Based on the point estimates in Tables 3 and 4, the actual FIT rate (¥38/kWh), and the installation statistics for 2013,[14] we calculate the effect of marginally increasing the FIT rate for (a) retrofit installations or (b) new-build installations, where the marginal effect is measured by the added capacity per unit of the additional FIT budget. We compare the marginal effects of FIT payments on solar PV capacity. Back-of-the-envelope calculations show that, averaged across the three IV specifications in Tables 3 and 4 that use the average electricity price as an explanatory variable, the marginal effect of FIT spending in case (a) is 17% higher than in case (b). This difference indicates that offering a higher FIT rate to retrofit installations than to new-build installations improves the cost-effectiveness of FIT spending, relative to the case of a uniform FIT rate.

Although it is outside the scope of this paper to make a detailed analysis of the reasons behind the contrasting responses to financial incentives, we outline some possible explanations below. First, our findings can result from households' optimal behavior when existing and new-build homes are different in terms of building and owner characteristics (e.g., house size, energy efficiency, installation costs, other monetary or non-monetary costs, wealth, household composition, and so on). For example, solar PV installation on a new-build property typically costs 10–20% less than installation on an existing property. In addition, large construction or renovation work such as solar PV installation is physically and psychologically less complicated and burdensome if it is performed for unoccupied properties including new-build homes. Furthermore, buyers of new builds tend to be wealthier than owners or buyers of existing homes. These factors can make new-build homes more likely to be equipped with solar PV than existing homes are, *irrespective of electricity prices or subsidies*, thus making new-build installations less sensitive to these financial incentives.

Second, the differential responses may be due to market failures and behavioral anomalies. A

[14]In fiscal year 2013, there are 151,533 retrofit installations with the average capacity of 4.81 kWh and 109,509 new-build installations with the average capacity of 4.17 kWh.

good example of the former is imperfect information, and that of the latter is diminishing sensitivity, as briefly discussed below.

Imperfect information and diminishing sensitivity both relate to the fact that some households adopt solar PV at the time of home purchase, whereas other households make their adoption decisions separately from home purchase. In our data set, national subsidy applications come from either new-build homes or existing homes. As stated before, the adoption rate during the period of our analysis is about 20% for new-build homes and about 3% for existing homes (excluding those that adopted solar PV when they were new). In the case of new-build installations, households make home purchase and solar PV adoption decisions at similar timings, and solar PV systems are installed as the homes are constructed. On the contrary, a vast majority of retrofitting residential solar PV installations in Japan are separate from home purchases in the sense that households install solar PV systems on existing properties that they have been residing in (rather than on existing properties that they have just purchased).[15] In other words, there are relatively few cases in which households adopt solar PV systems at the time of buying existing properties.

Owner households of existing homes who are not active in the housing market may face the issue of "imperfect information" with respect to solar PV adoption, although this type of households account for most of the retrofit adoptions (as detailed in footnote 15). Imperfect information can hamper households' and firms' investments in energy-cost-saving measures, as many studies show (see Gillingham, Newell and Palmer (2009) and Gillingham and Palmer (2014) for literature reviews). Households may receive useful information about the value of solar PV adoption during the process of home purchase (e.g., recommendations by architects or real estate agents). For buyers of new builds, the information thus obtained may be more crucial in their decisions than

[15]Solar PV installation on an existing home can take place either at about the same timing as the purchase of the existing home by a new owner, or at a different timing by an owner who has been residing there for some period of time. Although our data set does not allow us to distinguish these two types of cases, we are certain that a large portion of installations on existing homes are of the second category, as evidenced by the following data. Unlike in North America or Europe, new-build homes account for a dominant share in the Japanese housing market. For example, according to the statistics on owner-occupied properties, 1.11 million detached/tenement houses were built between January 2011 and September 2013 (with more than 99% being detached houses), whereas 0.24 million *used* detached/tenement houses were purchased during the same period. The total number of applications for the national subsidy program during the same period is 0.24 million for new-build homes (i.e., the adoption rate of 22%) and 0.51 million for existing homes. Even if 22% of the 0.24 million used detached/tenement houses purchased in this period had applied for the subsidy (which means the same adoption rate as in the case of new builds), they would have accounted for only 0.05 million cases out of the 0.51 million applications from existing homes. Thus, a vast majority of installations on existing homes take place separately from home purchases.

changes in electricity prices or subsidies, making them relatively unresponsive to these changes. In comparison, most owners of existing homes likely have fewer chances to learn about solar PV. Therefore, for these owners of existing homes, electricity prices and subsidies are relatively salient pieces of information in their decision making, resulting in larger marginal effects of these price signals for existing homes than for new-build homes.

Alternatively, the property of diminishing sensitivity investigated in prospect theory (e.g., Tversky and Kahneman, 1992) implies that a household tends to be less thoughtful about a solar PV investment if it is coupled with another large investment. For new-build homes, solar PV adoption is a relatively small, additional investment decision that accompanies a far more important decision on home purchase. Conversely, this is not the case for most retrofitting decisions that are made independently from home purchase decisions. Under these circumstances, the property of diminishing sensitivity implies that buyers of new builds, on average, are less attentive to their solar PV adoption decisions than owners of existing homes are. New-build installations are thus less sensitive than retrofit installations to the price signals that are relate to the economic benefits of solar PV adoption.

6 Conclusion

This paper examines the effects of financial incentives, particularly electricity prices, on the adoption behavior of energy-efficient or renewable-energy technologies for buildings, focusing on the case of rooftop residential solar PV diffusion in Japan for 2009–2014. We overcome two econometric hurdles (i.e., little variation in electricity prices after controlling for location and time fixed effects and the potential endogeneity of electricity prices) by using the 2011 Fukushima nuclear accident and subsequent shutdown of all nuclear power plants in Japan as a natural experiment. This shutdown increased the use of more expensive fossil fuels and thus led to sizable, exogenous, and regionally varying hikes in electricity generation costs, which allow us to identify the causal effect of electricity prices on residential solar PV adoption. Our results indicate the importance of instrumenting electricity prices, although they are typically assumed exogenous in the literature on the adoption of energy-efficient or renewable-energy technologies. That is, we find that not instrumenting electricity prices with the cost shifter results in a downward bias of about 40–50% in the estimated effect of electricity prices on PV adoption.

Our estimation results show strong and coherent evidence of a phenomenon previously unattended in the literature. Namely, retrofit installations on existing homes are much more sensitive to changes in financial incentives, such as electricity prices and subsidies, and thus more likely to be marginal cases where decisions are switched by such changes, than installations on new-build homes are. Whether the same tendency holds in the adoption of other energy-cost-saving measures for buildings is an important question for future research.

These results suggest the importance of targeting in designing subsidy schemes (e.g., FITs and installation subsidies) for rooftop solar PV systems (or other low-carbon building technologies). In many of these subsidy schemes, including the one we analyze in this study, retrofit installations and new-build installations are treated uniformly. Our results suggest that targeting existing homes more by, for example, setting a higher subsidy rate for them than for new-build homes can be a simple approach, in terms of policy design and implementation, to improve the cost-effectiveness of these subsidies. A simulation based on our empirical setting shows that the marginal effect of FIT spending is 17% higher for retrofit solar PV installations than for new-build installations.

In our data, it is impossible to distinguish between a retrofit that occurs alongside the purchase of an existing property and one that occurs independently from home purchase. The former category represents only a small share in our data because Japan's second-hand housing market is relatively thin (see footnote 15). It is, however, likely to account for a much larger fraction of retrofits in other places, such as North America and Europe, where trading of existing properties is common. It is an empirical question whether retrofits at the time of home purchase are similar to new-build installations or, alternatively, retrofits without home purchase (or neither of them) in terms of the effect of financial incentives on technology adoption. Given that a relatively large share of retrofits (of solar PV and other measures) likely occur with home purchase in many countries, this is an interesting question for further research that can offer useful insights into effective policy design.

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