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Contrasting effects of electricity prices on retrofit and new-build installations of solar PV: Fukushima as a natural experiment

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ABSTRACT

This study examines the effects of financial incentives, particularly electricity prices, on residential solar photovoltaic (PV) system installations. We highlight the importance of a factor in the adoption of low-carbon building technologies that the literature has largely overlooked: the distinction between retrofit and new-build installations. To address the endogeneity of electricity prices, we use the 2011 Fukushima nuclear accident and the subsequent shutdown of nuclear power plants in Japan as a natural experiment that caused substantial, exogenous, and regionally varying increases in electricity generation costs and prices. Electricity prices have a statistically significant, positive effect on PV system installations for existing homes (with a mean elasticity of 1.6), but a statistically insignificant, much smaller effect for new-build homes. A policy implication of these contrasting responses is that the cost-effectiveness of financial incentive schemes for low-carbon building technologies can be improved if they are targeted more at retrofits. We also find a large downward bias (40%–60%) in the estimated effect of electricity prices if they are not instrumented with exogenous cost-shifters.

1. Introduction

With buildings accounting for over 30% of global final energy consumption (International Energy Agency, 2019, Table 1.3), a priority for achieving a low-carbon economy is to reduce the use of non-renewable energy in buildings through the adoption of energy-efficient or renewable-energy building technologies, such as energy-efficient heating and cooling and rooftop solar photovoltaic (PV) power generation. Understanding the determinants of the adoption of these technologies is essential for a faster transition and more effective policy design. Previous studies (e.g., Hassett and Metcalf, 1995; Gillingham et al., 2012; Michelsen and Madlener, 2012; De Groote and Verboven, 2019) find that these determinants broadly 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., household or firm size, home ownership, and environmental preferences); and building characteristics (e.g., building age).

In this context, this paper highlights the importance of a factor that has been largely overlooked in the previous literature: the distinction between retrofit installations (i.e., installations for existing buildings) and new-build installations (i.e., installations for new buildings). Although retrofitting existing buildings with energy-efficient or renewable-energy technologies has great potential for carbon emissions reductions at relatively low costs (e.g., Bardhan et al., 2014), previous studies of the adoption of these technologies rarely account for this distinction. As a notable exception, Michelsen and Madlener (2012) survey adoption decisions

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for residential heating systems in Germany, finding that demographic, socio-economic, building, and location characteristics (as opposed to individual preferences) have a greater effect on retrofitting of these systems than on new-build fitting.

We consider a key determinant that is not covered by Michelsen and Madlener (2012), namely financial incentives that increase the economic benefits of adoption, such as electricity prices and installation subsidies. We find empirical evidence of a phenomenon left unattended in the literature: the two types of adoption react very differently to changes in these incentives.

Specifically, we examine the effects of various factors, particularly changes in electricity prices, on residential solar PV diffusion in Japan between 2009 and 2014. The price of electricity purchased from the grid affects solar PV adoption by changing the monetary benefits of replacing grid electricity with self-generated solar electricity. A distinctive feature of our prefecture-level panel dataset is that it separately reports the numbers of residential solar PV installations for existing and new-build homes. We estimate a two-way fixed effects model in which the number of retrofit or new-build installations is explained by the price of electricity; other regressors, such as the local subsidy rate for PV adoption; and location and time fixed effects. Separately analyzing retrofit and new-build installations in this framework reveals their differences in the marginal effects of electricity prices and installation subsidies on PV adoption.

This estimation framework exploits the substantial regional and temporal variation in electricity generation costs and prices that was exogenously triggered by the 2011 Fukushima nuclear accident. The nuclear accident led to a shutdown of all nuclear power plants in Japan. Nuclear power was replaced by more expensive fossil fuels (i.e., coal, liquefied natural gas (LNG), and oil), causing electricity prices to increase by up to 40% within a few years. Importantly, the magnitude of the surge in electricity generation costs and prices differed substantially across regions depending on each region's pre-earthquake share of nuclear power and post-earthquake fuel substitution.[1]

The sizable, exogenous, and regionally varying increases in electricity generation costs and prices during this period allow us to address two challenges that researchers often face in estimating the effects of electricity prices on energy-saving investments. The first is limited variation in electricity prices after partialing out location and/or time fixed effects, which makes it difficult to precisely estimate their effects (De Groote et al., 2016). The second is the potential endogeneity of electricity prices, which we address by exploiting this fuel substitution process and using each region's average fossil fuel cost and fossil fuel share of electricity generation as instrumental variables (IVs) for that region's electricity price.

Our estimation results show stark differences in the response to changes in price signals between retrofitting and new-build fitting. Higher electricity prices clearly induce more solar PV installations for existing homes, whereas similar effects are not statistically confirmed for new-build homes. Taking the average over our preferred specifications, we estimate the elasticity of solar PV installations with respect to the marginal electricity price to be 1.6 (highly statistically significant) for existing homes and 0.5 (statistically insignificant) for new-build homes. We obtain similar results for the effects of one-time PV installation subsidies.

We discuss possible reasons behind the differential responses. In the case of solar PV in Japan, a fundamental difference between new-build fitting and retrofitting is that the former is combined with a home purchase, whereas the latter is mostly carried out for the adopting household's current residence and, thus, is independent of a home purchase. The literature on the energy efficiency gap and, more broadly, behavioral economics provides plausible explanations as to how this difference in the timing of solar PV adoption relative to a home purchase can lead to the contrasting responses to price signals, particularly new-build installations' insensitivity to these signals. These explanations include uncertainty about electricity cost savings from technology adoption (Hassett and Metcalf, 1993; Anderson and Newell, 2004), relative thinking and diminishing sensitivity (Tversky and Kahneman, 1981; Bushong et al., 2020) due to a home purchase, and the provision of other, more salient information on the benefits of technology adoption (Davis and Metcalf, 2016; Gillingham and Tsvetanov, 2018).

An important policy implication of our results is that the cost-effectiveness of financial incentive schemes (e.g., feed-in tariffs (FITs) and one-time subsidies) for low-carbon building technologies may be improved by treating retrofit and new-build installations differently. This implication relates to the theory of tagging and targeting (e.g., Akerlof, 1978; Allcott et al., 2015). With our solar PV data, existing homes are estimated to be so much more responsive to price signals than new-build homes that financial incentive schemes will be more cost-effective if they are targeted more at existing homes. For example, simulations based on our estimation results and Japan's solar PV-related statistics show that if additional funds are available for the FIT scheme, using the funds to increase the FIT rate for retrofit installations is 37% more effective in increasing aggregate solar PV capacity than using them to increase the FIT rate for new-build installations. Similar calculations suggest an even larger gap in the case of one-time installation subsidies. Targeting based on the easily observable distinction between retrofitting and new-build fitting is a simple but underutilized approach to improving the cost-effectiveness of support schemes for low-carbon building technologies.

Additionally, from an econometric perspective, our results demonstrate the importance of using IVs to address the endogeneity of electricity prices when estimating their effects on energy-saving investments. The price of electricity is often treated as an exogenous explanatory variable in estimating the determinants of energy-efficient or renewable-energy investments (e.g., Durham et al., 1988; Kwan, 2012; Hughes and Podolefsky, 2015; Matisoff and Johnson, 2017; Crago and Chernyakhovskiy, 2017 in the case of solar PV adoption). We find that even after controlling for location and time fixed effects and several covariates, the estimated effect of the electricity price is biased downward by 40%–60% in both the retrofit and new-build regressions if the electricity price is not instrumented. A likely source of this endogeneity is the simultaneous determination of electricity prices and energy-saving investments, where higher electricity prices induce the adoption of energy-saving or low-carbon technologies, while the overall diffusion of these technologies shifts the demand curve for grid electricity downward, thus helping to lower electricity prices.

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[1] Neidell et al. (2021) also focus on this period to identify the prevention effect of electricity use on deaths due to cold weather.

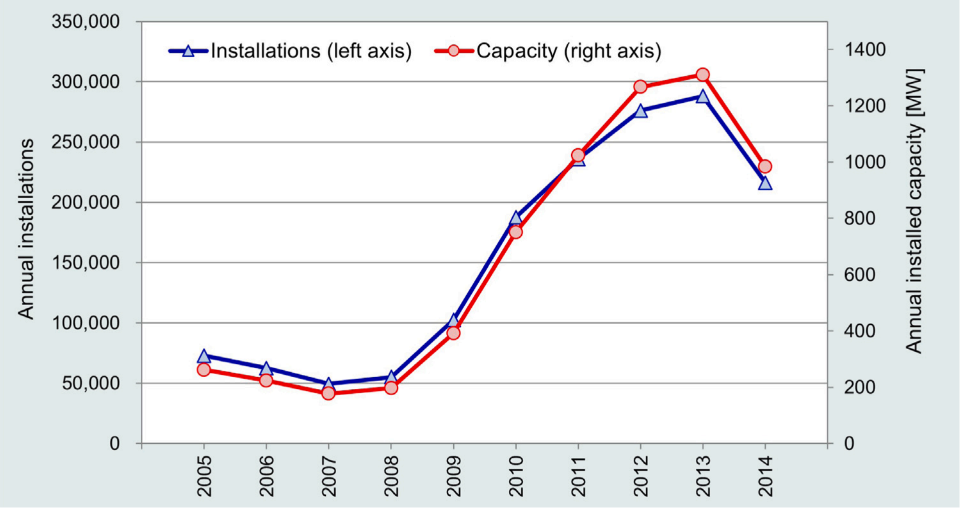

Fig. 1. Residential solar PV installations in Japan.

Sources: New Energy Foundation; New Energy Promotion Council; Japan Photovoltaic Energy Association.

The rest of the paper is organized as follows. Section 2 provides relevant background information regarding solar PV power generation 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 causes and implication. 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. Fig. 1 shows the number and aggregate capacity of annual residential solar PV installations between 2005 and 2014.[2] The pace of diffusion accelerated after 2009, likely owing to two national schemes that both started in 2009: a subsidy scheme for residential PV system installations and a FIT scheme for generated solar electricity. The increase after the 2011 Fukushima accident may have also been induced by rising electricity prices, a hypothesis that we aim to examine in this study.

Under the Japanese FIT scheme for residential solar PV power generation,[3] the price of electricity from the grid influences the economic benefit of solar PV adoption. The scheme legally requires electricity companies to purchase PV electricity from households at a fixed rate for 10 years. An important characteristic of the scheme is that solar PV owners can sell only surplus electricity. That is, a solar PV system first supplies electricity for domestic consumption ("Self-consumption" in Fig. 2) and then exports the surplus after this self-consumption to the electricity grid to earn a fixed FIT payment for each kilowatt-hour (kWh) ("Sales to the grid" in Fig. 2). Solar PV adoption therefore financially rewards households via two channels, namely by replacing the electricity purchased from the grid with self-generated solar electricity and by selling surplus solar electricity to the grid.

For the first channel, because the electricity cost saving from this replacement is roughly equal to the product of the grid electricity price and the amount replaced, higher grid electricity prices increase the benefit and, thus, the likelihood of solar PV adoption. Self-generated solar electricity can replace a sizable portion (typically, 30%–40%) of a household's grid electricity consumption. This reduction is much greater than the electricity saved by switching to energy-efficient home appliances (e.g., air conditioners and refrigerators) for which previous studies find positive effects of electricity prices on adoption (e.g., Rapson, 2014; Houde, 2018). Thus, it is reasonable to expect a strong positive relationship between electricity price changes and solar PV adoption.

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 national government (the Ministry of Economy, Trade and Industry). The country was divided into 10 regions, each of which was served by a vertically integrated monopoly responsible for electricity generation, transmission, and distribution. Each regional monopoly supplied electricity to all households

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[2] For example, there were 288,000 residential installations in 2013 only and cumulatively 1,547,000 residential installations by the end of 2013, which are estimated to have accounted for 0.15% and 0.82% of Japan's total electricity consumption in 2013, respectively.

[3] The term "residential" means less than 10 kilowatts of capacity.

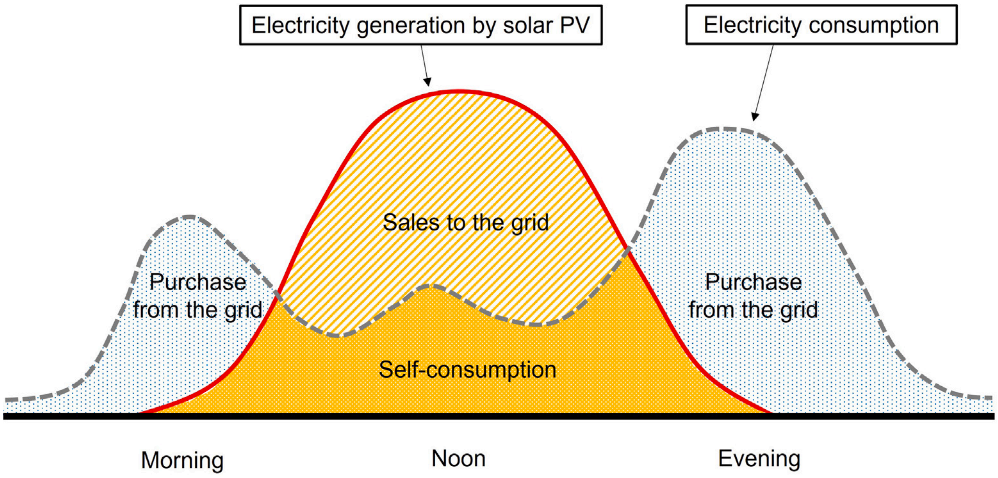

Fig. 2. Self-consumption and sales of self-generated solar electricity.

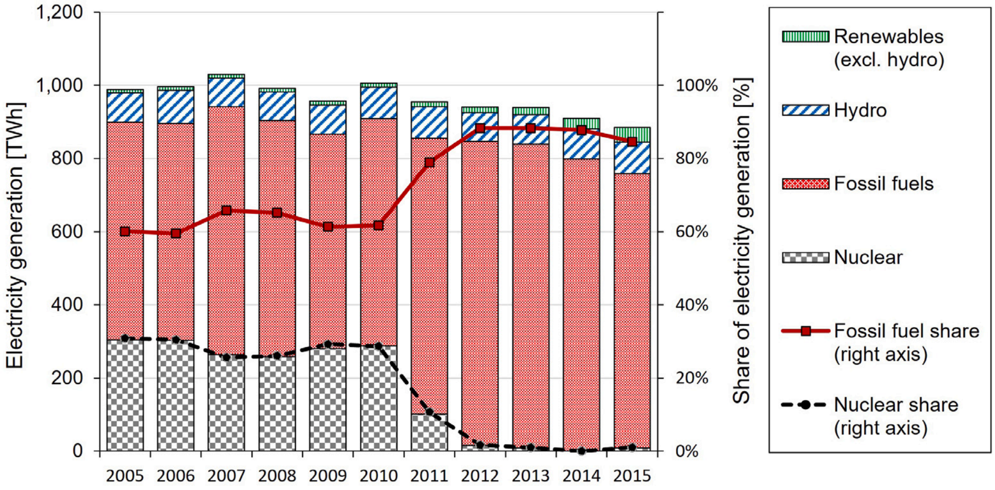

Fig. 3. Japan's electricity generation by energy source.
Source: Agency for Natural Resources and Energy (2017, Fig. 214-1-8).

in its region. For the protection of consumers, electricity prices could not be raised without the government's approval, with the exception of relatively small "fuel cost adjustments" that were calculated using predetermined formulae and fossil fuel import prices.

2.2.2. Electricity price changes after Fukushima

On March 11, 2011, a massive earthquake of magnitude 9.0 and subsequent tsunami hit the east coast of Japan, causing devastating meltdowns at Tokyo Electric Power Corporation's Fukushima No. 1 Nuclear Power Plant and the consequent 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 (Independent Investigation Commission on the Fukushima Nuclear Accident, 2014). All operating reactors were shut down one after the other by May 2012 due to safety concerns, and they were not allowed to resume operation. Although two reactors were permitted to restart in July 2012, their pre-scheduled periodic inspections in September 2013 resulted in another complete nuclear shutdown, which continued until August 2015 when a reactor resumed operation under stricter regulations. Fig. 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 0% in 2014.

Nuclear power was mostly replaced by fossil fuels (i.e., coal, LNG, and oil). In Fig. 3, the combined share of fossil fuels increased from 62% in 2010 to 88% in 2012, meaning that they took over most of nuclear power's pre-Fukushima share. Facing the nuclear

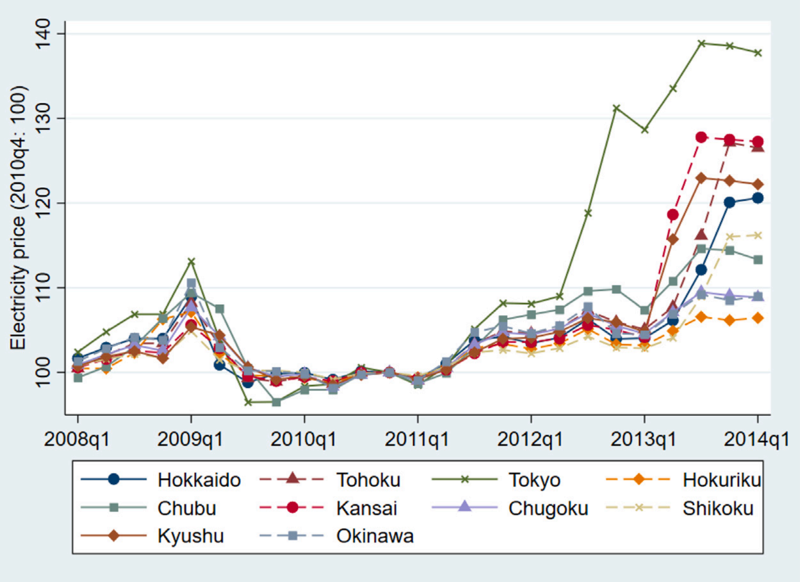

Fig. 4. Marginal electricity price by region (relative to 2010 Q4).
Source: Statistics Bureau of Japan (Retail Price Survey).

shutdown, electricity companies urgently expanded their use of fossil fuels by first reactivating old fossil-fuel-based generators and then building a small number of new ones.

The shutdown of nuclear power plants and substitution of fossil fuels sharply raised electricity prices because fossil fuels were more expensive sources of electricity generation than nuclear power.[4] Within four years of the 2011 earthquake, the average electricity price increased by 38% from ¥19.8/kWh to ¥27.3/kWh. During the period of our analysis (2009 Q1 to 2014 Q1), six electricity companies raised electricity tariffs substantially (beyond the automatic monthly fuel cost adjustments described above), and all these increases occurred after 2012. When these companies requested the government's approval for the tariff changes, they listed the increased fuel costs due to this fuel substitution as the primary reason. Some companies also referred to the additional nuclear safety and security costs under tightened regulations.

Whereas electricity prices soared in all regions of Japan following the Fukushima accident, the magnitudes of these increases varied substantially across regions. Fig. 4 presents the residential electricity price trends of different regions before and after the Fukushima accident.[5] Some regions (e.g., Tokyo, Kansai, and Kyushu) suffered significant price hikes starting in the second quarter of 2011 (i.e., about 20%–40% within three years), while other regions (e.g., Hokuriku, Chugoku, and Okinawa) experienced smaller hikes (i.e., less than 10% during the same period).

Figs. 5 and 6, together with Fig. 4, indicate two major factors in the magnitude of each region's electricity price hike after Fukushima. Fig. 5 shows substantial regional variation in the share of nuclear power in 2010, before the accident. The share was over 40% in the regions highly dependent on nuclear power (i.e., Hokkaido, Kansai, Shikoku, and Kyushu), whereas it was less than 5% in Chugoku and Okinawa.

Based on the information in Fig. 5, Fig. 6(a) plots the percentage-point increase in fossil fuels' share between 2010 and 2014 against the percentage-point decrease in nuclear power's share in the same period, showing that in all regions with non-marginal pre-Fukushima nuclear shares, nuclear power was mostly replaced by fossil fuels (i.e., coal, LNG, and oil) after the accident. Fig. 6(b) plots the percentage increase in the marginal electricity price between 2010 and 2014 (as observed in Fig. 4) against the percentage-point increase in the combined share of LNG and oil in the same period (as observed in Fig. 5). Fig. 6(b) suggests that the substitution of LNG and oil is positively correlated with the magnitude of the electricity price hike. As described in footnote 4, LNG and oil are more expensive energy sources than coal.[6]

Taken together, Figs. 4 to 6 suggest that electricity prices, which exhibited regionally varying post-Fukushima trends (Fig. 4), tended to increase substantially in regions where regionally monopolistic electricity companies depended heavily on nuclear power before Fukushima and significantly increased their use of LNG and oil, rather than coal, after Fukushima to replace nuclear power. We construct cost-shifter IVs for electricity prices based on these observations, as detailed in the next section.

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[4] The fuel cost in 2014 was estimated at ¥1.5/kWh for nuclear power, ¥5.5/kWh for coal, ¥10.8/kWh for LNG, and ¥21.7/kWh for oil (Ministry of Economy, Trade and Industry, 2015). The rank order remains the same if we consider the sum of the fuel, operation, and maintenance 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.

[5] To be precise, the figure shows the highest marginal price in each region's increasing block rate schedule.

[6] Notably, Hokuriku had a relatively high pre-Fukushima share of nuclear power (28%) but did not experience a large electricity price hike. This is likely because nuclear power was mainly replaced by coal in Hokuriku.

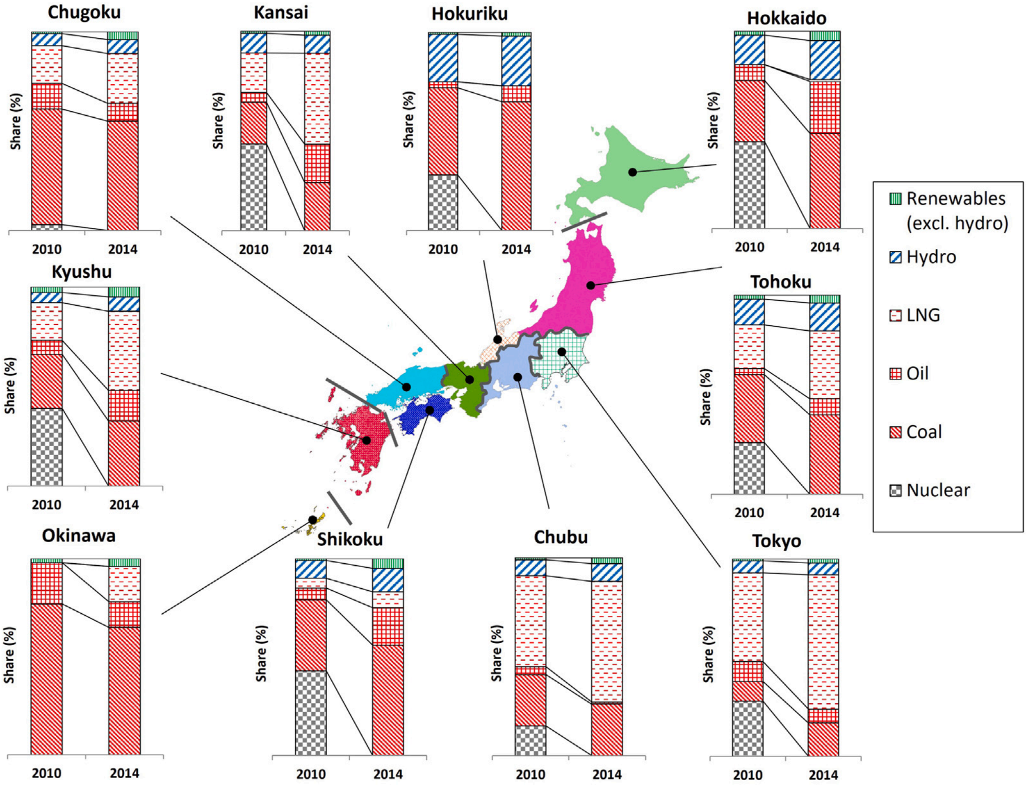
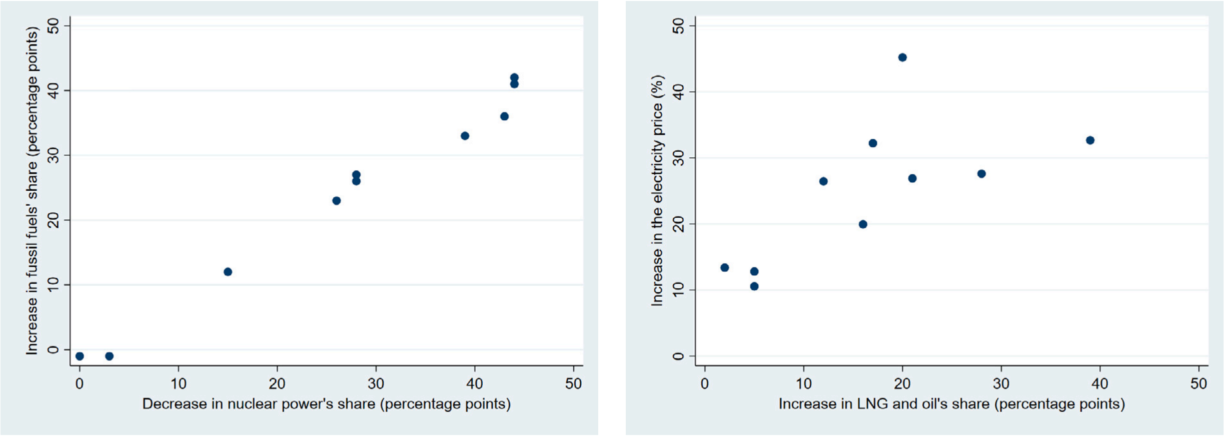


Fig. 5. Electricity generation mix by region in 2010 and 2014.
Sources: Electricity companies' annual reports.



(a) Increase in fossil fuels' share vs. decrease in nuclear power's share

(b) Increase in the electricity price vs. increase in LNG and oil's share

Fig. 6. Changes in the electricity generation mix and electricity price by region between 2010 and 2014.
Sources: Statistics Bureau of Japan (Retail Price Survey) and electricity companies' annual reports.

Table 1
Summary statistics.

Variable	Obs	Mean	St dev	Min	Max
National subsidy applications (all)	987	1285	1157	40	8313
National subsidy applications (retrofit)	987	843	710	27	4655
National subsidy applications (new-build)	987	443	485	6	4038
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 (¥1000/kl of oil equivalent)	987	31.00	7.94	19.59	54.09
Fossil fuel share (%)	987	59.21	16.00	22.07	91.30
Prefectural subsidy dummy (retrofit)[a]	987	0.52	0.50	0	1
Prefectural subsidy (¥1000/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 (¥1000/case; new-build)[b]	478	98.48	71.60	14	377
Cumulative residential solar PV installations	987	19,352	16,700	966	107,961
Detached homes without solar PV	987	579,350	420,960	146,470	1,736,750
Housing starts (for self-occupied properties)	987	1653	1323	222	7108
Residents' group collection rate (%)	987	4.59	2.57	0.10	10.99
Total waste recycling rate (%)	987	19.83	4.43	11.81	37.08
Population over age 15 (1000 people)	987	2361	2326	501	11,798
Average worker age	987	41.83	0.62	40.0	43.5
Average wage (¥1000/month)	987	269.91	28.12	222.2	377.4

Notes: The unit of observation is a prefecture in each quarter between 2009 Q1 and 2014 Q1.

[a] This variable equals 1 if a prefectural subsidy is offered to the corresponding type of solar PV installations in prefecture i during period t, and 0 otherwise.

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

3. Empirical framework and data

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

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

where i indexes 47 prefectures of Japan, and t indexes time periods (21 consecutive quarters between 2009 Q1 and 2014 Q1). We estimate this model separately for retrofit and new-build installations and for both types together. On the left-hand side, y_{it} is the number of solar PV installations and is represented by the number of applications to Japan's national subsidy program for residential solar PV installations. On the right-hand side, $p_{i,t-1}$ is the marginal or average electricity price, lagged by one quarter to reflect households' delayed responses to electricity price changes, and X_{it} is a vector of covariates, such as the PV installation subsidy offered by the prefectural government. Table 1 reports the summary statistics for these variables, and we provide more details later in the text. The time fixed effect η_t captures various factors in period t that are common to all prefectures, such as nationwide policies and the general quality and cost levels of solar PV systems.[7] The prefecture fixed effect μ_i controls for prefecture characteristics that are time-invariant over the sample period (2009–2014), such as basic climate conditions. The idiosyncratic error ε_{it} is clustered at the prefecture level.[8]

We also consider a semi-parametric estimator of Eq. (1) with which we nonparametrically estimate the effect of $p_{i,t-1}$ after partialing out the fixed effects and covariates (Baltagi and Li, 2002; Li and Racine, 2007). The results show 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).

3.1. Solar PV installations

We obtain data on y_{it} from the Japan Photovoltaic Energy Association, the operating body of the national PV installation subsidy program. This program ran from January 2009 to March 2014 and provided households adopting solar PV systems with a one-time subsidy that covered about 10% (5%) of the average cost of these systems in 2009 (2014). Households in all prefectures could apply for this subsidy, and no prefectures were subject to a quota. Households applied for the subsidy before installation, and over 96% of these applications were successfully approved and resulted in actual installations. The number of approvals for this subsidy is used by the government as the official number of residential solar PV installations, suggesting that the subsidy program covered nearly all residential PV installations.

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[7] Nationwide policies include the FIT scheme, the national subsidy for solar PV installations, and the so-called "renewable energy surcharge" that is added to each user's electricity bill to finance the FIT scheme.

[8] As described in Section 2.2, during our study period, all the prefectures in a given region were served by a regionally monopolistic electricity company and faced common electricity price schedules set by the company. For this reason, we also estimate a version of our model with the error term ε_{it} clustered at the regional level (rather than at the prefecture level), finding that the results are essentially unaffected.

We use subsidy applications rather than subsidy approvals as our dependent variable. It typically took several months for an application to be approved, but the time to approval varied across cases. Thus, applications capture the timing of household adoption decisions better than approvals.

Aggregated across prefectures over the period of 2009 Q1–2014 Q1, there were 831,637 retrofit applications and 436,852 new-build applications. Retrofit applications outnumbered new-build applications in most prefectures throughout the period. To provide context for the relative magnitudes of these numbers, Japan had 28.6 million detached homes in 2013, and 2.1 million housing starts for detached homes between 2009 and 2013. In other words, during the period of our analysis, about 20% of new-build homes installed solar PV systems during construction, and about 3% of the stock of existing homes retrofitted solar PV systems.[9]

For the most part, the data directly reflect each household's independent decision to adopt solar PV. According to an analyst who collected and organized the dataset, fewer than 1% of applications were from new-build detached homes that had PV systems preinstalled without home buyers' involvement. Even less frequent were applications from (new or existing) non-detached houses for which collective decisions by multiple households would be necessary. Additionally, leases of solar PV systems (as widely observed in California) were rare in Japan.

Lastly, a vast majority of retrofits in the data are carried out for the adopting households' current homes, independent of home purchases. A solar PV system can be retrofitted either when a new owner purchases an existing home or at other times irrespective of a home purchase. Although our dataset does not allow us to distinguish between these two retrofit categories, property market statistics suggest that a large fraction (about 90% or more) of retrofit installations fall into the second category. This is essentially because new-build properties account for a dominant share of Japan's housing market, unlike in North America or Europe.[10] Thus, our estimation results for retrofitting are mostly driven by the behavior of owners of existing homes who adopted solar PV systems independent of home purchases.

3.2. *Electricity prices*

Regarding the electricity price variable p_{it}, we construct quarterly residential electricity price data from the Retail Price Survey published by the Statistics Bureau of Japan. As described in Section 2.2, electricity tariffs can be increased only with the government's approval, with the exception of automatic and limited monthly fuel cost adjustments that reflect international fossil fuel prices. These electricity tariffs follow increasing block rate schedules, and the marginal price for the highest block (i.e., monthly consumption above 300 kWh, or above 280 kWh for Hokkaido) serves as our main regressor. The government uses 441 kWh as a standard household's monthly electricity consumption in its statistics and modeling, implying that almost all households adopting solar PV, who likely reside in relatively large detached homes, face this marginal price. As a robustness check, we also calculate the average electricity price for the standard household with monthly consumption of 441kWh and use that price in place of the marginal price.[11] As discussed in Section 2.2, these electricity prices exhibit substantial temporal and regional variation during our study period, especially after the Fukushima accident (Fig. 4).

A concern in estimating Eq. (1) with the simple fixed effects estimator is the potential endogeneity of electricity prices. Some previous studies of the effects of electricity prices on the adoption of energy-efficient home appliances (e.g., Jacobsen, 2015; Houde and Myers, 2021; Schwarz et al., 2021) consider the block rate pricing of electricity to be a potential source of measurement error. This issue may also arise in our framework if households tend to respond to electricity price signals that are different from the marginal price (e.g., Ito, 2014).

Additionally and more fundamentally, electricity prices may be endogenous in Eq. (1) because they are likely determined interdependently with the diffusion of various technologies that reduce electricity costs, including solar PV, among firms and households. Higher electricity prices likely induce firms and households to adopt these technologies, while the diffusion of these technologies shifts the demand curve for grid electricity downward, helping to lower electricity prices. As the model in Appendix A shows, this interdependence essentially results in a typical case of simultaneity bias. That is, conditional on fixed effects and other explanatory variables in an empirical model, unobserved factors that stimulate the diffusion of these technologies are negatively correlated with the equilibrium electricity price. Many of these unobservable factors are the same as or similar to those included in the error term of Eq. (1),[12] meaning that this error term is also likely to be negatively correlated with the electricity price. This negative correlation makes the electricity price endogenous in Eq. (1), biasing the estimate of β downward if the electricity price is not instrumented.

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[9] The difference in the overall adoption rate may result from households' optimal behavior when existing and new-build homes differ in terms of building and owner characteristics (e.g., solar PV installation costs, other monetary or non-monetary costs, electricity consumption, and so on). For example, a new-build installation typically costs 10%–20% less than a retrofit installation. In addition, substantial construction or renovation work, such as a solar PV installation, is physically and psychologically less complicated and burdensome when it is performed for unoccupied properties, including new-build homes.

[10] According to statistics on owner-occupied properties, 1.11 million detached or tenement houses were built between January 2011 and September 2013, more than 99% of which were detached houses. In contrast, 0.24 million *used* detached or tenement houses were purchased during the same period. The total numbers of applications for the national subsidy program during that period were 0.24 million for new-build homes (i.e., an adoption rate of 22%) and 0.51 million for existing homes. Even if 22% of the 0.24 million buyers of used detached or tenement houses in this period had applied for the subsidy (i.e., the same adoption rate as in the case of new builds), they would have accounted for only 0.05 million of the 0.51 million applications from existing homes.

[11] We acknowledge that households adopting solar PV tend to consume more electricity, so the average price they face is different from and most likely greater than the average price for the standard household.

[12] Firm-level factors may spill over to the household-level adoption of solar PV systems and other residential energy-saving measures. For example, Arimura et al. (2021) find that firm-level energy-saving practices in Japan have spillover effects to households.

(a) Share of energy-saving investments in small and mid-sized manufacturers' capital investments

(b) Major building renovations for energy-saving purposes

Fig. 7. Time trends in energy-saving investments.
Sources: (a) Japan Finance Corporation (Survey of Capital Investment Trends Among Small and Medium-sized Manufacturers); (b) Ministry of Land, Infrastructure, Transport and Tourism (Building Extension and Renovation Survey).

Electricity prices in Japan increased substantially around our study period, as did energy-saving investments by firms and households, as indicated by the firm and household survey results in Figs. 7(a) and 7(b). The upward trends observed in these surveys are consistent with the findings of Hitomi and Hoshino (2016), who use a macroeconomic model to decompose changes in Japan's electricity demand into contributions from various factors and find that the energy efficiency of the capital stock improved rapidly between 2006 and 2013. These drastic changes imply that the endogeneity of electricity prices due to this interdependence may be unignorable.

3.3. Instrumental variables

We address this potential endogeneity using IVs that affect the cost of electricity generation, as in the above-mentioned studies of the effects of electricity prices on technology adoption (Jacobsen, 2015; Houde and Myers, 2021; Schwarz et al., 2021). We construct these IVs by exploiting electricity companies' tariff-setting rules and the temporal and regional variation in fuel sources, as described in Section 2.2.

The first IV is each electricity company's (i.e., region's) average fossil fuel cost per kiloliter of oil equivalent, which the company uses to set the monthly variable part of its electricity tariffs based on predetermined rules. This cost is calculated as the weighted average of the lagged import prices of three fossil fuels (i.e., coal, LNG, and oil), where the weights are fixed at the respective fuels' shares of the region's fossil fuel power generation at the time of the most recent government-approved changes to the monthly invariant part of the company's electricity tariffs.[13] Fossil fuel import prices are taken from country-level trade statistics, so they are common to all electricity companies (i.e., regions) and are based on all imports of these fuels (rather than just imports for electricity generation).[14] We construct this average fuel cost variable for each quarter based on each electricity company's press releases and use it as an IV for the electricity price in the corresponding quarter. Fig. 8 plots this cost-shifter IV by region from 2008 to 2014, showing similar trends to regional electricity prices (Fig. 4).

The second IV for the electricity price $p_{i,t-1}$ is the share $s_{i,t-1}$ of fossil fuels in the generation mix of the electricity company that served prefecture i. We construct this fossil fuel share variable based on the database of the Federation of Electric Power Companies of Japan. As discussed previously, the share of fossil fuels generally increased owing to the post-Fukushima nuclear shutdown, but the degree of this increased dependence on fossil fuels varied across regions depending on each region's pre-Fukushima share of nuclear power. Unlike the first instrument, changes in the fossil fuel share of total electricity generation were not reflected in electricity prices each month, but only when the monthly invariant elements of electricity tariffs were changed with the government's approval. Given this relatively slow process, $p_{i,t-1}$ is instrumented with $s_{i,t-1}$ and three more lagged values, $s_{i,t-2}$, $s_{i,t-3}$, and $s_{i,t-4}$. Fig. 9 shows the trend in each region's fossil fuel share by plotting the difference in the share from the level in 2010 Q1.

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[13] Thus, for each electricity company, these three shares sum to one, and the weights are changed infrequently.

[14] Japan's domestic production of these fuels is negligible.

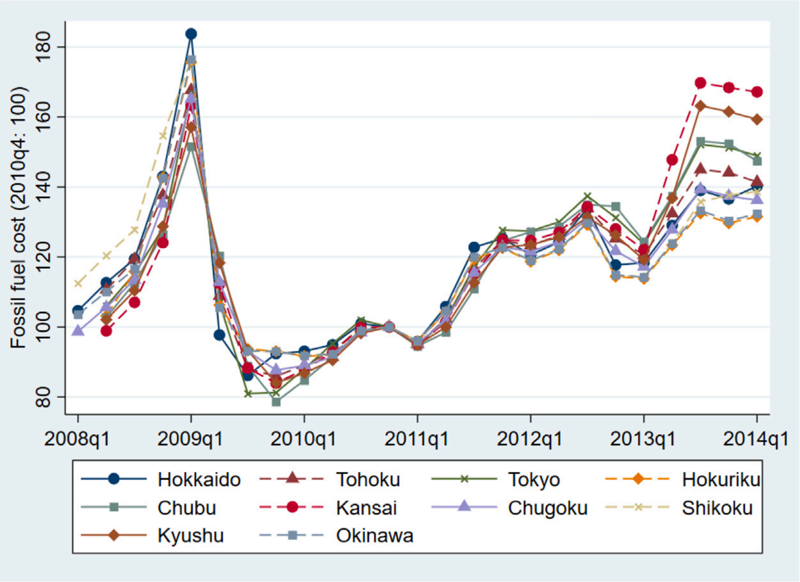

Fig. 8. Fossil fuel cost by region (relative to 2010 Q4).
Sources: Electricity companies' press releases.

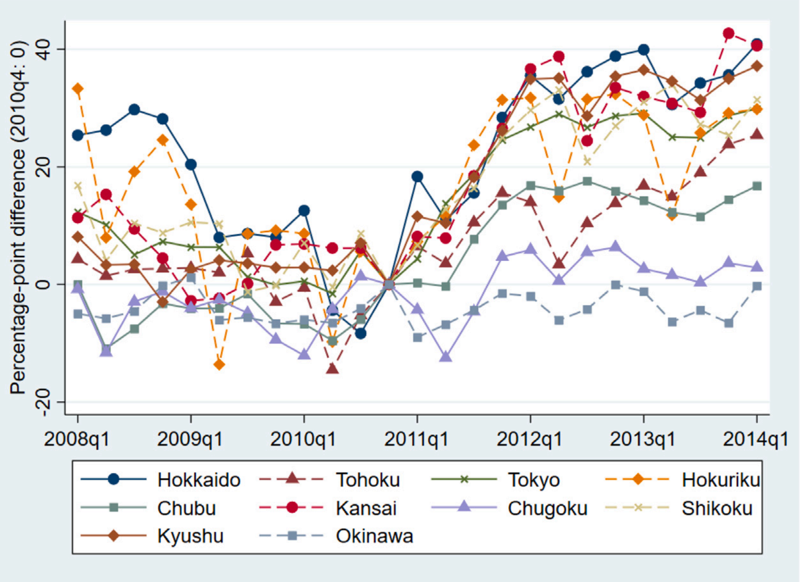

Fig. 9. Fossil fuel share by region (difference from 2010 Q4).
Source: Federation of Electric Power Companies of Japan.

3.4. Covariates

The covariates $\mathbf{X}_{it}$ 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 (i.e., prefectural and municipal) governments often provide subsidies for solar PV installations. Because no comprehensive information is available about municipal subsidies,[15] prefecture-level

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[15] In addition to prefectures, municipalities (e.g., cities) sometimes offer similar incentive programs. Japan has more than 1700 municipalities, and solar PV subsidy rules are often complex and qualitatively different across municipalities, making it practically impossible to construct numeric variables for municipal subsidy levels.

subsidies are used to proxy for all these local subsidies. Referring to prefectural governments' budgets, we construct the following two variables for each (i, t) combination and each installation type (i.e., retrofit or new-build installations): a dummy variable for the presence of a prefectural subsidy for residential solar PV adoption and the total amount of this subsidy for installing a residential PV system that has the average capacity size (kW) of these systems newly installed in each prefecture and year. We acknowledge the potential endogeneity of these local subsidies and interpret their estimated effects with caution (see Hughes and Podolefsky (2015) for a related discussion for California).[16]

As in previous studies (e.g., Durham et al., 1988; Kwan, 2012; Crago and Chernyakhovskiy, 2017), $\mathbf{X}_{it}$ includes other prefecture-level demographic and socio-economic variables. In addition to basic information (i.e., each prefecture's *population*, *average worker age*, and *average wage*), we control for variables relating to the scale of solar PV penetration and the pool of potential solar PV adopters (i.e., *cumulative residential solar PV installations*, *detached homes without solar PV*, and *housing starts* for self-occupied properties). We construct these variables based on the database of the Statistics Bureau of Japan and the solar PV installation data described above. Furthermore, we obtain the *residents' group collection rate* and *total waste recycling rate* from the Survey of General Waste Management by the Ministry of the Environment and use them as proxy variables for pro-environmental preferences and behavior.[17] Including these variables is particularly important in cross-sectional settings. In our panel data setting, their effects should be mostly absorbed by the fixed effects (particularly, the prefecture fixed effects) in any case because they change little within each prefecture over the study period.

4. Results

Tables 2 and 3 present the results of estimating Eq. (1) for retrofit and new-build installations, respectively. Table B.1 reports the results for both types of installations together, which basically fall between the results for retrofit and new-build installations, as expected. In each table, columns (1) and (3) (columns (2), (4), and (5)) are estimated without (with) the cost-shifter IVs. The electricity price, our main variable of interest, is represented by the one-quarter lagged marginal electricity price—we check the robustness of these results using different lag structures and the standard household's average electricity price.

In columns (1) and (2) of each table, even the simple model with no covariates shows the two main findings of this study about β (i.e., the effect of electricity prices on solar PV installations). A ¥1 increase in the marginal electricity price is estimated to increase retrofit installations by approximately 3.6% without IVs and 7.3% with IVs (both are highly statistically significant), and new-build installations by approximately 0.55% without IVs and 1.4% with IVs (both are statistically insignificant). In terms of the elasticity of installations with respect to the electricity price, these point estimates of β translate into elasticities of 0.90 without IVs and 1.85 with IVs for retrofitting and 0.14 without IVs and 0.35 with IVs for new-build fitting.[18] Thus, retrofit installations are more sensitive to electricity price changes than new-build installations. Additionally, not instrumenting the electricity price with the cost-shifter IVs leads to a downward bias in the estimate of β.

The first-stage results for the IV estimations in column (2) of Tables 2 and 3 are reported in column (1) of Table 4. The F statistic for all excluded instruments is 169, easily passing standard weak instrument tests. As expected from electricity companies' tariff-setting rules and the substitution of fossil fuels for nuclear power after Fukushima (Sections 2 and 3), the fossil fuel cost IV is significantly positively correlated with the electricity price, as are the four fossil fuel share IVs jointly. Additionally, Tables 2 and 3 report the p-values for Hansen's J test of overidentifying restrictions, which overall confirm the validity of our IV approach.

As discussed in Section 3 and Appendix A, the interdependent or simultaneous determination of electricity prices and energy-saving investments can explain the downward bias in the estimates of β in column (1) of Tables 2 and 3 relative to column (2) of the respective tables. That is, after controlling for the time and prefecture fixed effects (η_t and μ_i), this interdependence causes unobserved factors that stimulate the diffusion of residential solar PV to be negatively correlated with the electricity price, leading to the downward bias.

Columns (3) to (5) of Tables 2 and 3 account for other prefecture-level covariates ($\mathbf{X}_{it}$ in Eq. (1)), and column (5) additionally includes prefecture-by-quarter fixed effects (i.e., four quarterly fixed effects for each prefecture).[19] Regarding the effect of the electricity price, we continue to observe the above-mentioned results about the difference between retrofit and new-build installations and the downward bias due to not using IVs. As for the covariates, detached homes without solar PV and housing

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[16] For example, if some factors that are unobserved by the researcher incline residents of a prefecture or municipality to think positively about solar PV, then, all else equal, solar PV installations in the area will increase. In the meantime, these factors will also incentivize the governor or mayor and local councilors, who are elected by these residents, to set up a larger local solar PV subsidy. Hence, these unobserved factors, which are included in the error term, will be positively correlated with the subsidy rate. Conversely, the error term may contain unobserved factors that are negatively correlated with the subsidy rate, as the following example shows. While a local subsidy induces more solar PV installations in the area, the local government is likely to reduce the subsidy rate as solar PV diffuses there (as in the case of the national solar PV installation subsidy). Then, just as the interdependence between electricity prices and energy-saving investments does (see Section 3.2 and Appendix A), this interdependent determination of the subsidy rate and solar PV diffusion may lead to simultaneity bias whereby the negative correlation between the unobserved factors and the equilibrium subsidy rate biases the OLS estimate downward in a regression of solar PV installations on the subsidy rate.

[17] The residents' group collection rate ("*shudan kaishu*" in Japanese) measures the strength of residents' communal efforts to recycle household wastes. The total waste recycling rate measures the extent of overall recycling activities throughout the prefecture's economy, including the industrial, commercial, and residential sectors.

[18] These elasticities are evaluated at the sample mean electricity price.

[19] The first-stage results for columns (4) and (5) of Table 2 (retrofit installations) are reported in columns (2) and (3) of Table 4, respectively. The first-stage regressions corresponding to columns (4) and (5) of Table 3 give similar results. All these first-stage regressions with covariates $\mathbf{X}_{it}$ show essentially the same results as those with no covariates (column (1) of Table 4).

Table 2
Regression results: retrofit installations.

	(1)	(2)	(3)	(4)	(5)
Marginal electricity price$_{t-1}$	0.036* (0.018)	0.073*** (0.019)	0.029* (0.015)	0.069*** (0.018)	0.062*** (0.019)
Prefectural subsidy dummy (retrofit)			0.025 (0.056)	0.018 (0.055)	0.0056 (0.055)
Prefectural subsidy rate (retrofit)			0.00080** (0.00040)	0.00079** (0.00040)	0.00082** (0.00038)
ln(Cumulative solar PV installations)$_{t-1}$			0.20 (0.26)	0.061 (0.25)	0.069 (0.25)
ln(Detached homes without solar PV)$_{t-1}$			3.33** (1.65)	2.93* (1.58)	2.82* (1.60)
ln(Housing starts)			0.33*** (0.11)	0.35*** (0.11)	0.14 (0.12)
ln(Residents' group collection rate)			0.31* (0.18)	0.24 (0.18)	0.22 (0.18)
ln(Total waste recycling rate)			0.13 (0.39)	0.10 (0.35)	0.11 (0.35)
ln(Population)			−3.80 (4.83)	−5.37 (4.65)	−5.50 (4.72)
ln(Average wage)			0.59 (0.78)	0.73 (0.76)	0.90 (0.74)
ln(Average worker age)			0.61 (1.47)	0.33 (1.43)	0.38 (1.41)
Implied electricity price elasticity	0.90	1.85	0.74	1.73	1.56
Prefecture-by-quarter fixed effects	No	No	No	No	Yes
Instruments	No	Yes	No	Yes	Yes
p-value of Hansen's *J* test		0.24		0.48	0.68
Within R^2	0.77	0.77	0.79	0.79	0.79

Note: Refer to the notes below Table 3.

Table 3
Regression results: new-build installations.

	(1)	(2)	(3)	(4)	(5)
Marginal electricity price$_{t-1}$	0.0055 (0.0072)	0.014 (0.014)	0.012 (0.0085)	0.019 (0.015)	0.021 (0.015)
Prefectural subsidy dummy (new-build)			−0.00058 (0.028)	0.00035 (0.027)	0.0022 (0.028)
Prefectural subsidy rate (new-build)			−0.0000087 (0.00023)	−0.000029 (0.00023)	−0.000086 (0.00023)
ln(Cumulative solar PV installations)$_{t-1}$			−0.18 (0.21)	−0.21 (0.21)	−0.23 (0.21)
ln(Detached homes without solar PV)$_{t-1}$			4.15*** (1.23)	4.07*** (1.19)	4.02*** (1.10)
ln(Housing starts)			0.50*** (0.094)	0.50*** (0.092)	0.56*** (0.15)
ln(Residents' group collection rate)			0.14 (0.12)	0.13 (0.12)	0.17 (0.14)
ln(Total waste recycling rate)			0.16 (0.24)	0.16 (0.23)	0.12 (0.23)
ln(Population)			−5.95** (2.70)	−6.28** (2.64)	−6.14** (2.91)
ln(Average wage)			0.31 (0.39)	0.34 (0.37)	0.42 (0.36)
ln(Average worker age)			−2.19** (0.91)	−2.24** (0.90)	−2.37*** (0.89)
Implied electricity price elasticity	0.14	0.35	0.29	0.49	0.54
Prefecture-by-quarter fixed effects	No	No	No	No	Yes
Instruments	No	Yes	No	Yes	Yes
p-value of Hansen's *J* test		0.31		0.69	0.09
Within R^2	0.92	0.92	0.93	0.93	0.93

Notes: In Table 2 (Table 3), the dependent variable is the logarithm of the number of retrofit (new-build) residential solar PV installations. All specifications have 987 observations (47 prefectures over 21 quarters) and include prefecture fixed effects and time (year-quarter) fixed effects. Column (5) also includes prefecture-by-quarter fixed effects (i.e., four quarterly fixed effects for each prefecture). Variables with the subscript $t-1$ are lagged by one quarter. In columns (2), (4) and (5), the electricity price is instrumented with the fossil fuel cost and lagged fossil fuel shares. Cluster-robust standard errors are in parentheses, where the observations are clustered at the prefecture level. The implied electricity price elasticity of solar PV installations is calculated at the sample mean electricity price. The superscripts *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.

Table 4
First-stage results.

	(1)	(2)	(3)
Fossil fuel cost$_{t-1}$	0.35***	0.32***	0.32***
	(0.026)	(0.023)	(0.025)
Fossil fuel share$_{t-1}$	−0.032	0.054	0.27
	(0.42)	(0.42)	(0.68)
Fossil fuel share$_{t-2}$	0.40*	0.54**	0.00013
	(0.22)	(0.22)	(0.28)
Fossil fuel share$_{t-3}$	1.36***	1.63***	1.84***
	(0.34)	(0.40)	(0.53)
Fossil fuel share$_{t-4}$	−0.69*	−0.73**	−0.58
	(0.36)	(0.36)	(0.44)
Covariates	No	Yes	Yes
Prefecture-by-quarter fixed effects	No	No	Yes
F-statistic for excluded instruments	168.5	58.0	58.1
Adjusted R^2	0.842	0.857	0.838

Notes: Columns (1), (2), and (3) show the first-stage results for the IV estimations reported in columns (2), (4), and (5), respectively, of Table 2. The dependent variable (i.e., the endogenous regressor in the second stage) is the marginal electricity price in period $t-1$. The F-statistic for excluded instruments is for testing the joint significance of the excluded instruments. Cluster-robust standard errors are in parentheses, where the observations are clustered at the prefecture level. The superscripts *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.

starts are estimated to be positively associated with solar PV adoption. Additionally, the residents' group collection rate, a proxy variable for pro-environmental preferences and behavior, is positively associated with solar PV adoption, though not statistically significantly in many cases.

Interestingly, prefectural (local) subsidies show similar results regarding differential responses from existing and new-build homes. With acknowledging the potential endogeneity of PV adoption subsidies, we find that prefectural subsidies have a significantly positive effect on retrofit installations, but no such effect on new-build installations. An increase in the prefectural subsidy rate of ¥10,000 per case (roughly, a 10% increase) is estimated to increase retrofit installations by about 0.8%, but it has no statistically significant effect on new-build installations.

Table 5 confirms the robustness of our results to the number of lags of the electricity price variable. Replacing $p_{i,t-1}$ in column (4) of Tables 2 and 3 (or equivalently, in column (2) of Table 5) with the current or two- or three-quarter lagged electricity price ($p_{i,t}$, $p_{i,t-2}$, or $p_{i,t-3}$), we find that the results are consistent with those in Tables 2 and 3 discussed above. Owing to the high level of autocorrelation in the electricity price time series, the Akaike and Bayesian information criteria suggest including just one electricity price variable in each specification, as we have done, rather than simultaneously including electricity prices from multiple periods (e.g., $p_{i,t-1}$ and $p_{i,t-2}$).

Lastly, Tables B.2 to B.5 are analogous to Tables 2, 3, B.1 and 5, respectively, except that Tables B.2 to B.5 are estimated with the standard household's average electricity price instead of the marginal electricity price. Overall, the results with the average electricity price are qualitatively similar to those with the marginal electricity price, further confirming the robustness of our findings.[20]

5. Discussion

Across the different IV specifications with covariates in Tables 2, 3 and 5, we robustly find that the effect of electricity price changes is 2.5 to four times larger for retrofit installations than for new-build installations, with the effect on the former highly statistically significant but that on the latter statistically insignificant. We observe a similar and even stronger contrast with respect to the effect of local subsidy changes, although we acknowledge the possible endogeneity of local subsidies (see footnote 16). To the best of our knowledge, this difference between retrofit and new-build installations has not been identified in previous studies on the adoption of low-carbon building technologies, such as solar PV and energy-efficient heating and cooling.

It is worth emphasizing that we observe these contrasting responses to changes in price signals even though new-build homes are much more likely to adopt solar PV than existing homes during the period of our analysis (the adoption rates are 20% and 3%, respectively, as described in Section 3.1). This highlights the importance of distinguishing between the aggregate behavior of each group and the behavior of each group's marginal adopters. Our finding is about the latter: at the margin, retrofitting responds both statistically and economically significantly to changes in price signals, whereas new-build fitting responds little to these changes.

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[20] We also estimate our model using the natural logarithm of the marginal or average electricity price, and the estimated electricity price elasticity of solar PV installations is comparable to that obtained using the marginal or average electricity price.

Table 5
Regression results with different lags.

Panel R: retrofit installations

	(1)	(2)	(3)	(4)
Marginal electricity price$_t$	0.055^{***} (0.020)			
Marginal electricity price$_{t-1}$		0.069^{***} (0.018)		
Marginal electricity price$_{t-2}$			0.059^{***} (0.019)	
Marginal electricity price$_{t-3}$				0.082^{***} (0.024)
Implied electricity price elasticity	1.38	1.73	1.49	2.06
Covariates	Yes	Yes	Yes	Yes
Instruments	Yes	Yes	Yes	Yes

Panel N: new-build installations

	(1)	(2)	(3)	(4)
Marginal electricity price$_t$	0.020 (0.013)			
Marginal electricity price$_{t-1}$		0.019 (0.015)		
Marginal electricity price$_{t-2}$			0.017 (0.013)	
Marginal electricity price$_{t-3}$				0.020 (0.015)
Implied electricity price elasticity	0.50	0.49	0.44	0.51
Covariates	Yes	Yes	Yes	Yes
Instruments	Yes	Yes	Yes	Yes

Notes: In Panel R (Panel N), column (2) reprints the estimated coefficient for the one-quarter lagged marginal electricity price from the IV specification in column (4) of Table 2 (Table 3). Columns (1), (3), and (4) of each panel are also based on this IV specification except that they use the current, two-quarter lagged, and three-quarter lagged marginal electricity prices, respectively, instead of the one-quarter lagged marginal electricity price. The superscripts *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.

5.1. Explaining the contrasting responses

Although it is outside the scope of this study to analyze the reasons for the contrasting responses in detail, we outline some likely mechanisms based on the literature on the energy efficiency gap and, more broadly, behavioral economics (see, e.g., Gillingham et al. (2009) and Gillingham and Palmer (2014) for literature reviews). The literature offers several explanations for households' and firms' seemingly irrational decisions on energy-saving investments. In this study's context where owners of existing homes and buyers of new-build homes behave differently, plausible explanations should relate to differences that are rooted in the two groups' decision-making processes. We consider four such mechanisms: electricity consumption, uncertainty, relative thinking and diminishing sensitivity, and imperfect information.

First, the differential responses to electricity prices may result from the difference in electricity consumption between existing and new-build homes. Roughly speaking, the electricity cost saving from solar PV adoption equals the product of the marginal electricity price and self-consumed PV electricity (Fig. 2). Thus, although higher electricity prices increase the benefit of solar PV adoption for all households, the incremental benefit is larger for households with greater daytime electricity consumption. For detached homes in Japan, which account for almost all residential solar PV installations in the country, household electricity consumption tends to be higher in newer properties (Mitsubishi Research Institute, 2013, p. 58). This implies that new-build installations should be *more* sensitive to electricity price changes than retrofit installations, contrary to our estimation results. Thus, the difference in electricity consumption is unlikely to explain our finding.

The other three mechanisms (uncertainty, relative thinking, and imperfect information) all relate to a fundamental difference between retrofit and new-build installations of many low-carbon building technologies, including solar PV: the timing of a household's technology adoption relative to its home purchase and move. In the case of new-build fitting, a household makes a technology adoption decision at around the time of a home purchase, and the energy-saving technology is implemented during construction, before the household moves in. In contrast, in the case of residential solar PV in Japan, a vast majority of retrofit installations are separate from home purchases in the sense that households install solar PV systems in their current residences rather than in existing properties that they have just purchased (see footnote 10).

When making adoption decisions, new-build buyers have not yet moved in, thus facing greater uncertainty about their future electricity consumption and, consequently, about their potential electricity cost savings from solar PV adoption than owners of existing homes, who know their relevant past electricity bills. Uncertainty about the benefits of low-carbon investments significantly suppresses these investments because of risk or loss aversion (e.g., Hassett and Metcalf, 1993; Anderson and Newell, 2004; Heutel, 2019). Thus, uncertainty may explain the small and statistically insignificant response of new-build installations to electricity prices. However, our estimation results suggest that new-build installations are also insensitive to the *certain* benefit of one-time installation subsidies, indicating that uncertainty is not a primary factor in the differing responses.

Next, the theories of relative thinking and diminishing sensitivity in behavioral economics suggest that a cost saving is perceived as less valuable when it is measured relative to a larger reference value (Thaler, 1980; Tversky and Kahneman, 1981; Azar, 2007; Bushong et al., 2020). In other words, "(a) price cut of $10 feels smaller to a person when she is considering spending $1000 on a product than when she is considering spending $100" (Bushong et al., 2020). New-build fitting accompanies a home purchase, which requires much higher spending than a solar PV system (or any other low-carbon building technology), whereas retrofitting is mostly independent of a home purchase in our data (as described in Section 3.1). Thus, if a buyer of a new-build property perceives a solar PV investment as part of the total spending relating to the entire home purchase process, the buyer likely compares the incremental benefit of solar PV adoption due to increased electricity prices or subsidies to a much larger reference value than a potential retrofitter does without an accompanying home purchase. Then, the theories of relative thinking and diminishing sensitivity suggest that the new-build buyer perceives the incremental benefit of solar PV adoption as less valuable than the potential retrofitter does, leading to our estimation results.

Finally, owners of existing homes may be less informed about solar PV than buyers of new-build homes. Like uncertainty, imperfect information curtails households' and firms' investments in energy-saving measures, and conversely, information provision alleviates this problem (e.g., Newell and Siikamäki, 2014; Davis and Metcalf, 2016; Gillingham and Tsvetanov, 2018; Sadayuki and Arimura, 2021). Households may receive useful information about the value of solar PV adoption during the home purchase process (e.g., through recommendations by architects or real estate agents). For buyers of new builds, the information thus obtained may be more crucial in their decision making than changes in electricity prices or subsidies, making them relatively insensitive to these changes. In comparison, owners of existing homes who are not active in the housing market – as discussed, a vast majority of retrofits result from such homeowners – likely have fewer chances to be well informed about solar PV. Thus, for these owners of existing homes, electricity prices and subsidies are relatively salient pieces of information in their decision-making, leading to the significantly positive and large marginal effects of these price signals on retrofit installations.

5.2. Policy implication

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 et al., 2015). Specifically, our results imply that providing greater support for retrofitting than for new-build fitting improves the cost-effectiveness of solar PV subsidies because retrofit installations are more likely to be the marginal cases that would not have occurred without these subsidies. The same argument can apply to other energy-saving building technologies to the extent that similar contrasts exist between retrofit and new-build installations of these technologies. Essentially, the distinction between existing and new-build homes is an easily observable house(hold) characteristic along which tagging and targeting can be implemented to improve cost-effectiveness. This is parallel to price discrimination, in which a firm makes its product's price dependent on observable consumer characteristics, such as age, to increase profits.

Simple, illustrative simulations based on Japan's FIT scheme (see Section 2.1 and Fig. 2) can show the possible impact of such a policy change. Higher electricity prices are analogous to higher FIT rates in the sense that they both increase the recurring financial benefits of solar power generation. About 30% of the electricity generated by a residential solar PV system is domestically consumed, and the rest is sold to the grid. Thus, the financial benefit from a ¥1/kWh increase in the marginal electricity price is roughly equivalent to that from a ¥0.43($\approx 0.3/0.7$)/kWh increase in the FIT rate, assuming that the electricity price and FIT rate changes last for the same period of time.

Based on our point estimates and data on the actual FIT scheme and solar PV adoption in Japan,[21] we compare retrofitting with new-build fitting in terms of the marginal cost-effectiveness of FIT spending, which is defined as the increase in the aggregate solar PV capacity per unit of additional FIT spending when the FIT rate (per kWh) for the corresponding installation type (i.e., retrofitting or new-build fitting) is marginally increased. In other words, if an installation type has a higher marginal cost-effectiveness, using additional FIT funds to increase the FIT rate for this type is more "productive" in inducing solar PV diffusion. Back-of-the-envelope calculations show that the marginal cost-effectiveness of FIT spending is on average 37% higher for retrofitting than for new-build fitting.[22] This difference suggests that offering a higher FIT rate for retrofit installations than for new-build installations can improve the overall cost-effectiveness of the FIT program relative to offering a uniform FIT rate for both installation types.

A similar exercise with one-time installation subsidies shows an even larger disparity in the marginal cost-effectiveness, as suggested by the difference in the estimated effects of one-time prefectural subsidies on the two installation types (Tables 2 and 3).

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[21] We use the point estimates from the IV specifications with covariates (i.e., columns (4) and (5) in Tables 2 and 3 and columns (1), (3) and (4) in Table 5), the actual FIT rate (¥38/kWh), and installation statistics for fiscal year 2013 (i.e., 151,533 retrofit installations with an average capacity of 4.81 kWh and 109,509 new-build installations with an average capacity of 4.17 kWh). We assume for simplicity that households' responsiveness to FIT rate changes is the same as that to electricity price changes.

[22] We take the average of five sets of simulation results that are based on each of the five IV specifications with covariates in Tables 2, 3 and 5.

We focus on FITs in the above numerical example simply because the estimated effects of one-time subsidies are less reliable owing to the potential endogeneity of the local subsidy variables (as discussed in Section 3). From the perspective of policy design and implementation, differentiating subsidy rates between retrofit and new-build installations is simpler and, thus, more feasible under one-time subsidy schemes than under FIT schemes.

6. Conclusion

This study examines the effects of financial incentives, particularly electricity prices, on the adoption of energy-efficient or renewable-energy building technologies, focusing on rooftop residential solar PV diffusion in Japan between 2009 and 2014. We overcome two econometric hurdles (i.e., the limited 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 the subsequent shutdown of all nuclear power plants in Japan as a natural experiment. This shutdown forced electricity companies to substitute nuclear power with more expensive fossil fuels and, thus, led to sizable, exogenous, and regionally varying increases in electricity generation costs, which allow us to identify the causal effect of electricity prices on solar PV adoption.

From an econometric viewpoint, our results indicate the general importance of instrumenting for electricity prices when studying factors in the adoption of electricity-cost-saving technologies, even though electricity prices are often assumed to be exogenous in the literature. We find that not instrumenting for electricity prices with cost-shifter IVs biases the estimated effect of electricity prices on solar PV adoption downward by about 40%–60%. During the period of our analysis, both electricity prices and energy-saving investments increased significantly, and we argue that this downward bias is mainly attributable to their interdependence.

Our estimations provide strong and coherent evidence for a phenomenon left unattended in the literature. Namely, retrofit installations in existing homes are much more sensitive to changes in financial incentives, such as electricity prices and subsidies, than installations in new-build homes are. Taking the average over our preferred IV specifications, we estimate the elasticity of retrofitting with respect to the electricity price is 1.6 and highly statistically significant, whereas the corresponding elasticity of new-build fitting is 0.5 and statistically indistinguishable from zero.

This finding provides insights that can go beyond solar PV adoption and apply more generally to the adoption of low-carbon building technologies (e.g., advanced heating and cooling). This is likely to be the case if the contrasting responses result from differences in the decision-making processes for retrofit and new-build installations of these technologies. We refer to the literature on the energy efficiency gap and behavioral economics and argue that whether a household's technology adoption accompanies a home purchase or not is a key factor in its response to financial incentives because of, for example, relative thinking and imperfect information. We leave it to future research to investigate whether retrofitting and new-build fitting of other low-carbon building technologies exhibit similar patterns in terms of their sensitivity to financial incentives.

In our dataset, it is impossible to distinguish between a retrofit that occurs alongside the purchase of an existing property and one that occurs independently of a home purchase. Whereas the former category represents only a small share (i.e., less than 10%) of retrofits in our data, it likely accounts for a much larger fraction of retrofits in other places where trading of existing properties is common (e.g., North America and Europe). Thus, an interesting empirical question for further research is whether retrofitting at the time of a home purchase is similar to new-build fitting or to retrofitting without an accompanying home purchase (or to neither of them) in terms of the effects of financial incentives on technology adoption.

A policy implication of our study is the importance of targeting retrofits when designing financial incentive schemes (e.g., FITs and installation subsidies) for low-carbon building technologies. Many of these schemes, including the one we analyze in this study, treat retrofitting and new-build fitting uniformly. Our results suggest that targeting existing homes by, for example, setting a higher subsidy rate for retrofit installations than for new-build installations is a simple approach, in terms of policy design and implementation, to improve the cost-effectiveness of these subsidies. Simulations based on our empirical setting of residential solar PV in Japan show that the marginal effect of FIT spending is 37% higher for retrofit installations than for new-build installations.

Appendix A. A model of interdependence between electricity prices and energy-saving investments

This section presents a model of interdependence between electricity prices and investments in energy-saving technologies. This model provides an explanation for the downward bias that we observe in the estimated effects of electricity prices on solar PV installations when electricity prices are not instrumented with cost-shifter IVs.

Let q denote the economy-wide demand for grid electricity (i.e., the electricity received via the electricity grid), which is given by

$$q = d_0 - d_1 p - d_2 z + \epsilon_q, \tag{A.1}$$

where p is the unit price of grid electricity, z is the aggregate level of firms' and households' investments in technologies that save grid electricity, such as solar PV systems and energy-efficient machines and appliances, and ϵ_q is the error term. It is natural to assume $d_1 > 0$ and $d_2 > 0$, so the grid electricity demand curve drawn on the qp plane is downward sloping and shifts down through energy-saving investments.

Because the electricity cost saving from reducing grid electricity consumption increases with the grid electricity price, higher electricity prices induce more energy-saving investments, as modeled in the following equation:

$$z = a_0 + a_1 p + \epsilon_z, \tag{A.2}$$

where $a_1 > 0$. The error term ϵ_z captures other factors that affect z.

Given that electricity prices were highly regulated in Japan during the period of our analysis (Section 2.2), the monopolistic electricity company sets the electricity price (with the government's approval) by considering firms' and households' energy-saving investments z and the electricity generation cost c:

$$p = b_0 - b_1 z + b_2 c + \epsilon_p, \tag{A.3}$$

where $b_1 > 0$ and $b_2 > 0$. In other words, more energy-saving investments by firms and households lead the electricity company to set a lower electricity price (because these investments shift the grid electricity demand curve downward, as modeled in Eq. (A.1)), and a higher electricity generation cost results in a higher electricity price. The error term ϵ_p captures other determinants of p. The electricity company commits to meeting all the demand that arises at the set price.

Solving Eqs. (A.2) and (A.3) for p gives the equilibrium electricity price p^*:

$$p^* = \frac{b_0 - a_0 b_1 + b_2 c - b_1 \epsilon_z + \epsilon_p}{1 + a_1 b_1}. \tag{A.4}$$

Thus, p^* is negatively correlated with ϵ_z (i.e., $\mathrm{Cov}(p^*, \epsilon_z) = -\frac{b_1}{1+a_1 b_1}\mathrm{Var}(\epsilon_z) < 0$).

Econometrically, this negative correlation means that if we observe data points for z and p and estimate Eq. (A.2) by OLS, then the OLS estimator of a_1 suffers a downward bias. Eq. (A.4) also suggests that the electricity generation cost c can serve as an instrument for p when estimating Eq. (A.2).

Appendix B. Additional tables

See Tables B.1–B.5.

Table B.1
Regression results: all installations.

	(1)	(2)	(3)	(4)	(5)
Marginal electricity price$_{t-1}$	0.030**	0.058***	0.028**	0.059***	0.055***
	(0.012)	(0.015)	(0.011)	(0.016)	(0.016)
ln(Cumulative solar PV installations)$_{t-1}$			0.084	−0.029	−0.037
			(0.21)	(0.20)	(0.20)
ln(Detached homes without solar PV)$_{t-1}$			3.47**	3.18**	3.19**
			(1.47)	(1.39)	(1.37)
ln(Housing starts)			0.38***	0.39***	0.30**
			(0.096)	(0.094)	(0.13)
ln(Residents' group collection rate)			0.28**	0.23*	0.23*
			(0.13)	(0.13)	(0.14)
ln(Total waste recycling rate)			−0.072	−0.090	−0.091
			(0.29)	(0.27)	(0.27)
ln(Population)			−4.21	−5.51	−5.52
			(3.92)	(3.74)	(3.83)
ln(Average wage)			0.40	0.52	0.68
			(0.56)	(0.54)	(0.53)
ln(Average worker)			0.17	−0.057	−0.088
			(1.27)	(1.25)	(1.23)
Implied electricity price elasticity	0.74	1.46	0.71	1.49	1.37
Prefecture-by-quarter fixed effects	No	No	No	No	Yes
Instruments	No	Yes	No	Yes	Yes
p-value of Hansen's J test		0.21		0.59	0.35
Within R^2	0.85	0.85	0.87	0.87	0.87

Notes: The dependent variable is the logarithm of the number of all (i.e., retrofit and new-build) residential solar PV installations. All specifications have 987 observations (47 prefectures over 21 quarters) and include prefecture fixed effects and time (year-quarter) fixed effects. Column (5) also includes prefecture-by-quarter fixed effects (i.e., four quarterly fixed effects for each prefecture). Variables with the subscript $t-1$ are lagged by one quarter. In columns (2), (4) and (5), the electricity price is instrumented with the fossil fuel cost and lagged fossil fuel shares. Cluster-robust standard errors are in parentheses, where the observations are clustered at the prefecture level. The implied electricity price elasticity of solar PV installations is calculated at the sample mean electricity price. The superscripts *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.

Table B.2
Regression results with the average electricity price: retrofit installations.

	(1)	(2)	(3)	(4)	(5)
Average electricity price$_{t-1}$	0.056**	0.099***	0.047**	0.090***	0.082***
	(0.027)	(0.025)	(0.023)	(0.024)	(0.025)
Prefectural subsidy dummy (retrofit)			0.024	0.019	0.0062
			(0.056)	(0.055)	(0.055)
Prefectural subsidy rate (retrofit)			0.00080*	0.00078**	0.00081**
			(0.00040)	(0.00040)	(0.00038)
ln(Cumulative solar PV installations)$_{t-1}$			0.18	0.054	0.061
			(0.27)	(0.25)	(0.25)
ln(Detached homes without solar PV)$_{t-1}$			3.32**	3.04*	2.91*
			(1.65)	(1.58)	(1.60)
ln(Housing starts)			0.33***	0.34***	0.13
			(0.11)	(0.11)	(0.12)
ln(Residents' group collection rate)			0.31*	0.27	0.24
			(0.18)	(0.18)	(0.18)
ln(Total waste recycling rate)			0.14	0.12	0.13
			(0.38)	(0.35)	(0.36)
ln(Population)			−3.86	−5.00	−5.19
			(4.83)	(4.67)	(4.71)
ln(Average wage)			0.59	0.69	0.87
			(0.77)	(0.75)	(0.73)
ln(Average worker age)			0.59	0.38	0.42
			(1.48)	(1.43)	(1.41)
Implied electricity price elasticity	1.38	2.44	1.15	2.22	2.01
Prefecture-by-quarter fixed effects	No	No	No	No	Yes
Instruments	No	Yes	No	Yes	Yes
p-value of Hansen's J test		0.19		0.34	0.68
Within R^2	0.77	0.77	0.79	0.79	0.79

Note: Refer to the notes below Table B.3.

Table B.3
Regression results with the average electricity price: new-build installations.

	(1)	(2)	(3)	(4)	(5)
Average electricity price$_{t-1}$	0.0081	0.019	0.018	0.026	0.029
	(0.011)	(0.017)	(0.014)	(0.019)	(0.019)
Prefectural subsidy dummy (new-build)			−0.00055	0.0000077	0.0018
			(0.028)	(0.027)	(0.028)
Prefectural subsidy rate (new-build)			−0.000013	−0.000027	−0.000084
			(0.00023)	(0.00023)	(0.00023)
ln(Cumulative solar PV installations)$_{t-1}$			−0.19	−0.22	−0.23
			(0.21)	(0.21)	(0.21)
ln(Detached homes without solar PV)$_{t-1}$			4.15***	4.10***	4.05***
			(1.23)	(1.19)	(1.10)
ln(Housing starts)			0.50***	0.50***	0.56***
			(0.094)	(0.091)	(0.15)
ln(Residents' group collection rate)			0.15	0.14	0.17
			(0.12)	(0.12)	(0.14)
ln(Total waste recycling rate)			0.17	0.16	0.12
			(0.24)	(0.23)	(0.23)
ln(Population)			−5.97**	−6.18**	−6.03**
			(2.71)	(2.61)	(2.87)
ln(Average wage)			0.32	0.33	0.41
			(0.39)	(0.37)	(0.37)
ln(Average worker age)			−2.20**	−2.23**	−2.36***
			(0.91)	(0.89)	(0.89)
Implied electricity price elasticity	0.20	0.47	0.45	0.63	0.70
Prefecture-by-quarter fixed effects	No	No	No	No	Yes
Instruments	No	Yes	No	Yes	Yes
p-value of Hansen's J test		0.32		0.70	0.08
Within R^2	0.92	0.92	0.93	0.93	0.93

Notes: Tables B.2 and B.3 are analogous to Tables 2 and 3, respectively, except that Tables B.2 and B.3 are estimated with the standard household's average electricity price instead of the marginal electricity price. In Table B.2 (Table B.3), the dependent variable is the logarithm of the number of retrofit (new-build) residential solar PV installations. All specifications have 987 observations (47 prefectures over 21 quarters) and include prefecture fixed effects and time (year-quarter) fixed effects. Column (5) also includes prefecture-by-quarter fixed effects (i.e., four quarterly fixed effects for each prefecture). Variables with the subscript $t-1$ are lagged by one quarter. In columns (2), (4) and (5), the electricity price is instrumented with the fossil fuel cost and lagged fossil fuel shares. Cluster-robust standard errors are in parentheses, where the observations are clustered at the prefecture level. The implied electricity price elasticity of solar PV installations is calculated at the sample mean electricity price. The superscripts *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.

Table B.4
Regression results with the average electricity price: all installations.

	(1)	(2)	(3)	(4)	(5)
Average electricity price$_{t-1}$	0.046^{**} (0.018)	0.078^{***} (0.020)	0.045^{**} (0.017)	0.078^{***} (0.021)	0.073^{***} (0.021)
ln(Cumulative solar PV installations)$_{t-1}$			0.059 (0.21)	−0.036 (0.20)	−0.045 (0.20)
ln(Detached homes without solar PV)$_{t-1}$			3.47^{**} (1.47)	3.28^{**} (1.40)	3.27^{**} (1.38)
ln(Housing starts)			0.37^{***} (0.095)	0.38^{***} (0.093)	0.29^{**} (0.13)
ln(Residents' group collection rate)			0.29^{**} (0.13)	0.25^{**} (0.13)	0.26^{*} (0.14)
ln(Total waste recycling rate)			−0.066 (0.29)	−0.073 (0.27)	−0.075 (0.27)
ln(Population)			−4.28 (3.92)	−5.20 (3.74)	−5.26 (3.81)
ln(Average wage)			0.40 (0.56)	0.49 (0.53)	0.66 (0.52)
ln(Average worker age)			0.15 (1.27)	−0.019 (1.24)	−0.057 (1.22)
Implied electricity price elasticity	1.13	1.93	1.10	1.93	1.79
Prefecture-by-quarter fixed effects	No	No	No	No	Yes
Instruments	No	Yes	No	Yes	Yes
p-value of Hansen J test		0.18		0.48	0.31
Within R^2	0.85	0.85	0.87	0.87	0.87

Notes: Table B.4 is analogous to Table B.1 except that Table B.4 is estimated with the standard household's average electricity price instead of the marginal electricity price.

Table B.5
Regression results with different lags of the average electricity price.

Panel R: retrofit installations

	(1)	(2)	(3)	(4)
Average electricity price$_t$	0.074^{***} (0.028)			
Average electricity price$_{t-1}$		0.090^{***} (0.024)		
Average electricity price$_{t-2}$			0.077^{***} (0.024)	
Average electricity price$_{t-3}$				0.10^{***} (0.030)
Implied electricity price elasticity	1.83	2.22	1.90	2.51
Covariates	Yes	Yes	Yes	Yes
Instruments	Yes	Yes	Yes	Yes

Panel N: new-build installations

	(1)	(2)	(3)	(4)
Average electricity price$_t$	0.029^{*} (0.017)			
Average electricity price$_{t-1}$		0.026 (0.019)		
Average electricity price$_{t-2}$			0.023 (0.017)	
Average electricity price$_{t-3}$				0.026 (0.019)
Implied electricity price elasticity	0.71	0.63	0.56	0.63
Covariates	Yes	Yes	Yes	Yes
Instruments	Yes	Yes	Yes	Yes

Notes: Table B.5 is analogous to Table 5 except that Table B.5 is estimated with the standard household's average electricity price instead of the marginal electricity price. In Panel R (Panel N), column (2) reprints the estimated coefficient for the one-quarter lagged average electricity price from the IV specification in column (4) of Table B.2 (Table B.3). Columns (1), (3), and (4) of each panel are also based on this IV specification except that they use the current, two-quarter lagged, and three-quarter lagged average electricity prices, respectively, instead of the one-quarter lagged average electricity price. The superscripts *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.

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