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The Effect of Electricity Prices on Residential Solar PV Adoption: Fukushima as a Natural Experiment*

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Abstract

There are a range of private financial benefits of residential solar photovoltaic (PV) installation, such as a reduced electricity bill, tax incentives and a feed-in tariff for generated electricity. To empirically analyze how rising electricity prices affect household adoption decisions, we use the 2011 Fukushima nuclear disaster as a natural experiment. The shutdown of nuclear power plants across Japan led to a sizable increase in electricity prices that varied by region, allowing us to identify the effect of electricity prices on household PV system adoption. We find that higher electricity prices are significantly more influential on PV adoption on existing homes than on newly-built homes. Our estimated electricity price elasticity of PV systems ranges from 0.9 to 1.2 for existing homes and is much smaller and statistically insignificant for newly-built homes. We discuss behavioral mechanisms explaining this difference and implications for policies stimulating residential adoption of renewables.

Keywords: solar PV adoption, electricity prices, Fukushima, natural experiment

JEL Classifications: Q42, Q48, Q52

1 Introduction

Shifting from fossil fuel to renewable energy is a top priority in many countries as a way to achieve a low carbon economy. Residential rooftop solar power generation is a promising technology for

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this purpose. Up-scaled manufacturing and technology improvements have driven down the cost of solar panels, also known as photovoltaic (PV) panels, and they have gradually become a competitive electricity source (e.g., Dijkgraaf, van Dorp and Maasland, forthcoming).

There are a range of private financial benefits of residential solar panels installation, such as a reduced electricity bill, and direct and indirect subsidies. Empirical studies of household adoption of PV systems have commonly centered on the evaluation of various governmental schemes such as direct rebates or tax credits on installation, and feed-in-tariffs for electricity that flows back to the grid (e.g., Kwan, 2012, Bollinger and Gillingham, 2012, Hughes and Podolefsky, 2015, Burr, 2016, and Gillingham and Tsvetanov, 2016). Some previous studies also report the impact of electricity prices, though mostly as a covariate and not as an estimate of primary interest.[1] For example, Durham, Colby and Longstreth (1988) and Kwan (2012) use cross-sectional electricity price variations across geographical areas to find positive effects of electricity prices. Panel data analyses at the zip code or state level by Hughes and Podolefsky (2015), Matisoff and Johnson (2015), and Burr (2016) show mixed results for the effect of electricity prices.

Electricity prices are expected to influence a household's decision to have a PV system installed. Other things equal, higher electricity prices increase the savings from replacing electricity purchase from the grid with self-generation. The recent study by Borenstein (2017) suggests that California's tiered residential electricity tariffs indirectly contribute to a surge in residential solar PV adoption, implying an important role of electricity prices.

There are two challenges in estimating the impact of electricity prices. First, there is often little variation in electricity prices once location and/or time dummy variables (fixed effects) are controlled for – the reason the effect of electricity prices is often dropped from the estimation model. Second, endogeneity is an issue due to unobserved area characteristics and trends that affect both PV system adoption and electricity prices.[2] This endogeneity problem is a main concern for a cross-sectional setting, but even a panel setting may not be free from the problem.

[1] Some papers such as Burr (2016) estimate the effect of the net present value (NPV) of solar PV on household adoption behavior, where electricity prices are parametrically subsumed into NPV calculations.

[2] For example, a Renewable Portfolio Standard (RPS), which has been introduced in more than a half of the states in the US, 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).

We intend to contribute to the literature in two ways. First, to analyze empirically how electricity prices affect household solar panel adoption decisions, we use the substantial exogenous variation in electricity prices in Japan after the Fukushima nuclear disaster of 2011. The nuclear accident caused by an earthquake of magnitude 9.0 and subsequent tsunami led to shutdown of all nuclear power plants in Japan, most of which still have not resumed power generation after more than five years. Nuclear power was replaced by more expensive fossil fuels, raising electricity prices by as much as 20–30% within a few years. Importantly, the magnitude of electricity price hikes varied across Japanese regions, depending on the pre-earthquake share of nuclear power in each region and the pattern of fuel substitution. To exploit this significant variation in electricity prices (both over time and across regions), we estimate a two-way fixed effects model using a panel data set at the prefecture-quarter level. Our dependent variable is the number of applications to a national subsidy program and we use quarterly data for 2009-2014. Our estimates suggest a sizable impact of electricity prices on the recent expansion of residential solar power generation: installations in 2014 would have been about 18–24% fewer should the electricity prices had stayed at their 2011 levels. Our results are robust to various assumptions about time trends, different lags of electricity prices, and the inclusion of prefecture-level policies and characteristics.

The second contribution of the paper is a distinction between (owners of) existing homes and (owners of) new homes.[3] To our knowledge, no previous study has reported separate estimates for the effect of electricity prices on the PV system adoption by these two groups. Our results emphasize the empirical importance of this distinction: we find substantial difference in the response to electricity prices between existing and new homes. Overall, the results suggest that households owning or buying existing homes are up to 10 times more responsive to electricity prices than households with newly built homes, even though both groups of households faced mostly the same electricity prices and policies, and new homes have a higher solar PV adoption rate than existing homes. We discuss behavioral explanations of this difference, in particular imperfect information and diminishing sensitivity.

Finally, we consider the policy implications of our findings. We argue that policies promoting

[3]Throughout the paper, a new home is defined as a newly-built home, as opposed to a newly-acquired existing home. Similarly, a new-home owner (buyer) is defined as an owner (buyer) of a new home, as opposed to a new owner (buyer) of an existing home.

residential adoption of solar PV systems and other renewables could be made more cost-effective by taking account of contrasting response patterns across households, for example, by providing more support for households with existing homes who may be more responsive to such policies than households with new homes, as seen in the case of electricity price changes.

The rest of the paper is organized as follows. Section 2 provides the background about the Japanese electricity market before and after Fukushima, and trends and policies relating to residential solar PV in Japan. Section 3 describes our empirical framework and Section 4 describes the data used. Section 5 presents our results, and Section 6 discusses their implications. Section 7 concludes.

2 Electricity Market and Solar PV in Japan

2.1 Residential Electricity Market

2.1.1 Regulated Regional Monopolies

This paper studies residential solar PV adoption during 2009–2014. Japan's residential electricity market was not deregulated until April 2016, which is crucial to our investigation. Prior to liberalization, the residential electricity market was highly regulated by the central government (the Ministry of Economy, Trade and Industry, or METI) with the market divided into 10 regions, each of which was served by a monopolistic, vertically integrated electricity company METI granted permission to generate, transmit, and distribute electricity. Each regional monopolist supplied electricity to all households in the region. For the protection of consumers electricity prices in each monopolistic market could not be raised without METI's approval.

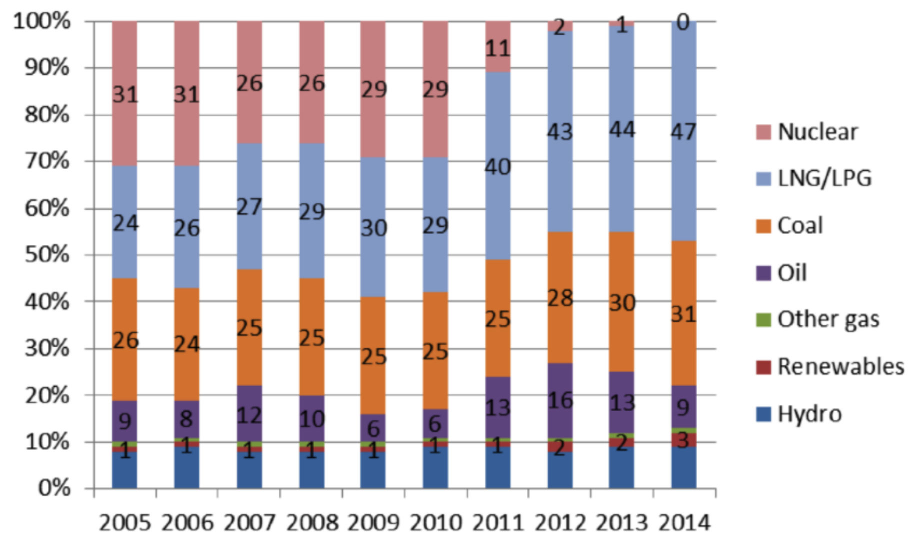


Figure 1: Japan's Electricity by Energy Source

2.1.2 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 a devastating meltdown at Tokyo Electric Power Corporation's Fukushima Daiichi (No.1) Nuclear Power Plant, triggering severe radioactive contamination of the environment. At the time of the accident, there were a total of 54 reactors in Japan, 37 of which were in operation (IIC, 2014). Safety concerns on nuclear power led all reactors in operation to shut down successively after the Fukushima accident, and reactors were not allowed to resume operation. By May 2012 there was no reactor in operation. Although two reactors were permitted to restart in July 2012, their periodic inspections in September 2013 resulted again in a complete nuclear shutdown, which continued until August 2015 when a reactor resumed operation under stricter regulations. The effect of the shutdown on Japan's electricity generation mix in recent years can be seen in Figure 1. 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 1, fossil fuels' share went up 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

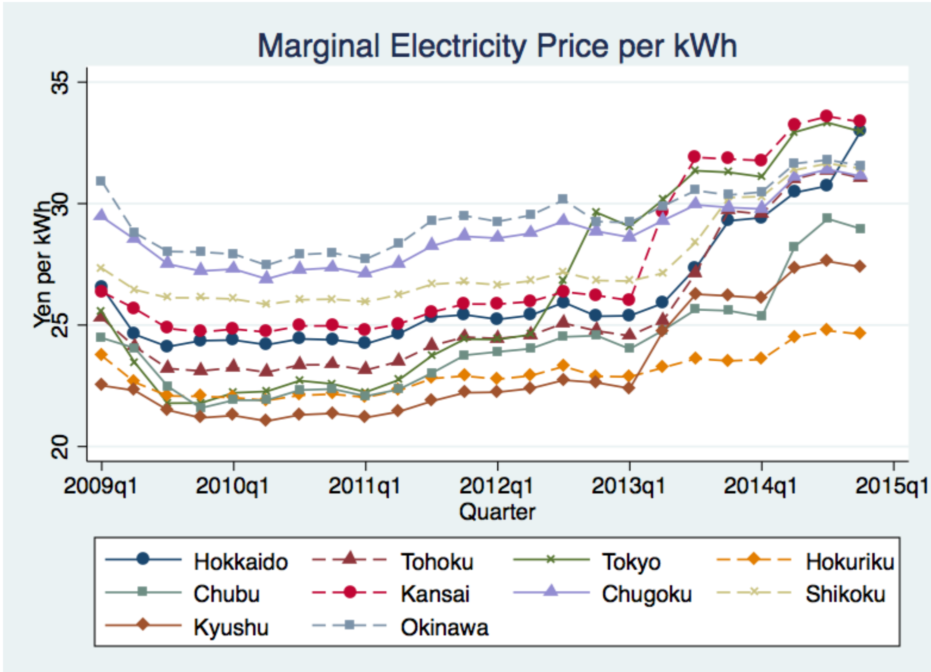


Figure 2: Marginal Electricity Price per kWh by Region

expanded the use of fossil fuels, primarily by reactivating old, idle fossil-fuel-based generators, which were typically small-sized and less efficient, and additionally by rushing to build 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 as fossil fuels are more expensive sources of electricity generation than nuclear power. [4] The average electricity price per kWh increased by 37% within four years of the earthquake, from ¥19.8/kWh to ¥27.3/kWh. Japan imported almost all fossil fuel used for this substitution, and METI (2015b) estimates that this raised the total costs of electricity generation by 0.49%, 0.65%, 0.75% and 0.69% of GDP in 2011, 2012, 2013 and 2014 respectively.

Although electricity prices went up in all regions of Japan the years following the Fukushima accident, the magnitude of the increase varied substantially across regions. Figure 2 shows the average residential electricity price per kWh by region before and after Fukushima. Some regions (e.g., Hokkaido, Tokyo, and Kansai) suffered a significant price hike starting in the second

[4] For instance, METI (2015a) reports fuel costs of electricity generation as follows: nuclear ¥1.5/kWh, coal ¥5.5/kWh, LNG ¥10.8/kWh, and oil ¥21.7/kWh. (¥ stands for Japanese yen. US$1 is ¥113 as of February 2017.) The order remains the same if we focus on the sum of operating and fuel costs: nuclear ¥4.8/kWh, coal ¥7.2/kWh, LNG ¥11.4/kWh, and oil ¥24.3-29.4/kWh.

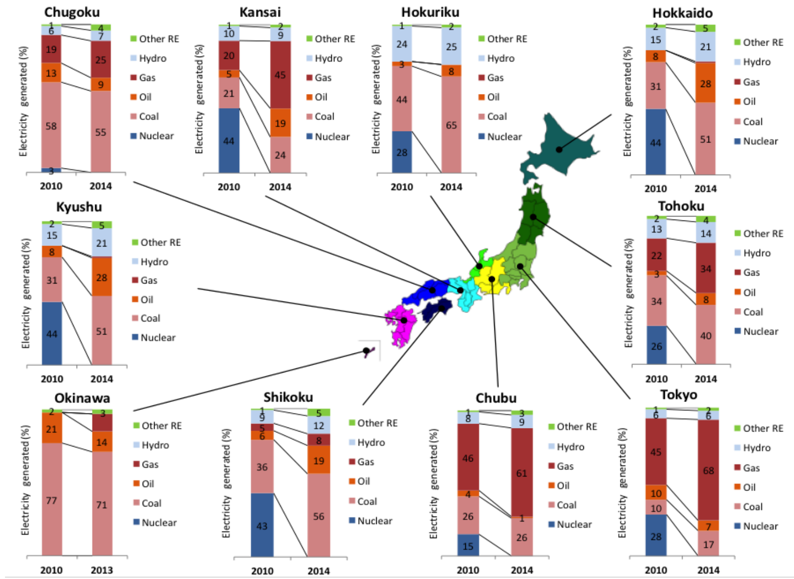


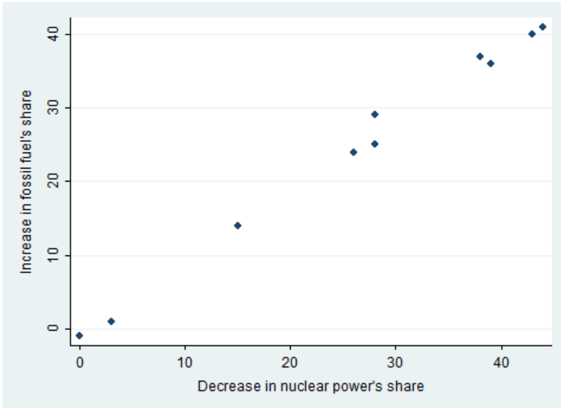
Figure 3: Electricity mix in 2010 and 2014

quarter of 2011 (about 20–30% in three years), while other regions (e.g., Hokuriku, Chugoku, and Okinawa) experienced a milder increase (7–11% in the same period).

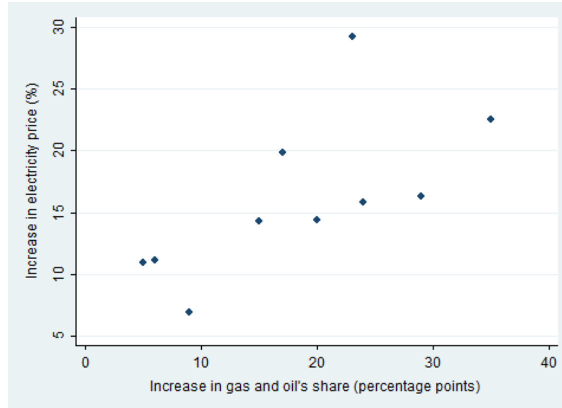
To investigate the drivers of the regional variation in electricity price trends, we reviewed documents that electricity companies had submitted to METI to obtain a permission for raising base electricity prices – a component of electricity prices that is independent of temporary fuel cost changes. During the period of our analysis (2009 Q1 to 2014 Q1), six electricity companies (regions) raised base electricity prices, with all increases occurring after 2012.[5] Application documents in these cases reveal that the primary reason mentioned by all the six companies was increasing fuel costs due to the nuclear shutdown and switch to fossil fuels. Some companies additionally listed higher safety/security costs on nuclear power plants under tightened regulations. Tokyo Electric Power Corporation, which owns Fukushima Daiichi Nuclear Power Plant, also stated that compensation for the damages caused by the Fukushima disaster pushed up their costs.

Overall, there are 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 (instead of coal) after Fukushima

[5]These six regions are Hokkaido, Tohoku, Tokyo, Kansai, Shikoku, and Kyushu.



(a) The increase in fossil fuel's share in electricity generation against the decrease in nuclear power's share



(b) The % increase in electricity price against the increase in gas and oil's share in electricity generation

Figure 4: Changes in nuclear power generation share and electricity prices between 2010 and 2013 for at the region level

to substitute for nuclear power. Figure 3 shows a substantial regional variation in the share of nuclear power before Fukushima (in 2010), where it was over 40% in the regions most dependent on nuclear power (Hokkaido, Kansai, Shikoku, Kyushu), while it was less than 5% in Chugoku and Okinawa. To see how nuclear power was substituted for, Figure 4a plots the increase in fossil fuel's share between 2010 and 2013 against the decrease in nuclear power's share in the same period. Figure 4a shows that nuclear power was mostly replaced by fossil fuels (coal, LNG, and oil). For 10 regions in Japan, Figure 4b plots the percentage increase in electricity prices between 2010 Q1 (1st quarter) and 2013 Q1 against the increase in the share of LNG and oil in the generation mix (i.e., share of LNG + share of oil) between 2010 and 2013. Figure 4b implies that additional use of LNG and oil as substitutes for nuclear power was positively associated with a region's electricity price hike.[6]

2.2 Diffusion of Residential Solar PV

Residential solar PV electricity generation has been expanding in Japan since the 1990s mainly because of decreasing panel costs, policies such as government subsidies on installation costs, and

[6]It is notable that Hokuriku Region 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.

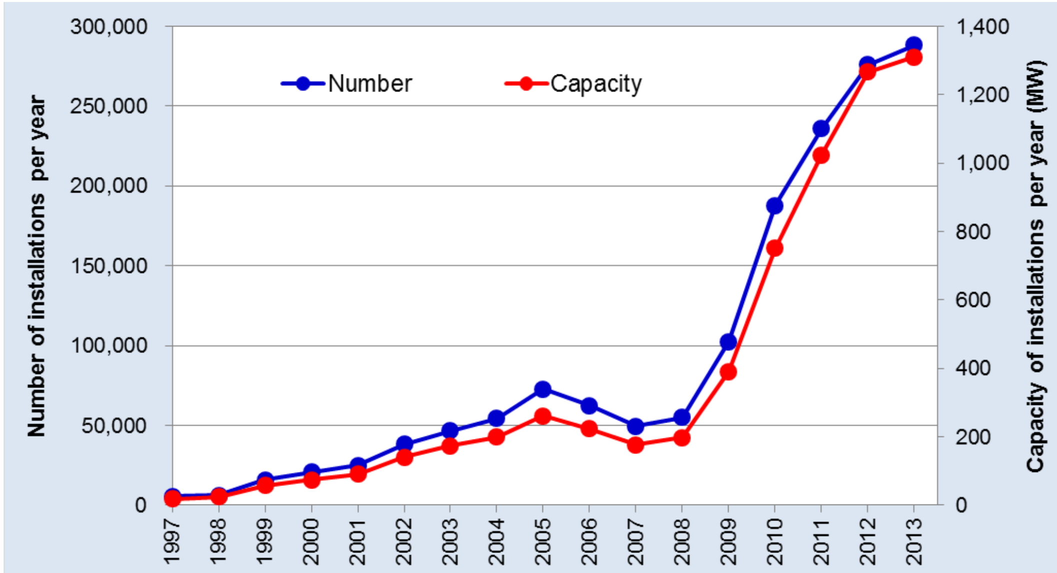


Figure 5: Residential Solar PV in Japan (1997-2013)
Source: NEF (New Energy Foundation), NEPC (New Energy Promotion Council), JPEA (Japan Photovoltaic Energy Association)

feed-in tariffs (FITs) on generated electricity. Figure 5 shows the number and capacity of annual residential solar PV installations between 1994 and 2014, indicating a gradual increase up to the mid-2000s and a rapid expansion after 2009. [7,8]

The surge in solar PV adoption after 2009 is attributable to a new national subsidy program for solar PV adoption, and a FIT scheme, both of which started in 2009. The increase after the 2011 earthquake may also be due to electricity price hikes, a hypothesis that we aim to examine in the paper. The national subsidy program was in place from January 2009 to March 2014, and provided lump-sum subsidies to households shortly after solar PV installation. Our estimation uses the number of applications for this subsidy during this period. The subsidy rate was at ¥70,000/kW in 2009, roughly equivalent to 10% of the average solar PV system cost per kW at that time. The rate was gradually reduced over time, and was at ¥20,000/kW in 2013 (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. We will further discuss the nature of this subsidy in Section 4 when explaining the data used.

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

[8] Unlike some other places (e.g., the US), the share of residential solar leasing, whereby a household introduces a solar PV system through a lease contract, is ignorable in Japan.

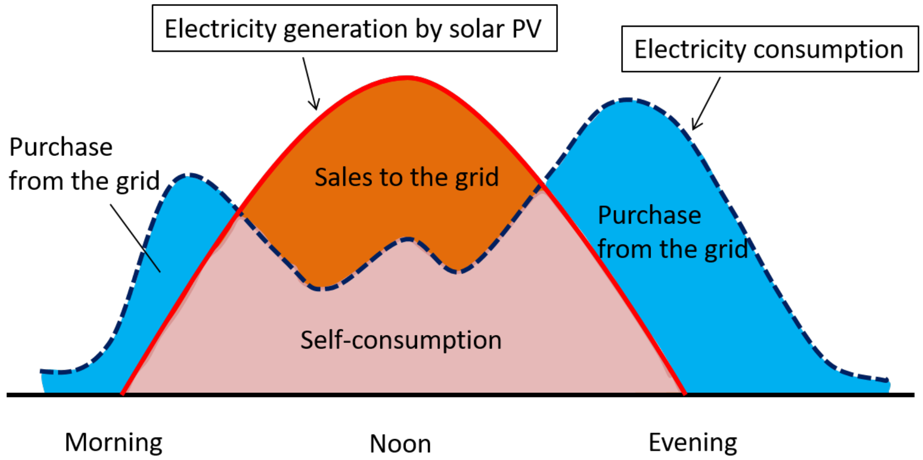


Figure 6: Self-consumption and sale of solar electricity

Japanese FIT scheme for solar PV electricity, the other factor of the rapid expansion, started in November 2009. Under the scheme, electricity companies are required by law to purchase surplus solar PV electricity from households at a fixed rate for 10 years. An important characteristic of Japan's solar PV FIT scheme is that an owner of a residential solar PV system (i.e., capacity of 10 kW or below) can sell only surplus electricity. That is, the solar PV system first supplies electricity for domestic consumption ("Self-consumption" in Figure 6), and sells only the surplus after domestic consumption to an electricity company at a fixed FIT rate ("Sale to the grid" in Figure 6). Therefore, installing residential solar panels benefit in two days: by reducing the electricity purchase from the grid and revenue by selling net electricity generation back to the grid. Electricity prices (for the purchase form the grid) thus affect household incentives to adopt solar PV: higher electricity prices will provide a larger incentive for residential solar PV because families can expect greater electricity cost savings from adoption.[9]

The rate of FITs was set high to facilitate the diffusion of PV systems, and the scheme was financed by extra charges on electricity users. The FIT rate was initially at ¥48/kWh, and it has been reduced gradually (e.g., ¥37/kWh in 2014) for later adopters. During the period of our analysis the rate remained higher than the (average or marginal) price of electricity purchased from an electricity company (Figure 2). The mandatory purchase of renewable electricity incurs

[9]FIT schemes in some countries make payment for electricity *generation* (rather than surplus, i.e., generation minus self-consumption, as in Japan). In these cases, prices of grid-electricity do not affect the benefits of a solar PV system, and thus likely have a smaller impact on solar PV adoption.

additional costs to electricity companies. These additional costs are financed by a mandatory "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).

This 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 (METI). This is important for our study, as the effect on solar PV adoption of changes in the FIT rate and the surcharge over the years can be controlled for by including time fixed effects.

3 Empirical Strategy

We investigate the impact of electricity prices on residential rooftop solar PV installation by using a two-way fixed effects approach:

$$\log(y_{it}) = \beta p_{i,t-2} + \mathbf{X}_{it}'\gamma + \eta_t + \mu_i + \varepsilon_{it} \tag{1}$$

where i stands for prefecture i, and t for period (quarter-year) t. The dependent variable $\log(y_{it})$ is the log of the number of applications to the national subsidy program on residential solar PV installation. These applications are a very good proxy for residential solar PV installations during the period of our analysis, as will be discussed in our Data Section. As for the independent variables, $p_{i,t-2}$ is the (two-quarter) lagged electricity price, and X_{it} is a set of controls – all these variables are described in more detail below. η_t represents the time fixed effect that captures various factors common to all prefectures at period t, including national policies and PV system costs; and μ_i refers to the prefecture fixed effect that controls for time-invariant characteristics of prefecture i, such as weather conditions. ε_{it} represents the idiosyncratic error term, clustered at the prefecture level (there are 47 prefectures). We implement the above model separately for existing homes and new homes, where a new home is defined as a newly-built privately owned home, as opposed to a newly-acquired existing home.

The electricity price variable $p_{i,t-2}$ is the marginal price of electricity (in kWh) for households that consume over 300 kWh a month (or 280 kWh for the Hokkaido region). Almost all households that would consider solar PV adoption face this marginal price.[10] As discussed in Section 2, $p_{i,t-2}$ exhibits substantial exogenous variations over time and across prefectures following the Fukushima accident – a key observation for identifying the effect of electricity prices by estimating (1). In most specifications, $p_{i,t-2}$ is lagged by two quarters to allow for a time gap between observing an electricity price change and making an installation decision.[11] Since the price is set by each of the 10 regional monopolies, prefectures in the same region face a common price.[12] Finally, we also examine log-log specifications in which β is interpreted as the electricity-price elasticity directly.[13]

In some specifications, we include the vector $\mathbf{X}_{it}$ to control for other observable factors, particularly local government subsidies, that may affect the dependent variable and that have variations both over time and across prefectures. This serves as a robustness test that electricity prices are not affected by either including or excluding these covariates, confirming that the electricity prices are unlikely to be systematically correlated with these factors once prefecture and time fixed effects are controlled for.

On top of the national subsidy discussed above, local (prefectural and municipal) governments often provided subsidies for residential solar PV installation as well (receiving local subsidies does not affect the eligibility for the national subsidy). To control for the variation in the level of such local subsidies, we construct variables linked to prefectural government subsides on solar PV installation (*no prefectural subsidy*, *max prefectural subsidy*, and *effective prefectural subsidy*). In addition to prefectures, local municipalities (e.g., cities) often have similar incentive programs. There are more than 1,700 municipalities in Japan, and subsidy schemes often vary significantly across municipalities, making it practically impossible to construct variables to reflect the level

[10]According to METI, the monthly consumption by a "standard" household is 441 kWh (> 300 kWh or 280 kWh). Households to adopt solar PV most likely consume more than 441 kWh because they typically live in larger, detached homes.

[11]As a robustness check, we will report results with different lags, but the results remain more or less the same.

[12]For this reason, we also estimate our models with the error term ε_{it} clustered at the region (rather than prefecture) level. The results are by and large the same.

[13]We also run a semi-parametric version of equation (1) where the electricity price variable is allowed to be distributed non-parametrically after partialling out the fixed effects and the exogenous controls (Baltagi and Li, 2002; Li and Racine, 2006). It shows a relatively linear (though sensitive at the extreme ends of the distribution) relationship between $\log(y_{it})$ and $p_{i,t-2}$, thus supporting the specification in (1). The results are available upon request.

of municipal subsidies. Thus, we assume that other incentives from local municipalities are approximated by the prefecture-level variables.

Following the earlier literature (e.g., Durham, Colby and Longstreth, 1988; Kwan, 2012), some of our regressions further include other demographic variables (*population*, *housing starts*, *average income*, *average age of workers*) in $\mathbf{X}_{it}$. In our panel data setting, most of the effects of these variables are likely absorbed in fixed effects (particularly, prefecture fixed effects) anyway, as these variables show little inter-temporal variations over the study period. We include these demographic variables in some of our regressions to make them consistent with the previous studies that are often based on cross-sectional data.

The identification assumption in this framework is that the spatial and temporal variation in electricity prices that is not explained by prefecture or time fixed effects is uncorrelated with unobservable factors that are not absorbed in prefecture or time fixed effects (i.e., vary across prefectures *and* over time) and that affect solar PV adoption. A potential scenario in which the identification assumption would be violated is where the *regional* variation in the *pace* of solar PV diffusion is one of the factors that affect the *regional* variation in the electricity price *trends* as observed in Figure 2 (reverse causality). This may be the case because solar PV diffusion and FITs may incur additional costs on electricity companies. As mentioned in Section 2.2, the mandatory "renewable energy surcharge" has been added to each user's electricity bill to finance the FIT scheme, and the surcharge rate has been increased over time. Importantly for our estimation, this rate is common across the nation, so that it is absorbed in the time fixed effects, and does not affect the *regional* variation in the electricity price trends. In the documents submitted to METI, which we discussed in Section 2.1, no company listed the diffusion of solar PV or other renewable sources, or regulations/standards on these sources (such as feed-in tariffs), as a reason for increasing electricity prices. This suggests that the regional variation in electricity price trends (i.e., the variation in electricity prices that is not explained by prefecture or time fixed effects) is exogenous in the determination of the regional variation in renewable energy – including solar PV – adoption trends, thus supporting our identification assumption.

Studies in psychology and sociology suggest that natural disasters can potentially stimulate pro-environmental behavior (Kollmuss and Agyeman, 2002; Doherty and Clayton, 2011). The earthquake and Fukushima likely boosted the interest in solar PV across the country, but its impact may be heterogeneous across prefectures. For example, the prefecture of Fukushima, where the damaged reactors are located, and the eight prefectures served by TEPCO (Tokyo Electric Power Company), the operator of the damaged reactors, were affected more severely in the aftermath of the accident. As a robustness check, we re-run our regressions with these prefectures removed.

Similarly, if the disaster made residents in close proximity of nuclear plants particularly keen on replacing nuclear power, Fukushima's (unobservable) impact on solar PV adoption could be larger in prefectures with nuclear plants, where electricity prices may have also increased more significantly due to the nuclear plant shutdown. To resolve the issue of this potential correlation, we will allow different time trends (dummies) for prefectures with nuclear plants.[14] Note that this approach can also control for any other trend in these prefectures that may be correlated with electricity prices or other regressors.

4 Data

Our regression analysis is based on data from multiple sources, as summarized in Table 1. For residential solar PV installations, we use applications to the national subsidy program on residential solar PV installation, which was in effect from 2009 Q1 (quarter one) to 2014 Q1. We obtained these prefecture-level data from the Japan Photovoltaic Energy Association (JPEA), the organization that handled the implementation of the subsidy program. Subsidy applications had to be submitted prior to installation of solar panels, and our dependent variable, the number of subsidy applications by quarter, is based on the date of receipt of an application by the JPEA. Over 96% of the applications were successfully approved for subsidy payment and resulted in actual installations (typically several months after applying). The number of approvals for this subsidy is used by the government as the official statistic for the number of residential solar

[14] These prefectures are Hokkaido, Aomori, Miyagi, Fukushima, Niigata, Ibaraki, Shizuoka, Ishikawa, Fukui, Shimane, Ehime, Saga, Kagoshima. In particular, three prefectures (Fukushima, Niigata and Fukui) have significantly larger capacities, so we will consider additional separate dummies for the three prefectures.

Variable	Obs	Mean	Std. Dev.	Min	Max
Number of national subsidy applications (existing homes)	987	842.59	709.99	27	4655
Number of national subsidy applications (new homes)	987	442.61	485.41	6	4038
Marginal electricity price (¥/kWh)	987	25.20	2.79	21.05	31.9
Average electricity price (¥/kWh)	987	24.61	1.83	22.05	29.95
Presence of prefectural subsidy (existing homes)	987	0.52	0.50	0	1
Max. prefectural subsidy (existing homes, ¥1,000)[a]	511	131.43	171.45	14	1000
Effective prefectural subsidy (existing homes, ¥1,000)[a]	511	103.73	74.69	14	434
Presence of prefectural subsidy (new homes)	987	0.48	0.50	0	1
Max. prefectural subsidy (new homes, ¥1,000)[a]	478	126.62	173.22	14	1000
Effective prefectural subsidy (new homes, ¥1,000)[a]	478	98.48	71.60	14	377
National subsidy (¥1,000/kW)	987	49.62	19.67	20	70
Solar PV system cost (¥1,000/kW)	987	522.43	75.07	398	622
Feed-in tariff rate (¥/kWh)	799	42.82	3.70	38	48
Population over age 15 (1,000 people)	987	2360.87	2325.62	501	11798
Housing starts, owned	987	1652.82	1323.12	222	7108
Average monthly compensation per worker (¥1,000)	987	269.91	28.12	222.2	377.4
Average age of workers	987	41.83	0.62	40	43.5

Table 1: Summary Statistics

[a] Conditional on presence of prefectural subsidy.

PV installations, suggesting that almost all households considering PV installations during the period took advantage of this program.

We choose subsidy applications as our dependent variable rather than subsidy approvals because the former better capture the timing of household adoption decisions than the latter. Generally speaking, after observing an electricity price change, households would take some time before deciding to install solar panels and submitting a subsidy application. It took further time before the system was actually installed and the application was approved. This time gap between an application and its approval was typically several months, but varies case by case, making the number of applications a better indicator of household adoption decisions.

Aggregated across prefectures over the five year period, there were 831,637 applications for installation of solar panels in existing homes, and 436,852 applications for new homes. For the understanding of 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, the solar PV adoption rate for new homes is about 20 percent.

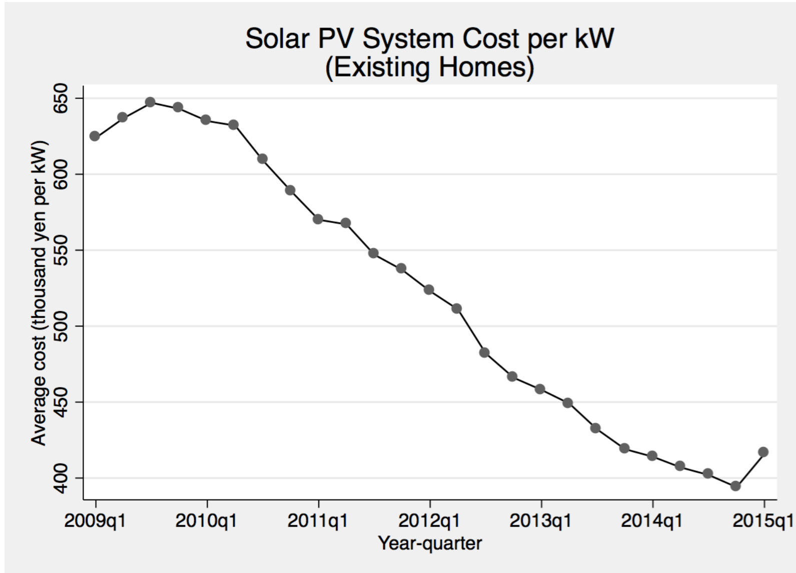


Figure 7: Average solar PV system cost for existing homes

Applications from ready-built new detached houses with pre-installed PV systems, for which adoption decision might be made by developers, accounted for less than 1% of the subsidy applications. Applications from (new or existing) non-detached houses, for which collective decisions may be necessary, were even fewer. Therefore, the data will allow us to look into individual households' adoption decisions.

The data on residential electricity prices were constructed from the Retail Price Survey published monthly by the Statistics Bureau of the Government of Japan. We aggregate the monthly data to create a quarterly data set. Figure 2 shows the time trends of the marginal electricity price (for consumption over 300 kWh a month, or 280 kWh for the Hokkaido region), which we use as the main regressor in our empirical analyses below.

We gathered data on prefectural subsidies on PV installation from each prefecture's budget information in each fiscal year. We constructed three variables (*no prefectural subsidy*, *max prefectural subsidy*, and *effective prefectural subsidy*). *No prefectural subsidy* is a dummy variable for the absence of prefectural subsidies. *Max prefectural subsidy* is the maximum amount that can be claimed per installation. *Effective prefectural subsidy* is the amount of the prefectural subsidy for a household installing the average system capacity (kW) in the prefecture during the quarter. Generally, the effective subsidy is much lower than the maximum subsidy.

Other controls used in the regressions include the average solar PV system cost (source: JPEA), the rates of the national subsidy and the FIT (source: METI), and prefecture-level characteristics (population, housing starts, average income per capita, and average worker age; all obtained from the Portal Site of Official Statistics of Japan). In particular, Figure 7 shows that the average solar PV system cost has been decreasing almost linearly over time.

5 Results

Table 2 shows our baseline results where we include only prefecture fixed effects, time (quarter-year) fixed effects and lagged electricity prices. As explained above, our dependent variable is the number of applications to the national subsidy program. The electricity price variable ($p_{i,t-2}$) is lagged by two quarters to reflect a delay in household responses to electricity price changes – we test the robustness of this assumption. Estimation results are presented separately for existing homes and new (newly-built) homes. The marginal price of electricity is used as a regressor in column (1), and its logarithm in column (2). For existing homes, the (marginal) price elasticity of solar PV installation is significantly estimated at 0.9, where the implied elasticity of installation in column (1) is evaluated at the mean of $p_{i,t-2}$ (over i and t). This implies that a 20% increase in electricity prices as experienced post-Fukushima led to roughly an 18% increase in solar PV installations. With the sample of new homes, in contrast, the effect is much lower (less than 0.08), and statistically insignificant. It is important to note that our result is *not* about new homes being less likely to adopt solar PV systems. Indeed, as described in Section 4, new homes actually have a much higher rate of solar PV adoption than existing homes. Instead, what our result suggests is that new homes are less responsive to electricity prices. As a robustness check, columns (3) and (4) use the average, rather than marginal, price of electricity for a standard household.[15] Columns (3) and (4) present a similar result that the electricity price elasticity is positive and statistically significant for existing homes, while it is much smaller and statistically insignificant for new homes.

[15] METI assumes that a standard household consumes 441 kWh a month. We acknowledge the possibility that households who adopt solar PV tend to consume more electricity, so that the average price they face is generally different from that for a standard household.

(a) Existing Homes

	(1)	(2)	(3)	(4)
		log(Applications)		
Marginal price$_{t-2}$ (¥/kWh)	0.0353*			
	(0.0194)			
log(Marginal price$_{t-2}$)		0.9148*		
		(0.5079)		
Average price$_{t-2}$ (¥/kWh)			0.0543*	
			(0.0273)	
log(Average price$_{t-2}$)				1.3913*
				(0.6989)
Implied elasticity	0.8755	0.9148	1.3195	1.3913
Prefecture FE	Yes	Yes	Yes	Yes
Quarter-year FE	Yes	Yes	Yes	Yes
Observations	987	987	987	987
Within R^2	0.769	0.769	0.770	0.769

(b) New Homes

	(1)	(2)	(3)	(4)
		log(Applications)		
Marginal price$_{t-2}$ (¥/kWh)	0.0032			
	(0.0071)			
log(Marginal price$_{t-2}$)		0.0610		
		(0.1895)		
Average price$_{t-2}$ (¥/kWh)			0.0030	
			(0.0111)	
log(Average price$_{t-2}$)				0.0476
				(0.3016)
Implied elasticity	0.0785	0.0610	0.0726	0.0476
Prefecture FE	Yes	Yes	Yes	Yes
Quarter-year FE	Yes	Yes	Yes	Yes
Observations	987	987	987	987
Within R^2	0.916	0.916	0.916	0.916

Notes: Cluster-robust standard errors are in parentheses, where the observations are clustered at the region level. Prices (marginal or average) are two-quarter lagged electricity prices. The dependent variable is the log of applications to the national subsidy on residential solar PV installation.

* Significance at the 10 percent level.

** Significance at the 5 percent level.

*** Significance at the 1 percent level.

Table 2: Baseline Regression Results

(a) Existing Homes

	(1)	(2)	(3)
		log(Applications)	
Marginal price$_{t-2}$ (¥/kWh)	0.0375*	0.0426**	0.0435**
	(0.0193)	(0.0178)	(0.0189)
Implied elasticity	0.9296	1.0560	1.0783
Prefecture FE	Yes	Yes	Yes
Quarter-year FE	Yes	Yes	Yes
Separate time trends	No	No	Yes
Excluded area	Fukushima	TEPCO area	
Observations	966	819	987
Within R^2	0.775	0.761	0.786

(b) New Homes

	(1)	(2)	(3)
		log(Applications)	
Marginal price$_{t-2}$ (¥/kWh)	0.0045	0.0061	0.0071
	(0.0071)	(0.0172)	(0.0075)
Implied elasticity	0.1116	0.1512	0.1760
Prefecture FE	Yes	Yes	Yes
Quarter-year FE	Yes	Yes	Yes
Separate time trends	No	No	Yes
Excluded area	Fukushima	TEPCO area	
Observations	966	819	987
Within R^2	0.917	0.905	0.923

Notes: Robust standard errors clustered at the prefecture level are reported in parentheses. Prices (marginal or average) are two-quarter lagged electricity prices. The dependent variable is the log of applications to the national subsidy on residential solar PV installation.

* Significance at the 10 percent level.

** Significance at the 5 percent level.

*** Significance at the 1 percent level.

Table 3: Regression Results with Separate Non-Parametric Time Trends

Table 3 considers the robustness of the above findings against the possibility that the Fukushima accident caused some prefectures to have systematically different trends from others (as discussed in Section 3). Columns (1) excludes the prefecture of Fukushima where the damaged nuclear reactors are located. Column (2) excludes the eight prefectures served by TEPCO (Tokyo Electric Power Company), the operator of the damaged reactors, and thus presumably have been affected more severely in the aftermath of the accident. In order to account for the possibility that prefectures with nuclear power plants may have experienced systematically different patterns in the time fixed effects after Fukushima, column (3) includes separate sets of quarter-year dummy variables for three groups of prefectures: high (over 8 million kW), low and no nuclear capacity. Across all the specifications for existing homes (Panel (a)), the implied (marginal electricity price) elasticity remains statistically significant and ranges from 0.9 to 1.1, coherent with Table 2(a). For new homes (Panel (b)), it is again much smaller than the effect on existing homes, and is statistically insignificant.

Table 4 adds other covariates to the regression, especially prefecture-level subsidies. In column (1), we include a dummy variable for the absence of prefectural subsidies, along with the cumulative adoption rate of solar PV among detached houses (*cumulative adoption*). This specification shows the correlation between solar PV installations (subsidy applications) and prefectural subsidies, conditional on other included regressors and prefecture and time fixed effects. If prefectural subsidies induce more installations, we would expect a negative coefficient estimate on the no-prefectural-subsidy dummy. Panel (a) (existing homes) shows a negative (and statistically significant) estimate, and Panel (b) (new homes) a positive (and statistically significant) estimate. This suggests that the prefectural subsidy variable is potentially endogenous due to reverse causality – a prefectural government may reduce solar PV subsidies if installations are on an upward trend in the prefecture (after controlling for other regressors and prefecture and time fixed effects). Therefore, in subsequent specifications we will present regression results with and without the prefectural subsidy variables.[16]

[16] Ideally, one would use instrumental variables to control for the endogeneity. We have explored instrumenting prefectural subsidies with variables from prefecture-level public finance accounts, such as allocations from the central government and tax revenue. However, conditional on prefecture and time fixed effects, these variables are too weak to identify the model. In the absence of an appropriate set of instruments, we present results with and without this potentially endogenous variable to show the robustness of our results on electricity prices.

(a) Existing Homes

	(1)	(2)	(3)	(4)
	log(Applications)			
Marginal price$_{t-2}$ (¥/kWh)	0.0404**	0.0502***	0.0442**	0.0451**
	(0.0194)	(0.0139)	(0.0169)	(0.0168)
1(No prefectural subsidy)	-0.0713*	-0.0048	0.0340	0.0336
	(0.0406)	(0.0490)	(0.0626)	(0.0616)
Max prefectural subsidy (¥1,000/application)		0.0006***		
		(0.0002)		
Effective prefectural subsidy (¥1,000/application)			0.0011**	0.0011***
			(0.0004)	(0.0004)
Cumulative adoption (%)	0.1006	0.0931	0.1715	0.1562
	(0.2960)	(0.2845)	(0.2832)	(0.3138)
log(Population)				-0.5674
				(4.8727)
log(Avg. income)				0.3567
				(0.7892)
log(Avg. worker age)				0.7292
				(1.6660)
Prefecture FE	Yes	Yes	Yes	Yes
Quarter-year FE	Yes	Yes	Yes	Yes
Observations	987	987	987	987
Within R^2	0.789	0.795	0.795	0.795

(b) New Homes

	(1)	(2)	(3)	(4)	(5)
	log(Applications)				
Marginal price$_{t-2}$ (¥/kWh)	0.0085	0.0080	0.0084	0.0134	0.0139
	(0.0077)	(0.0079)	(0.0078)	(0.0104)	(0.0085)
1(No prefectural subsidy)	0.0320*	0.0287	0.0436	0.0383	0.0332
	(0.0187)	(0.0211)	(0.0297)	(0.0292)	(0.0304)
Max prefectural subsidy (¥1,000/application)		-0.0000			
		(0.0001)			
Effective prefectural subsidy (¥1,000/application)			0.0001	0.0001	0.0001
			(0.0003)	(0.0003)	(0.0003)
Cumulative adoption (%)	-0.0910	-0.0906	-0.0826	-0.1465	-0.1072
	(0.2537)	(0.2531)	(0.2550)	(0.2578)	(0.2590)
log(Population)				-2.6299	
				(3.0540)	
log(Housing starts)					0.3839***
					(0.1060)
log(Avg. income)				0.2190	0.0594
				(0.5056)	(0.5359)
log(Avg. worker age)				-1.8186	-2.3063*
				(1.0976)	(1.2028)
Prefecture FE	Yes	Yes	Yes	Yes	Yes
Quarter-year FE	Yes	Yes	Yes	Yes	Yes
Observations	987	987	987	987	987
Within R^2	0.924	0.924	0.924	0.925	0.929

Notes: Robust standard errors clustered at the prefecture level are reported in parentheses. *Marginal price* is the two-quarter lagged marginal electricity price. The dependent variable is the log of applications to the national subsidy on residential solar PV installation.

* Significance at the 10 percent level.

** Significance at the 5 percent level.

*** Significance at the 1 percent level.

Table 4: Regression Results with Prefecture-level Policies and Other Controls

The next columns of Table 4 include two additional variables about prefectural subsidies. Column (2) adds *max prefectural subsidy*, the maximum of each prefecture's subsidy on solar PV installation, on top of the national subsidy. Column (3) replaces *max prefectural subsidy* with *effective prefectural subsidy*, the amount of the prefectural subsidy for a household installing the average system capacity (kW) in the prefecture during the quarter. Following the earlier literature (e.g. Durham, Colby and Longstreth (1988)), we also control for other prefecture-level demographics (population, income, age, and housing starts) in column (4), and Panel (b) column (5), though the effects of these variables absorbed in fixed effects, so many of them are mostly statistically insignificant after controlling for prefecture and time fixed effects. Throughout these specifications, the above findings on the estimated electricity price elasticity remain robust after the addition of prefecture-level subsidy variables and other controls.

As explained in Section 3, our baseline regressions use the two-quarter lagged electricity price to allow for a time gap between households observing new electricity prices and making installation decisions. Table 5 shows the robustness of our results to the number of lags in the electricity price variable. Using the one-quarter lagged or current electricity price ($p_{i,t-1}$ or $p_{i,t}$), instead of ($p_{i,t-2}$), we find that the results are consistent with those in our previous tables (i.e. Tables 2 to 4).

6 Discussion

Across the different specifications reported above, we have robustly found that price signals such as electricity prices and one-time prefectural subsidies are more influential on owners of existing homes than on owners (buyers) of new (newly-built) homes. In our estimates, existing homes are often over 10 times more responsive to electricity prices than new homes. To our knowledge, previous studies have not separately analyzed the two groups with regard to solar PV adoption, so our paper is the first to report the difference. Below we will consider possible mechanisms to explain this substantial difference, and their policy implications.

A possible mechanism is the difference in electricity consumption between new and existing homes, but it unlikely explains our findings as discussed below. Cost savings from replacing grid

(a) Existing Homes

	(1)	(2)	(3)	(4)
	log(Applications)			
Marginal price$_{t-1}$ (¥/kWh)	0.0428**	0.0417**		
	(0.0174)	(0.0165)		
Marginal price$_t$ (¥/kWh)			0.0451**	0.0432**
			(0.0169)	(0.0165)
1(No prefectural subsidy)		0.0273		0.0223
		(0.0609)		(0.0593)
Effective prefectural subsidy (¥1,000/application)		0.0010**		0.0010**
		(0.0004)		(0.0004)
Cumulative adoption (%)		0.1517		0.1364
		(0.2858)		(0.2845)
Prefecture FE	Yes	Yes	Yes	Yes
Quarter-year FE	Yes	Yes	Yes	Yes
Observations	987	987	987	987
Within R^2	0.787	0.795	0.790	0.797

(b) New Homes

	(1)	(2)	(3)	(4)
	log(Applications)			
Marginal price$_{t-1}$ (¥/kWh)	0.0097	0.0109		
	(0.0078)	(0.0085)		
Marginal price$_t$ (¥/kWh)			0.0105	0.0114
			(0.0080)	(0.0086)
1(No prefectural subsidy)		0.0425		0.0411
		(0.0294)		(0.0291)
Effective prefectural subsidy (¥1,000/application)		0.0001		0.0001
		(0.0003)		(0.0003)
Cumulative adoption (%)		-0.0956		-0.1002
		(0.2603)		(0.2617)
Prefecture FE	Yes	Yes	Yes	Yes
Quarter-year FE	Yes	Yes	Yes	Yes
Observations	987	987	987	987
Within R^2	0.923	0.924	0.923	0.924

Notes: Robust standard errors clustered at the prefecture level are reported in parentheses. *Marginal price* is the marginal electricity price (one-quarter lagged or current).

* Significance at the 10 percent level.

** Significance at the 5 percent level.

*** Significance at the 1 percent level.

Table 5: Regression Results with Different Lags

electricity with self-generated solar electricity are greater for households with higher electricity consumption.[17] According to a survey commissioned by METI in 2012–2013,[18] household electricity consumption in a detached home – most solar PV systems are installed on this dwelling type – is generally higher for a newer home. It suggests that new-home owners should be *more* attentive to electricity prices than existing-home owners, in contrast to our findings.

Two other probable mechanisms to explain the result are "imperfect information" and "diminishing sensitivity." Both relate to the fact that some households adopt solar PV at the time of home purchase, while others make their adoption decisions separately from home purchase. In our data set, national subsidy applications come from either new (newly-built) homes, or existing homes. During the period of our analysis, the adoption rate is about 20% for new homes, while it is about 3% for existing homes (excluding those that adopt solar PV when they were new). Relatively speaking, an owner of a new home decides home purchase and solar PV adoption at similar times, and the solar PV system is installed as the home is built. For a vast majority of owners of existing homes, on the other hand, solar PV adoption is a separate decision from home purchase – they install a solar PV system on a property where they have been residing for some period of time (rather than on an existing home that they are purchasing).[19]

First, existing-home owners may, on average, have less information about the value of solar PV adoption than new-home owners ("imperfect information"). There are a number of studies in energy efficiency economics that investigate the effect of imperfect information on energy cost saving investment by households or firms (see Gillingham, Newell and Palmer (2009) or Gillingham and Palmer (2014) for a review). During the process of home purchase, households may

[17]Total cost savings from this substitution equal the marginal electricity price multiplied by self-supplied solar power (assuming a constant marginal electricity price). Thus, marginal cost savings from the substitution with respect to the marginal electricity price equal the amount of solar power self-supplied.

[18]`http://www.meti.go.jp/meti_lib/report/2013fy/E003078.pdf`, page 58, in Japanese.

[19]Solar PV installation on an existing home can take place either at about the same time 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 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, newly-built homes account for a dominant share in the Japanese housing market. For instance, the number of detached or tenement houses that are built between January 2011–September 2013 and owner-occupied is 1.11 million (more than 99% are detached houses), while the number of *used*, detached or tenement houses that are purchased for own occupation during the same period is 0.24 million. Since the total number of applications for the national subsidy program during the same period is 0.24 million for new (newly built) homes, and 0.51 million for existing homes, a vast majority of installations on existing homes take place separately from home purchase.

come across useful information about the value of solar PV adoption through, for instance, recommendations by architects or real estate agents. For new-home owners, the information thus obtained may be more crucial in their decision than changes in electricity prices, making them unresponsive to electricity prices. On the other hand, for most existing-home owners who adopt solar PV independently of home purchase, and thus have limited chances to learn about solar PV, electricity prices are a relatively important piece of information in their choice, resulting in a larger electricity price elasticity for existing homes.

Second, with the property of diminishing sensitivity as studied in the prospect theory (Tversky and Kahneman, 1992), a household will be less thoughtful about a solar PV investment if it is coupled with another large investment. For new-home buyers, solar PV adoption is essentially a relatively small, additional investment that accompanies a much larger expenditure on a house, while this is not the case for most existing-home owners. Under these circumstances, the property of diminishing sensitivity implies that new-home buyers, on average, are less attentive in deciding solar PV adoption than existing-home owners, making (owners of) new homes less susceptible to electricity prices.

An important policy implication of the contrasting responses to price signals is that the effectiveness of policies to support residential solar PV adoption (e.g., subsidies or tax credits on solar PV installation, and FITs) may be improved by taking account of the the timing of solar PV adoption relative to home purchase also affects. Other things equal, better access to information and/or diminishing sensitivity will make a home-buying household more likely to install solar PV regardless of government support (whether the home is new or used). In other words, home-buying households are more likely to invest in solar PV even in the absence of government support. On the other hand, households already residing in existing homes are more likely to be marginal adopters whose decisions are changed by the level of government support. Thus, policies to promote residential solar PV diffusion can be more cost-effective by focusing more on and providing larger support to the second group of households who are considering solar PV investment independently of home purchase.

7 Conclusion

There are a number of financial reasons and incentives for household adoption of rooftop solar PV systems, such as lower electricity bills thanks to self-supplied solar electricity, decreasing costs of solar panels, subsidies or tax credits for panel purchase and installation costs, and feed-in tariffs for generated electricity. Among them, this paper has particularly analyzed how household adoption decisions are affected by rising electricity prices which increase the electricity cost savings from solar PV. We overcome econometric hurdles – little variation in electricity prices after controlling for location and time fixed effects, and potential endogeneity of electricity prices – by taking advantage of the 2011 Fukushima nuclear disaster as a natural experiment. The shutdown led to sizable and exogenous increases in electricity prices due to increased reliance on more expensive fossil fuels, allowing us to identify the causal effect of electricity prices on household adoption. We collect data on prefecture-level residential solar PV adoptions for 2009–2014, and estimate its elasticity with respect to electricity prices. A unique feature of the paper is that we distinguish existing homes and new (newly-built) homes, and separately estimate and compare the responses from the two types of home owners.

For installations on existing homes, we estimate the electricity price elasticity to range from 0.9 to 1.2 across different specifications. This implies that solar PV installations in 2014 would have been reduced by 18% to 24% should the electricity prices had remained at the levels of 2011. Similarly, if electricity prices had been ¥1/kWh (about 4%) more expensive in 2013, it would have led to 6,850 more installations for existing homes, generating around 34 GWh a year – roughly equivalent to electricity generated by an ordinary nuclear reactor in 1.5 days.

Despite facing the same electricity prices and policies as owners of existing homes, our analysis shows that owners of new homes consistently exhibit a much smaller and statistically insignificant response of electricity prices on solar PV adoption. To our knowledge, this is the first study to point out the difference between existing and new homes. The timing of solar PV adoption relative to home purchase would explain the contrasting responses: households adopting solar PV at the time of home purchase (in our data, these are all installations on new homes, plus a fraction of installations on existing homes) likely have good access to information on the benefits of solar PV, and/or exhibit diminishing sensitivity to additional, relatively small investment on solar PV, as compared to households adopting solar PV separately from home purchase (in our data, these are most installations on existing homes). Our results suggest that policies to support residential solar PV adoption could be more cost-effective considering whether adoption is combined with or separate from home purchase. We believe that this is an interesting area for future research.

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