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Extreme Temperatures and Health Impacts: Lights and Shadows of the Diffusion of Renewable Energy

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Extreme Temperatures and Health Impacts:
Lights and Shadows of the Diffusion of Renewable Energy

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Abstract

Rising extreme temperatures and increasing energy costs pose growing public health risks by constraining households' ability to maintain safe indoor environments. This study examines whether residential solar photovoltaics (PV) can mitigate these risks by reducing households' dependence on grid electricity. Using prefecture-by-month mortality and morbidity data from Japan for 2009–2014, a period marked by a sharp increase in electricity prices following the 2011 Great East Japan Earthquake, we find that residential solar PV adoption significantly reduces temperature-related mortality and morbidity, particularly among individuals aged 65 and older. These findings highlight the role of renewable energy in strengthening climate resilience and underscore the importance of policies that expand access to solar PV to protect vulnerable populations. However, because adoption remains concentrated among higher-income households, associated health benefits may accrue unevenly, highlighting the need for targeted policies.

1. Introduction

Climate change has increased exposure to extreme temperatures, intensifying mortality risks worldwide. The World Health Organization projects that climate-related health costs attributable to extreme temperatures will reach US$2–4 billion annually by 2030 (WHO, 2023).[1] A large literature documents a U-shaped relationship between temperature and mortality, with both extreme heat and extreme cold increasing mortality risk (Heal and Park, 2016).

Households mitigate temperature-related health risks primarily through climate-

[1] For more detailed information, refer to the 2023 WHO fact sheets on climate change: https://www.who.int/news-room/fact-sheets/detail/climate-change-and-health

control technologies, most notably air conditioning (Barreca et al., 2016). The effectiveness of such technologies, however, depends critically on access to affordable electricity. Rising energy prices—driven by supply disruptions, inflationary pressures, and geopolitical shocks—have increased the cost of maintaining safe indoor environments. Recent evidence shows that higher electricity prices increase mortality during periods of temperature extremes (Neidell et al., 2021; Chirakijja et al., 2024), underscoring the importance of energy affordability for public health.

This paper examines whether residential solar photovoltaics (PV) mitigate mortality and morbidity risks by reducing households' dependence on grid electricity. By enabling on-site electricity generation, solar PV can partially insulate households from energy price increases and improve households' ability to maintain safe indoor environments when exposed to extreme temperatures. While the environmental benefits of renewable energy adoption are well established, its role as a climate adaptation and public health intervention remains largely unexplored.

We study this question using prefecture-by-month mortality and morbidity data from Japan for 2009–2014. Our empirical setting is shaped by the sharp and persistent increase in electricity prices following the 2011 Great East Japan Earthquake, which led to widespread nuclear power shutdowns. This episode provides a salient backdrop in which households faced rising energy costs, allowing us to examine whether access to residential solar PV mitigates the health impacts of temperature exposure.

We find that residential solar PV adoption significantly reduces mortality and morbidity during periods of extreme temperatures, with effects concentrated among individuals aged 65 and older. These results highlight distributed renewable energy as an important source of climate resilience when households face rising energy costs. At the same time, solar PV adoption is disproportionately concentrated among higher-income households, suggesting that the health benefits of renewable energy may accrue unevenly and raise concerns about inequality.

This paper contributes to the literature in three ways. First, it identifies residential solar PV as a previously underexplored channel of adaptation to climate-related health risks. Second, it complements existing work on energy prices and health by showing that self-sufficient electricity generation can mitigate the health impacts of temperature exposure in settings with high energy costs. Third, it informs energy and climate policy by demonstrating that renewable energy deployment has public health implications beyond emissions reduction.

The remainder of this paper is organized as follows: Section 2 presents the literature review; Section 3 provides the empirical methodology and data; Section 4 discusses the estimation results; and Section 5 draws conclusions.

2. Literature Review

A large literature documents a robust, non-linear relationship between temperature and mortality, characterized by a U-shaped pattern in which both extreme heat and extreme cold increase mortality risk. Global evidence from Gasparrini et al. (2015) shows that temperature extremes contribute substantially to excess deaths across diverse climatic contexts. Micro-level studies further document pronounced vulnerability among older populations, who face elevated mortality risks during both heatwaves and cold spells (Anderson and Bell, 2009). This literature establishes temperature exposure as a major public health concern and motivates the search for effective adaptation mechanisms.

A related strand of research highlights the importance of energy affordability in shaping temperature-related health outcomes. Households rely on energy-intensive climate-control technologies to mitigate exposure to temperature extremes, but rising energy costs can constrain their ability to maintain safe indoor environments. Recent studies show that higher electricity prices increase mortality, particularly among economically vulnerable households (Neidell et al., 2021; Chirakijja et al., 2024). These findings underscore energy affordability as a key mediator between temperature exposure and health, especially during periods of extreme weather.

Another body of work emphasizes the protective role of climate-control technologies, most notably air conditioning, in reducing heat-related mortality. Barreca et al. (2016) attribute much of the long-run decline in heat-related deaths in the United States to the diffusion of air conditioning, while Sera et al. (2020) document similar protective effects across multiple countries. However, reliance on grid-based, energy-intensive technologies introduces a vulnerability when electricity prices rise, potentially limiting households' ability to operate cooling or heating systems during periods of temperature stress. This tension highlights the limits of conventional adaptation strategies that depend on stable and affordable grid electricity.

In contrast, the literature on renewable energy has primarily emphasized health benefits through environmental channels, such as reductions in air pollution. For example, Rivera et al. (2024) show that solar deployment displaces coal generation and reduces hospital admissions linked to air pollution exposure. While recent work has begun to recognize the importance of resilient and clean energy systems for coping with climate-related health risks (Seddighi et al., 2023), evidence on whether renewable energy mitigates temperature-related mortality by improving household energy affordability remains limited.

This paper contributes to the literature by examining residential solar photovoltaics as a household-level adaptation to temperature-related health risks. We focus on whether on-site electricity generation can reduce mortality and morbidity by easing households' dependence on grid electricity during periods of extreme temperature exposure. Using the sharp increase in electricity prices following the 2011 Great East Japan Earthquake as a salient background context, our analysis complements existing work on energy prices and health while shifting attention from the environmental co-benefits of renewable energy to its potential role as a public health intervention.

3. Methodology and Data

3.1 Methodology

Residential solar PV adoption is potentially endogenous to health outcomes. Households that install solar PV may differ systematically from non-adopters along unobserved dimensions, such as housing quality, energy efficiency investments, environmental preferences, or broader climate adaptation strategies, all of which may independently affect mortality and morbidity. As a result, ordinary least squares estimates of the effect of solar PV adoption on health outcomes are likely to be biased.

To address this concern, we employ an instrumental variable (IV) strategy within a two-stage least squares (2SLS) framework, exploiting exogenous variation in incentives for residential solar PV adoption. Our empirical specification builds on the climate–health literature by allowing for non-linear temperature effects through temperature bins and by interacting temperature exposure with solar PV adoption to capture its moderating role.

We estimate the following equation:

$$(1) \qquad \mathrm{Y}_{itm} = \sum_{n=1}^{N} \alpha_n Temp_{itm} + \sum_{n=1}^{N} \beta_n Temp_{itm} \times SolarPV_{itQ(m)} + \gamma_1 SolarPV_{itQ(m)} + \mathbf{Z}_{itm}\delta + \theta_{im} + \lambda_{it} + \nu_{mt} + \varepsilon_{itm},$$

where Y_{itm} denotes the logarithm of the mortality (or morbidity) rate in prefecture i, month m, and year t, $Temp_{itm}$ represents the number of days in month m with daily mean temperatures falling into the n-th temperature bin. In the baseline specification, temperature bins are defined as below 15°C, 15–30°C, and above 30°C.[2]

[2] From a statistical perspective, we categorize daily mean temperature into three bins (<15°C, 15–30°C,

$SolarPV_{itQ(m)}$ is the logarithm of cumulative residential solar PV installations in prefecture i as of the most recent quarter preceding month m. Specifically, for months January–March, this variable corresponds to the fourth quarter of year $t-1$; for April–June, the first quarter of year t; for July–September, the second quarter of year t; and for October–December, the third quarter of year t. This timing reflects information available to households when making electricity consumption decisions while avoiding simultaneity with monthly mortality outcomes.[3]

The vector $\mathbf{Z}_{itm}$ includes time-varying controls for weather conditions—mean monthly precipitation, wind speed, and snow depth—as well as ambient air pollution measures, including sulfur dioxide (SO_2) and suspended particulate matter (SPM), all discretized into decile bins. Income is likewise discretized into deciles to flexibly account for nonlinear income effects on health.

We include a rich set of fixed effects to account for unobserved heterogeneity across space and time. Prefecture-by-year fixed effects (λ_{it}) absorb prefecture-specific, time-varying determinants of health, such as changes in demographic composition, income distribution, healthcare capacity, and hospital quality. Prefecture-by-month fixed effects (θ_{im}) control for area-specific seasonal factors, including persistent differences in climate patterns and regionally targeted policies such as energy assistance programs for low-income households. Year-by-month fixed effects (ν_{mt}) capture time-varying shocks common to all prefectures, including macroeconomic conditions and nationwide energy and climate policies. Standard errors are clustered at the prefecture level.

To address the endogeneity of residential solar PV adoption, we instrument $SolarPV_{itQ(m)}$ using the interaction of long-run global solar radiation and lagged electricity prices. Specifically, the instrument is constructed as the product of average summer global solar radiation over the preceding five years and the electricity price in the same quarter of the previous year.

This instrument satisfies relevance for two reasons. First, global solar radiation directly affects the productivity and economic return of solar PV systems, making

and >30°C) to flexibly capture non-linear temperature–health relationships while limiting overfitting. Consistent with He and Tanaka (2023), we find no statistically significant differences in effects within the 15–30°C range, which we therefore use as the reference category. This allows the estimated coefficients to be interpreted as the relative effects of colder (<15°C) and hotter (>30°C) temperatures on mortality and morbidity. Results are robust to alternative specifications that use finer temperature bins.

[3] Since solar PV installation data is available only at the quarterly level, using past values ensures proper alignment with the mortality data, which is recorded monthly. Without this adjustment, estimates for months like April may be misattributed, as the reported solar PV value for April actually represents cumulative installations from April to June. By lagging the solar PV variable, the analysis correctly reflects the exposure period, preventing potential misestimation of its effect on the temperature-mortality (or morbidity) relationship.

adoption more attractive in regions with higher long-run solar potential. Using a multi-year average smooths short-term weather fluctuations and reflects the information relevant for household investment decisions.[4] Second, higher electricity prices increase the potential savings from self-generated electricity, strengthening incentives for PV adoption.[5] Together, long-run solar radiation provides cross-sectional variation across prefectures, while lagged electricity prices introduce time variation, and their interaction captures changes in the economic attractiveness of solar PV.

The exclusion restriction is supported by the construction of the instrument and the fixed-effects structure of the model. Long-run global solar radiation reflects predetermined geographic variation in solar potential and is plausibly unrelated to short-run health shocks conditional on temperature exposure and weather controls. While geographic differences in solar radiation may correlate with broader regional characteristics—such as climate, industrial structure, urbanization, or healthcare capacity—these factors are either time-invariant or evolve slowly over time and are absorbed by prefecture-by-year fixed effects. Prefecture-by-month fixed effects further control for persistent seasonal patterns within prefectures, while year-by-month fixed effects capture common national shocks. Electricity prices are lagged by one year to rule out contemporaneous effects on health outcomes. Conditional on these controls and fixed effects, the interaction between long-run solar radiation and lagged electricity prices affects mortality and morbidity only through its impact on residential solar PV adoption.

This IV strategy allows us to isolate the causal effect of residential solar PV adoption on the health impacts of temperature exposure.

3.2 Data

3.2.1 Mortality, Morbidity, Household Characteristic and Electricity Price Data

Monthly mortality data, household characteristics—including income—and air pollution measures, as well as electricity price data, are obtained from He and Tanaka (2023).[6]

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[4] Residential solar PV adoption exhibits substantial cross-prefecture variation that is positively correlated with long-run global solar radiation. Appendix Figure A1 illustrates the spatial distribution of cumulative residential solar PV installations, while Appendix Figure A2 visualizes their relationship with global solar radiation.

[5] Electricity prices in Japan exhibit substantial time variation following the 2011 Fukushima nuclear accident; Appendix Figure A3 provides a visual illustration of this pattern using data from Neidell et al. (2021).

[6] Following He and Tanaka (2023), we exclude three prefectures—Iwate, Miyagi, and Fukushima—from

Monthly morbidity data are drawn from the Report on the Medical-Care System for the Latter-Stage Elderly, an administrative dataset compiled by Japan's Ministry of Health, Labour and Welfare (MHLW), which covers medical care utilization and expenditures for individuals aged 65 and older and are available from March 2010 onward.[7]

3.2.2 Residential Solar PV Installation Data

We use quarterly data on residential solar PV installations from the Japan Photovoltaic Energy Association (JPEA), which administered a nationwide subsidy program for household solar PV systems. The program operated from January 2009 through March 2014 and provided financial support to households installing residential PV systems in all prefectures. Households were required to apply for the subsidy prior to installation, and more than 96 percent of applications were approved, resulting in completed installations.

The number of approved subsidy applications is reported by the government and widely used as the official measure of residential solar PV installations during this period. Given the near-universal approval rate and nationwide coverage, the subsidy data capture the vast majority of residential PV installations in Japan over our sample period. We therefore interpret approved applications as a close proxy for actual installations.

Unlike Kiso et al. (2022), who focus on application timing to study adaptation behavior, we use approval-based installation data to measure the presence of solar PV systems in operation. This distinction is important for our analysis, which examines how access to installed residential solar PV moderates the health impacts of temperature exposure rather than the timing of adoption decisions.

All installation measures are lagged to ensure that PV systems are in place prior to the mortality and morbidity outcomes studied.

3.2.3 Weather Data

Daily weather data are obtained from the Agro-Meteorological Grid Square Data published by the National Agriculture and Food Research Organization (NARO). These data provide high-resolution (1-km grid) coverage of meteorological conditions across Japan. Consistent with the climate–health literature, we use daily mean temperature to construct temperature exposure measures and include precipitation, wind speed, and snow

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our primary analysis, as these regions were directly affected by the earthquake and tsunami, making them less comparable to other prefectures.

[7] The Medical-Care System for the Latter-Stage Elderly primarily covers individuals aged 75 and older; however, individuals aged 65–74 who meet specified disability criteria are also included.

depth as control variables. Global solar radiation is also drawn from this source and is used in the construction of the instrumental variable for residential solar PV adoption.

To align the grid-level weather data with prefecture-level outcomes, we aggregate daily observations to the prefecture level using official mesh-to-municipality correspondence tables provided by the Statistics Bureau of Japan. Monthly measures are then constructed by summing daily temperature exposures within each temperature bin and averaging other weather variables over the month.

The analysis covers the period from 2009 to 2014. To account for differences in demographic composition across prefectures and over time, we construct an age-adjusted mortality rate by weighting age-specific mortality rates for three age groups (0–19, 20–64, and 65 and older) by each group's population share. This adjustment facilitates comparisons across regions and periods without confounding from changes in age structure. In addition, we estimate age-specific mortality rates separately for each group to examine heterogeneity in temperature-related health effects.

During the sample period, the average monthly mortality rate per 100,000 population is 2.1 for individuals aged 0–19, 11.6 for those aged 20–64, and 317.3 for those aged 65 and older, with elderly individuals accounting for more than 95 percent of total deaths. The distribution of daily mean temperatures within a typical month indicates that, on average, 15.5 days fall below 15°C, 15.4 days fall within the 15–30°C range, and 0.1 days exceed 30°C.[8] The average cumulative number of residential solar PV installations per quarter is 12,351 units. The average monthly morbidity, measured as medical care expenditures per 1,000,000 insured individuals aged 75 and older (including individuals aged 65–74 with qualifying disabilities), is 76,701.6 yen over the period from March 2010 onward. Summary statistics for key variables are reported in Table 1.[9]

4. Empirical Results

4.1 OLS Estimates: The Impact of Temperature on Mortality

The estimation sample covers 44 of Japan's 47 prefectures; three prefectures severely affected by the 2011 Great East Japan Earthquake and tsunami (Iwate, Miyagi, and Fukushima) are excluded, as their post-disaster conditions render them not comparable to

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[8] To apply the temperature bin method, we standardize each month to have 31 days, ensuring consistency across all months in the dataset.

[9] For reference, the mean monthly morbidity of 76,701.6 yen per 1,000,000 insured individuals corresponds to approximately USD 500 per 1,000,000 insured individuals, using an exchange rate of 150 yen per U.S. dollar.

the rest of the country (see footnote 6). Table 2 presents ordinary least squares estimates of the relationship between temperature exposure and mortality. All specifications include the full set of control variables and fixed effects described in Section 3. The temperature bin covering 15–30°C is omitted as the reference category, consistent with prior evidence that mortality effects are relatively flat over this range (He and Tanaka, 2023).

Column (1) reports estimates using the age-adjusted mortality rate, which accounts for differences in population age composition across prefectures and over time. We find a statistically significant and economically meaningful response to temperature extremes. An additional day with a daily mean temperature below 15°C increases the age-adjusted mortality rate by 0.14 percent, while an additional day above 30°C increases mortality by 0.43 percent. Figure 1 illustrates the estimated temperature–mortality relationship and corresponding 95 percent confidence intervals.[10]

Columns (2)–(4) report age-specific estimates for individuals aged 0–19, 20–64, and 65 and older, respectively. The results indicate that both cold- and heat-related mortality effects are concentrated among individuals aged 65 and older. In contrast, estimates for younger age groups are small and statistically insignificant. These patterns closely mirror the age-adjusted results and reflect the dominant contribution of the elderly population to overall mortality during periods of temperature extremes.

4.2 2SLS Estimates: The Effect of Residential Solar PV Installations on the Temperature–Mortality Relationship

Table 3 presents the two-stage least squares estimates of the interaction between temperature exposure and residential solar PV adoption. The results indicate that solar PV adoption significantly attenuates the mortality effects of extreme heat. Specifically, the interaction between solar PV and temperatures above 30°C is negative and statistically significant for both the age-adjusted mortality rate and the mortality rate among individuals aged 65 and older. In contrast, we find no statistically significant interaction effects at cold temperatures. Consistent with the baseline OLS results in Table 2, we also find no significant effects for younger age groups. The first-stage results indicate that the interaction between long-run global solar radiation and lagged electricity prices is a strong predictor of residential solar PV adoption, with F-statistics well above conventional thresholds (see Appendix Table A1).

Figure 2 plots the estimated interaction effects between temperature exposure and

[10] As a robustness check, Appendix Figure A4 illustrates the OLS relationship between temperature and mortality using finer temperature bins, showing a similar U-shaped pattern.

residential solar PV adoption across alternative estimation methods and fixed-effect structures. The negative interaction between solar PV and temperatures above 30°C is robust across both two-way and multi-way fixed-effect specifications in the IV estimates, although the magnitude is larger under the two-way specification and attenuated when the more demanding multi-way fixed effects are included. Interaction effects at cold temperatures remain small and statistically insignificant across specifications. Differences between OLS and IV estimates underscore the importance of accounting for endogenous solar PV adoption.

The asymmetry between heat and cold effects is robust across specifications.[11] Taken together, these findings indicate that residential solar PV adoption moderates the health impacts of temperature exposure primarily at high temperatures, while its scope for affecting cold-related mortality appears limited.

4.3 Placebo and Heterogeneity Analyses

To assess whether the estimated effects of residential solar PV adoption reflect temperature-related health mechanisms rather than unobserved confounding, we conduct a series of placebo and heterogeneity analyses for the population aged 65 and older. Table 4 reports the placebo test results, and Table 5 presents the heterogeneity analyses.

We begin with a placebo test based on cause-specific mortality. Table 4 compares cardiovascular mortality, which is closely linked to temperature exposure, with accident-related mortality, which is unlikely to be affected by either temperature extremes or solar PV adoption. The results show that residential solar PV significantly attenuates the heat-related increase in cardiovascular mortality, while no statistically significant effects are observed for accident-related deaths. This contrast supports the validity of our identification strategy and suggests that the estimated effects operate through temperature-related health risks rather than unrelated confounding factors.

We next examine heterogeneity in the effects of residential solar PV adoption. Table 5 reports results by climatic conditions and electricity price changes. Columns (1) and (2) examine heterogeneity by climatic conditions. The mitigating effect of solar PV on heat-related mortality is concentrated in warmer prefectures, defined based on average summer temperatures, where exposure to extreme heat and cooling demand are greater.

[11] Our results are robust to alternative constructions of the instrumental variable, including using four-year versus five-year averages of global solar radiation and alternative measures of electricity prices. Corresponding estimates are reported in Appendix Table A2. The estimated effects are also robust to alternative measures of residential solar PV adoption, including scaling installations by housing units or households; corresponding results are reported in Appendix Table A3.

In cooler prefectures, the estimated interaction effects are smaller and statistically insignificant, indicating more limited scope for solar PV to affect mortality where extreme heat is less prevalent.

Columns (3) and (4) report heterogeneity by electricity price changes following the 2011 nuclear power shutdown. We find stronger protective effects of solar PV in prefectures that experienced larger increases in electricity prices, whereas effects are weaker and statistically insignificant in regions with smaller price changes. This pattern is consistent with greater benefits from self-generated electricity when grid electricity becomes more expensive.

Taken together, these heterogeneity results indicate that the health benefits of residential solar PV are concentrated in settings where exposure to extreme heat is greater and electricity costs are higher—conditions under which electricity-dependent cooling is most critical.

Finally, we document important distributional and mechanism-related patterns. Residential solar PV adoption is strongly positively associated with income, suggesting that access to PV is disproportionately concentrated in higher-income areas and has the potential to widen health disparities as climate risks intensify.[12]

We also examine suggestive evidence on potential mechanisms. We find that, during periods of high temperatures, residential solar PV adoption is associated with lower reliance on purchased electricity, indicating reduced dependence on grid electricity when cooling demand is high. This pattern is consistent with residential solar PV easing constraints on electricity-intensive cooling during hot weather.[13]

4.4 Robustness: Morbidity Outcomes

To assess whether the protective effects of residential solar PV extend beyond mortality, we examine robustness using alternative morbidity outcomes for the population aged 65 and older. Table 6 reports two-stage least squares estimates using medical care

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[12] Using a population-weighted prefecture–quarter panel, we regress the logarithm of cumulative residential solar PV installations on the logarithm of income, controlling for prefecture–year, prefecture–quarter, and year–quarter fixed effects. The estimated coefficient on log income is positive and statistically significant, indicating a modest within-prefecture association between income and residential solar PV adoption ($\beta = 0.098$, SE = 0.039; N = 1,012; 44 prefectures).

[13] This result is based on auxiliary regressions of log purchased electricity consumption on temperature exposure indicators and their interaction with residential solar PV adoption, controlling for electricity prices, income, population, and the full set of fixed effects used in the main analysis. The interaction between high-temperature exposure (days above 30°C) and solar PV adoption is negative and statistically significant ($\beta = -0.0005$, SE = 0.0002; N = 1,012; 44 prefectures). This evidence is intended as suggestive and is not interpreted as causal.

expenditures as outcome variables, including total medical expenditures per person as well as inpatient, outpatient, and dental expenditures.

The results show that exposure to temperatures above 30°C significantly increases overall medical expenditures and inpatient expenditures. Importantly, the interaction between high temperatures and residential solar PV adoption is negative and statistically significant for both total medical expenditures and inpatient expenditures, indicating that higher PV adoption attenuates heat-related increases in medical spending. In contrast, we find no statistically significant interaction effects for outpatient or dental expenditures, which are less directly linked to acute heat-related health conditions.

These findings are consistent with the mortality results and suggest that residential solar PV adoption reduces heat-related health burdens that manifest in more severe medical outcomes requiring inpatient care. The absence of effects for outpatient and dental expenditures further supports the interpretation that the estimated effects operate through temperature-related health risks rather than general changes in health care utilization.

5. Conclusion

This study provides evidence that residential solar photovoltaic (PV) adoption mitigates the adverse health impacts of extreme heat. Using prefecture-by-month data from Japan, we show that solar PV adoption significantly reduces heat-related mortality and morbidity, with effects concentrated among individuals aged 65 and older. In contrast, we find no comparable effects at cold temperatures. This asymmetry reflects the technological nature of solar PV: electricity generation from solar systems is highest during periods of strong sunlight, which coincide with high ambient temperatures and peak demand for electricity-intensive cooling.

Our placebo and heterogeneity analyses further demonstrate that these protective effects are concentrated in cardiovascular mortality, are stronger in warmer prefectures, and are larger in regions facing greater electricity price increases. Together, these patterns indicate that residential solar PV enhances households' ability to cope with heat exposure in settings where access to affordable electricity for cooling is most critical and where the economic value of self-generated electricity is greatest.

At the same time, we document that solar PV adoption is disproportionately concentrated among higher-income households. As a result, the associated health benefits accrue unevenly and may exacerbate existing health inequalities. This distributional dimension is particularly important in aging societies, where vulnerable populations face both heightened exposure to extreme heat and tighter constraints on energy affordability.

Overall, our findings highlight residential solar PV as not only a clean energy technology but also a potentially important climate adaptation and public health intervention. Policies that reduce financial and institutional barriers to solar PV adoption—especially in hotter regions and among lower-income households—may generate substantial health benefits in addition to environmental gains. More broadly, our results underscore the close link between energy policy, climate adaptation, and population health in a warming world.

Finally, the current analysis relies on prefecture-level aggregate data; future research exploiting household-level micro-data, if and when such data become available, would allow for a more precise identification of distributional effects and the mechanisms through which solar PV adoption affects individual health outcomes.

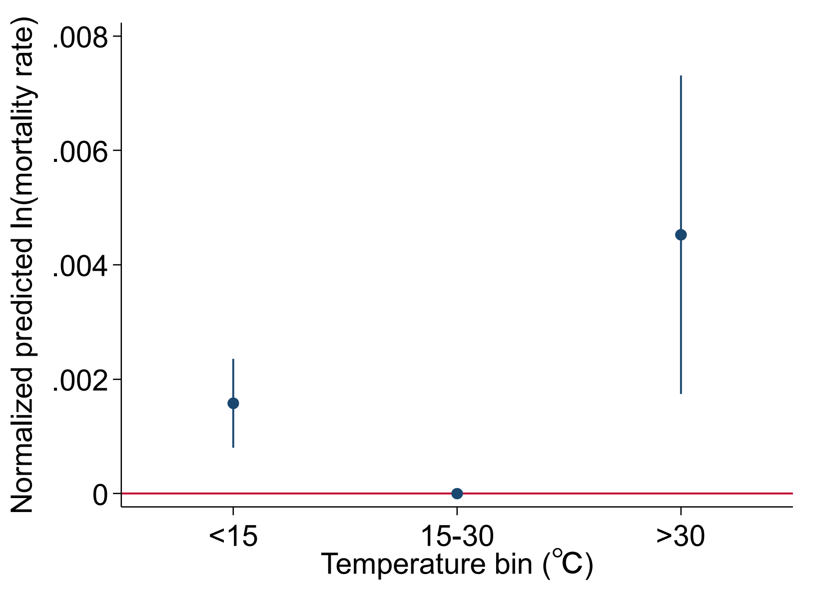

Figure 1: Relationship between temperature and mortality rate

Notes: Estimates display the change in age-adjusted mortality rate under an extra day of exposure to a given ℃ temperature bin relative to a day spent at base temperature bin. The lines are 95 percent confidence intervals.

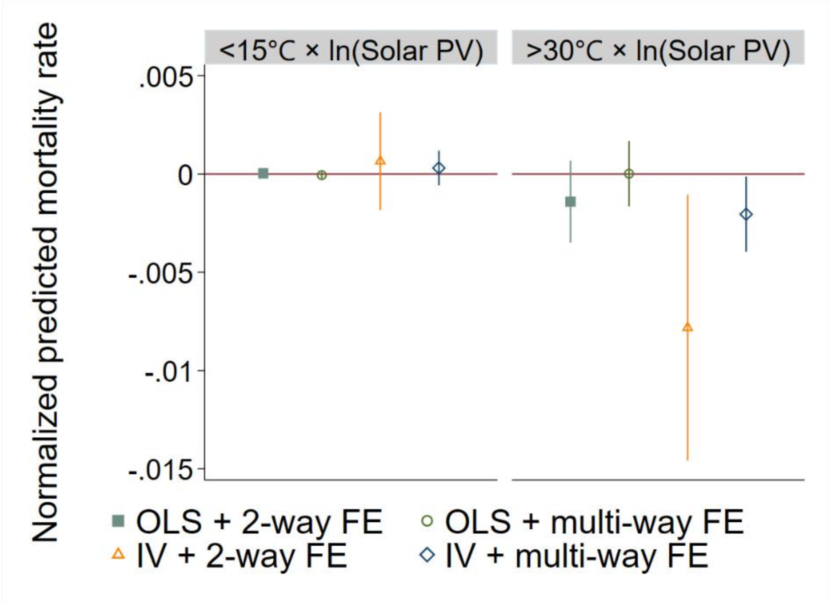

Figure 2: Interaction effects between temperature exposure and residential solar PV adoption

Notes: The figure reports estimated coefficients and 95 percent confidence intervals for interactions between temperature bins and the logarithm of cumulative residential solar PV installations. Estimates are shown for OLS and IV specifications under alternative fixed-effect structures. Two-way fixed effects include prefecture and year-by-month fixed effects. Multi-way fixed effects include prefecture-by-year, prefecture-by-month, and year-by-month fixed effects. The reference temperature category is 15–30°C. Mortality outcomes are normalized for comparability across specifications.

Table 1—Summary statistics for key variables

	Obs.	Mean	SD	Min	Max
Age-adjusted mortality rate (per 100,000)	3,036	83.6	10.4	60.6	125.7
Mortality rate age 0–19 (per 100,000)	3,036	2.1	0.9	0.0	8.4
Mortality rate age 20–64 (per 100,000)	3,036	11.6	2.1	5.0	20.6
Mortality rate age over 65 (per 100,000)	3,036	317.3	38.4	230.3	449.8
<15 °C (days)	3,036	15.5	13.7	0.0	31.0
15–30 °C (days)	3,036	15.4	13.6	0.0	31.0
>30 °C (days)	3,036	0.1	0.6	0.0	13.2
Cumulative residential solar PV installations	3,036	12,351.0	14,238.2	24.0	91,530.0
Morbidity (per 1,000,000 insured in yen)	2,552	76,701.6	8,887.6	57034.3	102081.9

Notes: The unit of observation (Obs.) for mortality rates and temperature exposure is the prefecture–month for the period 2009–2014. The unit of observation for residential solar PV installations is the prefecture–quarter over the same period. Morbidity is measured as medical care expenditures per 1,000,000 insured individuals (in yen) among people aged 75 and older, as well as individuals aged 65–74 with qualifying disabilities, and is available at the prefecture–month level from March 2010 onward.

Table 2—Results of the nonlinear temperature effects on mortality rate

	(1) age-adjusted	(2) 0–19	(3) 20–64	(4) above 65
<15°C	0.0014***	-0.0051	0.0009	0.0015***
	(0.0004)	(0.0068)	(0.0014)	(0.0004)
>30°C	0.0043***	-0.0045	0.0047***	0.0044**
	(0.0015)	(0.0120)	(0.0015)	(0.0017)
Observations	3,036	2,985	3,036	3,036
Num. of prefectures	44	44	44	44
Control var.	Yes	Yes	Yes	Yes
F statistic	9.38	0.34	4.82	10.77
Prob > F	0.0004	0.7136	0.0129	0.0002
Adj. R-squared	0.9591	0.0325	0.7475	0.9543

Notes: ***, **, and * denote 1 percent, 5 percent, and 10 percent significant level, respectively. Column 1 reports result for the age-adjusted mortality rate, while Columns 2–4 present estimates for different age groups, as indicated at the top of each column; see the main text for details. The excluded category is the daily mean temperature in the 15–30°C range. All models include control variables and multiple fixed effects, as described in the main text. Three prefectures that were heavily damaged by the earthquake are excluded from the regressions. All regressions are weighted by population. Standard errors clustered at the prefecture level are reported in parentheses. Since the minimum mortality rate for the younger age group is sometimes 0, taking the natural logarithm leads to the loss of these observations in the estimation.

Table 3—The impact of residential solar PV installation on the temperature-mortality relationship

	(1) age-adjusted	(2) 0–19	(3) 20–64	(4) above 65
<15℃	-0.0008	-0.0240	0.0018	-0.0009
	(0.0041)	(0.0272)	(0.0082)	(0.0045)
<15℃ × PV	0.0003	0.0020	-0.0001	0.0003
	(0.0005)	(0.0034)	(0.0009)	(0.0005)
>30℃	0.0208**	-0.0516	-0.0141	0.0241**
	(0.0097)	(0.1421)	(0.0284)	(0.0117)
>30℃ × PV	-0.0017*	0.0048	0.0019	-0.0020*
	(0.0010)	(0.0154)	(0.0029)	(0.0011)
PV	-0.0244	0.1269	-0.0139	-0.0268
	(0.0308)	(0.3396)	(0.0714)	(0.0327)
Observations	3,036	2,985	3,036	3,036
Num. of prefectures	44	44	44	44
Control var.	Yes	Yes	Yes	Yes
SW F (cold)	37.18	39.52	38.09	37.18
SW F (hot)	54.82	47.19	46.74	54.82
SW F (PV)	9.17	11.13	9.94	9.17

Notes: ***, **, and * denote 1 percent, 5 percent, and 10 percent significant level, respectively. Column 1 reports result for the age-adjusted mortality rate, while Columns 2–4 present estimates for different age groups, as indicated at the top of each column; see the main text for details. The excluded category is the daily mean temperature in the 15–30℃ range. All models include control variables and multiple fixed effects, as described in the main text. Residential solar PV adoption is measured as the logarithm of cumulative residential solar PV installations. We report first-stage Sanderson–Windmeijer (SW) partial F-statistics for each endogenous regressor: cold = 15 °C× PV and hot = 30 °C×PV. Three prefectures that were heavily damaged by the earthquake are excluded from the regressions. All regressions are weighted by population. Standard errors clustered at the prefecture level are reported in parentheses. Since the minimum mortality rate for the younger age group is sometimes 0, taking the natural logarithm leads to the loss of these observations in the estimation. Some observations are lost due to the lagged structure of solar PV installation, as the first few periods in the dataset do not have prior-quarter values available for estimation.

Table 4—Placebo analyses: population aged 65 and older

	(1) Cause of death: CVD	(2) Cause of death: accident
<15℃	-0.0082	-0.0037
	(0.0068)	(0.0179)
<15℃ × PV	0.0013*	0.0003
	(0.0007)	(0.0021)
>30℃	0.0439**	-0.0191
	(0.0216)	(0.0466)
>30℃ × PV	-0.0040*	0.0005
	(0.0022)	(0.0047)
Observations	3,036	3,036
Num. of prefectures	44	44

Notes: The table reports two-stage least squares estimates for the population aged 65 and older. Columns (1)–(2) present a placebo test using cause-specific mortality, comparing cardiovascular deaths with accident-related deaths. All specifications include the full set of control variables and fixed effects described in Section 3, and standard errors are clustered at the prefecture level. Residential solar PV adoption is measured as the logarithm of cumulative residential solar PV installations. The omitted temperature category is 15–30°C. The estimation sample and instrumental variable specification are identical to those used in the baseline IV results. Accordingly, the Sanderson–Windmeijer (SW) first-stage partial F-statistics are the same as those reported in Table 3: 37.18 for the cold-temperature interaction (<15°C × PV), 54.82 for the hot-temperature interaction (>30°C × PV), and 9.17 for the PV term.

Table 5—Heterogeneity analyses: population aged 65 and older

	(1) Climate: warmer	(2) Climate: colder	(3) Energy Price change: large	(4) Energy price change: small
<15℃	-0.0212	0.0031	-0.0160	0.0049
	(0.0184)	(0.0033)	(0.0115)	(0.0031)
<15℃ × PV	0.0024	-0.0003	0.0019	-0.0004
	(0.0019)	(0.0005)	(0.0012)	(0.0004)
>30℃	0.0510***	0.0297	0.0542***	0.0574
	(0.0168)	(0.0446)	(0.0179)	(0.0472)
>30℃ × PV	-0.0047**	-0.0024	-0.0052***	-0.0052
	(0.0017)	(0.0046)	(0.0017)	(0.0047)
Observations	1,518	1,518	1,518	1,518
Num. of prefectures	22	22	22	22
SW F (cold)	6.83	11.07	9.51	9.99
SW F (hot)	28.15	9.29	21.67	2.06
SW F (PV)	9.79	1.81	6.68	1.77

Notes: The table reports two-stage least squares estimates for the population aged 65 and older. Columns (1)–(2) examine heterogeneity by climate, where “warmer” (“colder”) prefectures are defined as those with above- (below-) median average daily mean temperature in summer (July–September). Columns (3)–(4) examine heterogeneity by electricity price changes, where “large” (“small”) price increases are defined by the above- (below-) median change in average summer (July–September) real electricity prices between the pre-period (2009–2010) and post-period (2011–2014). All specifications include the full set of control variables and fixed effects described in Section 3, and standard errors are clustered at the prefecture level. Residential solar PV adoption is measured as the logarithm of cumulative residential solar PV installations. The omitted temperature category is 15–30°C. The strength of the first-stage varies across subsamples and is strongest for the high-temperature interaction in warmer prefectures and regions with larger electricity price increases.

Table 6—Robustness checks: morbidity outcomes (population aged 65 and older)

	(1) log(medical expense per person)	(2) log(medical expense: inpatient)	(3) Placebo: log(medical expense: outpatient)	(4) Placebo: log(medical expense: dental)
>30℃	0.0093**	0.0189**	-0.0010	-0.0017
	(0.0035)	(0.0080)	(0.0029)	(0.0065)
>30℃ × PV	-0.0009***	-0.0019**	0.0001	0.0002
	(0.0003)	(0.0008)	(0.0003)	(0.0007)
Observations	2,552	2,552	2,552	2,552
Num. of prefectures	44	44	44	44

Notes: The table reports two-stage least squares estimates for the population aged 65 and older. Morbidity is measured using log medical care expenditures, including total expenditures per person, inpatient expenditures, outpatient expenditures, and dental expenditures. The morbidity data primarily cover individuals aged 75 and older, with inclusion of individuals aged 65–74 who qualify under the disability criteria of the Medical-Care System for the Latter-Stage Elderly. All specifications include the full set of control variables and fixed effects described in Section 3, and standard errors are clustered at the prefecture level. Residential solar PV adoption is measured as the logarithm of cumulative residential solar PV installations. For this sample, the Sanderson–Windmeijer (SW) first-stage partial F-statistics are 18.53 for the cold-temperature interaction (<15 °C × PV), 29.14 for the hot-temperature interaction (>30 °C × PV), and 19.16 for the PV term. The omitted temperature category is 15–30°C. Morbidity data are available from March 2010 onward.

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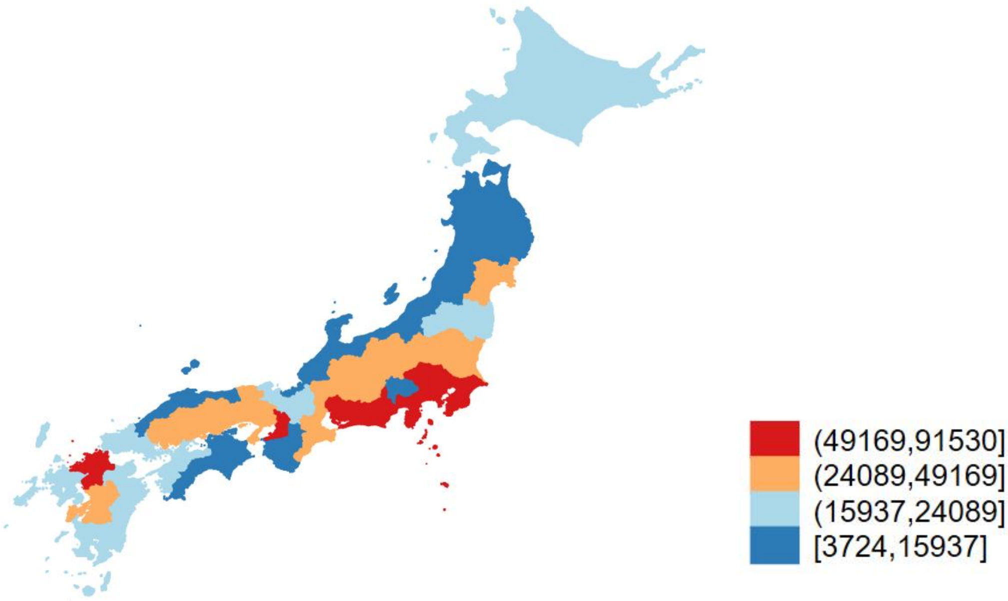
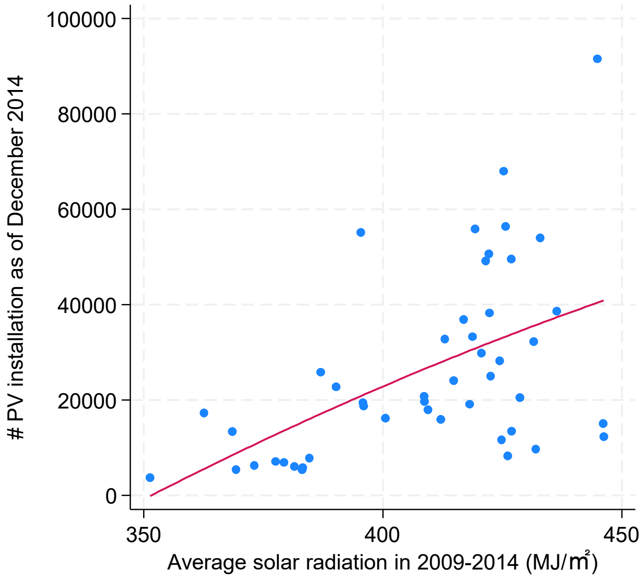
7. Appendix

Appendix Figure A1—Residential solar PV adoption across Japan



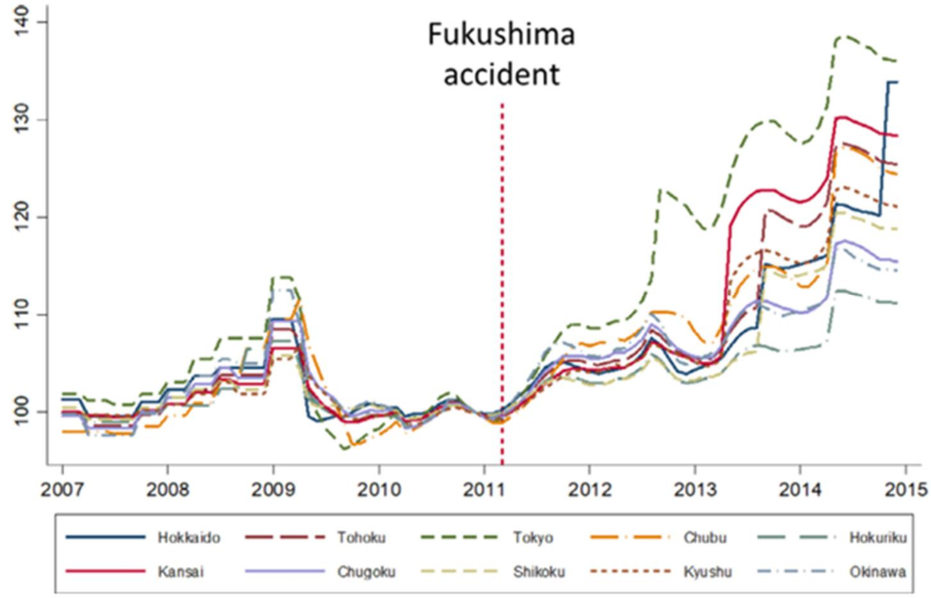
Notes: The figure shows cumulative residential solar PV installations by prefecture as of the end of the sample period (December 2014). There is substantial cross-prefecture variation in adoption levels.

Appendix Figure A2—Residential solar PV installations and global solar radiation



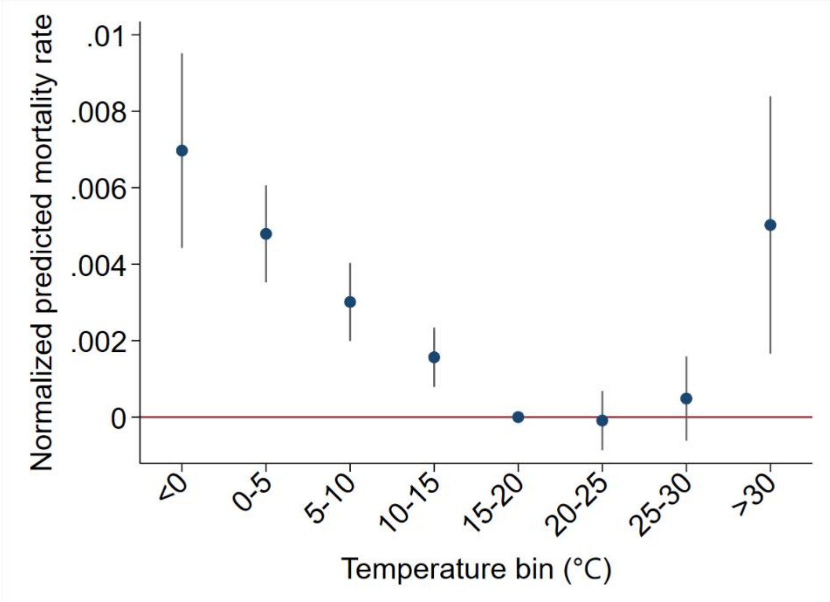
Notes: The figure plots cumulative residential solar PV installations by prefecture as of December 2014 against average global solar radiation over the period 2009–2014. The positive association illustrates the relevance of global solar radiation for explaining cross-prefecture variation in residential solar PV adoption.

Appendix Figure A3—Electricity price trends in Japan



Notes: This figure reproduces monthly average residential electricity price indices by region in Japan from Neidell et al. (2021). The vertical dashed line indicates March 2011, when the Great East Japan Earthquake and the Fukushima Daiichi nuclear accident occurred. The figure illustrates the substantial increase in electricity prices over time following the nuclear shutdown. This figure is included for illustrative purposes only.

Appendix Figure A4—Temperature–mortality relationship with finer temperature bins (OLS)



Notes: The figure plots normalized predicted mortality rates and 95 percent confidence intervals from an OLS regression using finer temperature bins. The reference category is 15–20°C. The figure illustrates the non-linear, U-shaped relationship between temperature and mortality. This specification is included for robustness and is not used in the main analysis.

Table A1—First-stage results for residential solar PV adoption

	(1) Temp <15℃ × PV	(2) Temp >30℃ × PV
Temp × past GSR ×	0.7719***	1.3441***
past log(price)	(0.1842)	(0.2961)
Observations	3,036	3,036
Num. of prefectures	44	44
SW F	37.18	54.82
SW F Prob > F	0.0000	0.0000

Notes: This table reports first-stage estimates from the two-stage least squares specification for the mortality among population aged 65 and older. The dependent variable is the interaction between temperature exposure and the logarithm of cumulative residential solar PV installations. The instrument is the interaction between long-run global solar radiation and lagged real electricity prices. All specifications include the full set of control variables and fixed effects described in Section 3. Standard errors are clustered at the prefecture level.

Table A2—Robustness of IV results to alternative instrument definitions (mortality among population aged 65 and older)

	(1) 5-year moving average: summer GSR × 2-year moving average: electricity price of same quarter	(2) 4-year moving average: summer GSR × previous year: electricity price of same quarter	(3) 4-year moving average: summer GSR × 2-year moving average: electricity price of same quarter	(4) 5-year moving average: GSR of same quarter × previous year: summer electricity price
>30℃	0.0250**	0.0262**	0.0260**	0.0280**
	(0.0120)	(0.0103)	(0.0123)	(0.0137)
>30℃ × PV	-0.0022*	-0.0023**	-0.0023*	-0.0025*
	(0.0012)	(0.0010)	(0.0012)	(0.0014)
Observations	3,036	3,036	3,036	3,036
Num. of prefectures	44	44	44	44
SW F (cold)	23.71	24.26	20.73	22.17
SW F (hot)	66.12	90.22	69.62	48.15
SW F (PV)	12.45	10.75	10.97	8.60

Notes: This table reports two-stage least squares estimates using alternative constructions of the instrumental variable. The estimation setting—including control variables, fixed effects, sample restrictions, and weighting—is the same as in the baseline IV specification. Residential solar PV adoption is measured as the logarithm of cumulative residential solar PV installations. We report first-stage Sanderson–Windmeijer (SW) partial F-statistics for the endogenous interaction terms between residential solar PV adoption and cold (<15 °C) and hot (>30 °C) temperature exposure. Standard errors are clustered at the prefecture level. All regressions are weighted by population. Three prefectures heavily affected by the Great East Japan Earthquake are excluded.

Table A3—Robustness of IV results to alternative measures of residential solar PV adoption (mortality among population aged 65 and older)

	(1) PV/housing	(2) PV/household
>30℃	0.0196***	0.0194***
	(0.0072)	(0.0071)
>30℃ × PV	-0.0018**	-0.0018**
	(0.0008)	(0.0008)
Observations	3,036	3,036
Num. of prefectures	44	44
SW F (cold)	43.19	43.39
SW F (hot)	75.85	76.69
SW F (PV)	11.15	11.17

Notes: This table reports two-stage least squares estimates using alternative measures of residential solar PV adoption. In Column (1), residential solar PV adoption is measured as the logarithm of cumulative residential solar PV installations per 1,000,000 housing units. In Column (2), residential solar PV adoption is measured as the logarithm of cumulative residential solar PV installations per 1,000,000 households. Both measures are constructed by scaling cumulative installations by the number of housing units or households, respectively. The estimation setting—including IV, control variables, fixed effects, sample restrictions, and population weighting—is identical to the baseline IV specification. We report first-stage Sanderson–Windmeijer (SW) partial F-statistics for the endogenous interaction terms between residential solar PV adoption and cold (<15 °C) and hot (>30 °C) temperature exposure. Standard errors are clustered at the prefecture level. Three prefectures heavily affected by the Great East Japan Earthquake are excluded.

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