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Reducing Health Risks from Extreme Temperatures in the Elderly: The Role of Solar Photovoltaics

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Reducing Health Risks from Extreme Temperatures in the Elderly: The Role of Solar Photovoltaics

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Abstract

Rising extreme temperatures and escalating energy costs threaten public health by limiting households' ability to regulate indoor climates. This study investigates whether residential solar photovoltaics (PVs) can mitigate these risks by lowering energy expenses. Using Japan's prefecture-month-level mortality data from 2009 to 2014, we exploit the electricity price surge following the 2011 Great East Japan Earthquake. Our findings show that solar PV installation significantly reduces temperature-related health risks, particularly among the elderly. These results underscore the importance of renewable energy in enhancing climate resilience and call for policies that promote solar PV adoption to protect vulnerable populations.

1. Introduction

Adverse health outcomes have increased with the rise in extreme temperatures caused by climate change. According to the 2023 WHO fact sheets, health costs from temperature-related impacts are projected to reach US$2-4 billion annually by 2030.[1] These impacts include acute conditions like hypothermia and hyperthermia, as well as chronic illnesses such as respiratory and cardiovascular diseases. Existing literature highlights a U-shaped relationship between temperatures and health risks–e.g., both extreme cold and heat increase mortality rates (Heal and Park 2016).

Home climate control devices, such as air conditioning, serve as a form of household self-protection against extreme temperatures (Barreca et al. 2016). However, their reliance on energy makes them vulnerable to rising energy costs. With global energy prices escalating due to recent inflation and geopolitical instability, insufficient indoor temperature control can worsen health outcomes. Recent studies confirm that higher

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[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

energy prices are linked to increased mortality rates (Neidell et al. 2021; Chirakijja et al. 2024).

This research investigates self-sufficient renewable energy technologies as a potential solution to mitigate the health risks under the pressure of high energy prices. Specifically, we explore the extent to which residential solar photovoltaics (PVs) can reduce the health risks. Solar PVs convert solar energy into power for household use as electricity or heat, lowering energy expenses and enabling more flexible energy use. By shifting the focus from renewable energy's environmental benefits, such as CO2 reduction, to the energy-health nexus, this study emphasizes the public health implications of sustainable energy adoption.

Using Japan's prefecture-month-level mortality data from 2009 to 2014, we evaluate our hypotheses within the context of the 2011 Great East Japan Earthquake, which triggered a sharp increase of electricity prices due to a shift away from nuclear power.

Our findings highlight that residential solar PV installations significantly mitigate the negative health impacts of extreme temperatures, especially for individuals aged 65 and older. These results emphasize the crucial role of renewable energy technologies in improving resilience to both extreme temperature events and fluctuations in energy prices. The robustness of our findings across various model specifications reinforces the notion that adopting renewable energy contributes to greater household resilience in the face of climate and energy price shocks.

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

The relationship between extreme temperatures and mortality rates is well-documented globally, with numerous studies showing that both extreme cold and heat increase mortality risks in a U-shaped pattern. Gasparrini et al. (2015) found that temperature-related mortality is a significant concern worldwide, with many countries exhibiting this relationship and experiencing increased mortality risks from both cold and heat. These findings underscore the widespread nature of the temperature-mortality relationship, particularly in regions with vulnerable populations such as the elderly and individuals with pre-existing health conditions. Anderson and Bell (2009) further highlight that in the U.S., older individuals are particularly susceptible to higher mortality risks from both extreme heat and cold, reinforcing the need for targeted interventions during temperature extremes. This established understanding of the direct impact of temperature on mortality provides a foundation for exploring how external factors, such as energy prices and climate control technologies, may influence the severity of these impacts.

Building on this, the impact of rising energy prices on the temperature-mortality relationship has become an area of increasing interest. Studies by Neidell et al. (2021) and Chirakijja et al. (2024) show that higher energy costs can exacerbate mortality rates, particularly among low-income households that may struggle to afford heating or cooling systems during extreme weather events. These findings suggest that energy affordability plays a key role in mitigating health risks associated with temperature extremes. As energy prices rise, the affordability of climate control becomes a major concern, with vulnerable populations facing greater health risks. This reinforces the need for solutions that not only address temperature-related health risks but also tackle the underlying issue of energy access and affordability.

Air conditioning and heating systems are often seen as essential tools for mitigating the adverse health impacts of extreme temperatures. Barreca et al. (2016) highlight that air conditioning significantly reduces mortality during heatwaves and attribute the long-term decline in heat-related deaths in the U.S. to widespread adoption of cooling technologies. Similarly, Sera et al. (2020) find that increased air conditioning prevalence is associated with lower heat-related mortality across multiple countries, reinforcing its protective role against extreme temperatures. However, this reliance on energy-intensive technologies introduces a new vulnerability: as energy prices rise, even those with access to air conditioning may face heightened mortality risks if they cannot afford to operate their cooling or heating systems during extreme conditions. This creates a paradox where climate control systems intended to protect public health may, in fact, exacerbate health risks due to their reliance on expensive and often volatile energy sources. Thus, while these devices provide short-term relief, their long-term effectiveness is increasingly threatened by rising energy costs.

Given the limitations of energy-intensive climate control, renewable energy technologies, particularly solar PVs, offer a promising alternative. Solar PVs reduce household reliance on external energy sources, lower energy costs, and provide a buffer against price volatility. Rivera et al. (2024) demonstrate that solar energy not only displaces coal generation but also improves public health by reducing hospital admissions linked to air quality improvements. Seddighi et al. (2023) highlight the importance of resilient, clean energy systems in addressing health challenges, particularly those arising from extreme temperatures. While these studies emphasize air quality and respiratory health benefits, there remains limited research exploring the direct link between renewable energy adoption and public health implications, particularly in relation to temperature-related mortality.

This study aims to fill that gap by investigating how residential solar PV installations can reduce mortality risks associated with temperature extremes, particularly for elderly populations, who are disproportionately affected by both heatwaves and cold spells. By focusing on the energy-health nexus, this study shifts the conversation from the environmental to the public health benefits of renewable energy adoption, providing new insights into how renewable energy can improve resilience to climate-related health risks.

Furthermore, the context of the 2011 Great East Japan Earthquake offers a unique opportunity to explore the intersection of energy price volatility, temperature extremes, and health outcomes. Following the earthquake, Japan saw a sharp increase in electricity prices due to the shift away from nuclear power. In this context, solar PV adoption increased as households sought to mitigate rising energy costs, making this an ideal setting for studying the potential health benefits of renewable energy in protecting against both energy price shocks and extreme temperature events. Relatedly, He and Tanaka (2023) find that Japan's post-earthquake energy-saving campaign, which encouraged households to reduce electricity consumption, unintentionally led to an increase in temperature-related mortality. As households cut back on heating and cooling to conserve energy, vulnerable populations faced heightened risks during extreme temperatures. Their findings underscore the unintended consequences of energy policies that prioritize conservation without ensuring adequate access to affordable climate control. Building on this insight, this study extends the literature by directly examining whether solar PV installations—by lowering energy costs and enhancing energy security—can further mitigate temperature-related mortality, particularly in the aftermath of energy price shocks.

3. Methodology and Data

3.1 Methodology

The decision to install residential solar PV systems is likely endogenous to mortality outcomes due to two main factors: omitted variable bias and reverse causality.

First, omitted variable bias arises because households that install solar PVs may differ from those that do not in ways that are difficult to measure. For example, households adopting solar PVs may also engage in other energy-saving behaviors, such as improving home insulation or using energy-efficient appliances, which independently reduce the risk of temperature-related mortality. These unobserved characteristics, such as household attitudes toward sustainability, financial resources, or climate adaptation strategies, can influence both solar PV adoption and mortality outcomes. If not accounted for, these factors introduce bias in estimating the true effect of solar PV adoption on mortality rates.

Second, reverse causality is a concern because the decision to install solar PVs may be influenced by past extreme temperatures or anticipated future climate risks. Households that have experienced severe heatwaves or cold spells may be more likely to adopt solar PV systems in response to these events, seeking to mitigate future risks. This creates a situation where higher solar PV adoption is correlated with heightened awareness of climate-related health risks rather than the direct protective effect of solar PVs itself. As a result, the estimated relationship between solar PV adoption and mortality may reflect this reverse causality, rather than a true causal effect.

Given these concerns, a simple regression analysis would yield biased estimates. To address this, this study uses an instrumental variable (IV) approach with a two-stage least squares (2SLS) model, which allows us to isolate exogenous variation in solar PV adoption and obtain more accurate estimates of its impact on temperature-related mortality. We employ the following empirical model:

$$(1) \qquad \mathrm{Y}_{itm} = \alpha_0 + \sum_{n=1}^{N} \alpha_n Temp_{itm} + \sum_{n=1}^{N} \beta_n Temp_{itm} \times SolarPV_{itQ(m)} + \gamma_1 SolarPV_{itQ(m)} + \mathbf{Z}_{itm}\delta + \theta_{im} + \lambda_{it} + \nu_{mt} + \varepsilon_{itm},$$

where:

$SolarPV_{itQ(m)}$ represents solar PV installation in the most recent quarter before month m.[2]

- If m = 1, 2, 3, then it refers to Q4 of year t-1.
- If m = 4, 5, 6, then it refers to Q1 of year t.
- If m = 7, 8, 9, then it refers to Q2 of year t.

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[2] 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 relationship.

- If m = 10, 11, 12, then it refers to Q3 of year t.

Y_{itm} is the log of mortality rate in prefecture i in month m of year t, $Temp_{itm}$ denotes the number of days where the daily mean temperature is in the n^{th} of the N bins (<15, 15–30, >30°C).[3] A vector $\mathbf{Z}_{imt}$ includes the mean monthly precipitation, wind speed, and snow depth, as well as income, that are classified into ten quantile groups. The inclusion of income is particularly pertinent as health is known to be influenced by household income levels. θ_{im} is the prefecture by month fixed effect, λ_{it} is the prefecture by year fixed effect, ν_{mt} is the year-by-month fixed effect, and ε_{itm} indicates the error term.

To address the endogeneity of solar PV installation, we use an IV that combines global solar radiation during the summer months over the past five years with electricity prices from the same month in the previous year. This instrument is valid for the following reasons: Global solar radiation directly influences the financial attractiveness of solar PV systems. Regions with higher solar radiation levels are more suitable for PV installations as they yield greater energy output, enhancing the economic viability of solar adoption. Using a five-year average of solar radiation helps smooth short-term fluctuations and provides a more accurate estimate of long-term solar potential, which is more relevant for household investment decisions. However, solar radiation alone may not provide sufficient variation across regions to serve as an effective instrument, as its effect on PV adoption could be relatively uniform in areas with similar solar conditions. To address this limitation, we combine solar radiation with electricity prices, which vary seasonally and significantly influence the financial incentives for PV adoption. Higher energy prices increase the potential savings from self-generated electricity, making solar adoption more attractive. By using electricity prices from the same month in the previous year, this instrument captures seasonal price variations that households consider when deciding to invest in solar PVs, while avoiding any contemporaneous effects on mortality outcomes. The interaction between global solar radiation and lagged electricity prices strengthens the instrument's relevance. Areas with both high solar potential and high electricity prices face stronger economic incentives for adopting solar PVs, making this combined

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[3] From a statistical perspective, we categorize temperature into three bins: <15°C, 15–30°C, and >30°C to reduce model complexity and minimize potential overfitting. This approach simplifies the estimation while retaining the key variations in temperature exposure. Additionally, based on He and Tanaka (2023)'s findings, temperatures within the 15–30°C range do not exhibit statistically significant differences in their effects on mortality. Therefore, we set the 15–30°C range as the reference category, which is dropped in the estimation. This allows us to interpret the estimated coefficients as the relative effects of colder (<15°C) and hotter (>30°C) temperatures on mortality. By grouping this range into a single category, we improve the efficiency of our estimates without losing meaningful information.

instrument more effective in explaining variation in solar PV adoption. This approach provides a more reliable estimate of the causal impact of solar PV installations on temperature-related mortality.

3.2 Data

3.2.1 Mortality, Household Characteristic and Electricity Price Data

The monthly mortality data and household characteristics, such as income, used in this study are obtained from He and Tanaka (2023).[4] The monthly marginal electricity price data is from Retail Price Survey (Trend Survey) from Statistics Bureau, Ministry of Internal Affairs and Communications.[5] Since the government uses 441 kWh as the standard monthly electricity consumption for households in its statistics and modeling, we calculate the average electricity price based on this standard and use it in the analysis.

3.2.2 Residential Solar PV Installation Data

This study utilizes data on quarterly residential solar PV installations from the Japan Photovoltaic Energy Association (JPEA), which oversaw a national subsidy program for solar PV systems. Running from January 2009 to March 2014, the program provided financial support for households installing solar PVs. The subsidy was available to households across all prefectures. To qualify for the subsidy, households had to apply before installation, and over 96% of applications were approved, leading to successful installations. The number of approved applications is used by the government as the official count of residential solar PV installations, suggesting that the subsidy program covered nearly all residential solar PV installations during this period. Unlike Kiso et al. (2022), who focus on the timing of adaptation behaviors using application data, this study uses approval data. Our goal is to examine the actual impact of solar PV installation on the temperature-mortality relationship, specifically how having solar PVs in place affects the household's vulnerability to temperature extremes.

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[4] Following He and Tanaka (2023), we exclude three prefectures—Iwate, Miyagi, and Fukushima—from our primary analysis, as these regions were directly affected by the earthquake and tsunami, making them less comparable to other prefectures.

[5] See Statistics Bureau, Ministry of Internal Affairs and Communications for more detailed information of the survey: https://www.stat.go.jp/english/data/kouri/doukou/index.html.

3.2.3 Weather Data

The weather data utilized in this study is sourced from Agro–Meteorological Grid Square Data, NARO.[6] They provide 14 types of daily meteorological weather data by 1km square (third–order grid unit) covering the entirety of Japan. Consistent with previous studies, our analysis focuses on three key weather variables: daily mean temperature, precipitation, wind speed, and snow depth. Additionally, global solar radiation is utilized as an IV in our analysis. To harmonize the grid–level data with prefecture–level data, we leverage a list of mesh codes by city provided by the Statistics Bureau of Japan. This facilitates the seamless integration of these datasets, ensuring robust analysis at the prefecture level.

This study analyzes data from 2009 to 2014, with Table 1 providing an overview of the key variables. During this period, the average monthly mortality rate per 100,000 people across the study prefectures was 2.1 for individuals aged 0–19, 11.7 for those aged 20–64, and 318.2 for those aged 65 and above. Notably, the elderly accounted for over 95% of all deaths. Given the significant differences in mortality rates across age groups, direct comparisons between regions or time periods can be misleading due to variations in age composition. To address this, the study first estimates age-specific mortality rates separately for the three age groups. These rates reflect the mortality risk within each group but do not account for how different age groups contribute to the total population. To enable meaningful comparisons, an age-adjusted mortality rate is constructed by weighting each age group’s mortality rate by its respective population share. This adjustment standardizes the mortality measure, ensuring that observed differences are not driven by changes in demographic structure. The resulting monthly age-adjusted mortality rate is 83.7 per 100,000, which provides a more accurate representation of overall mortality risk across prefectures and over time. The distribution of daily mean temperatures over a typical month (31 days) indicates that, on average, 16.1 days experience temperatures below 15°C, 14.8 days fall within the 15–30°C range, and 0.1 days exceed 30°C.[7] Additionally, the cumulative residential solar PV installations per quarter average 11,837.8 units. Figure 1 displays the average quarterly cumulative residential solar PV installations across the studied prefectures during the study period. The vertical axis represents the total number of installations, while the horizontal axis

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[6] See Agro–Meteorological Grid Square Data, NARO for more detailed information: https://amu.rd.naro.go.jp/wiki_open/doku.php?id=start.

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

indicates the year and quarter. The figure provides insights into the temporal patterns of solar PV adoption, highlighting variations in installation levels over time.

Table 1—Summary statistics

	Obs.	Mean	SD	Min	Max
Mortality rate age 0–19 (per 100,000)	3,168	2.1	0.9	0	8.4
Mortality rate age 20–64 (per 100,000)	3,168	11.7	2.1	5	21.7
Mortality rate age over 65 (per 100,000)	3,168	318.2	38.4	230.3	449.8
Age-adjusted mortality rate (per 100,000)	3,168	83.7	10.3	60.6	125.7
<15 ℃ (days)	3,168	16.1	13.8	0	31
15–30 ℃ (days)	3,168	14.8	13.7	0	31
>30 ℃ (days)	3,168	0.1	0.6	0	13.2
Cumulative residential solar PV installations	3,168	11,837.8	14,154.1	3	91,530

Notes: The unit of mortality rate and temperature bins are a prefecture in each month between 2009 and 2014, while the unit of observation for solar PV installation is a prefecture in each quarter over same timeframe.

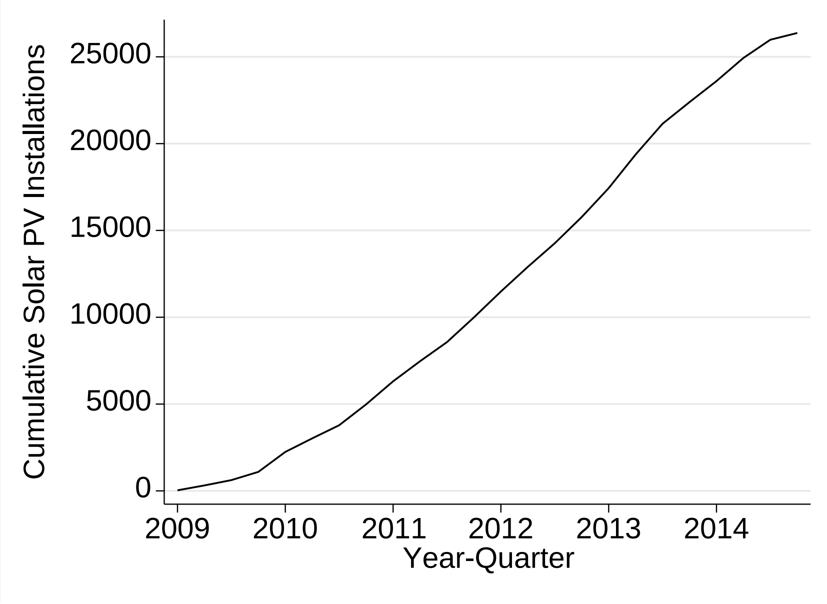

Figure 1. Average quarterly cumulative residential solar PV installations across study prefectures (2009–2014)

4. Empirical Results

4.1 OLS Estimates: The Impact of Temperature on Mortality

The estimation results are presented in Table 2. All models include control variables and multiple fixed effects, as detailed in the methodology and data section. The temperature range of 15–30°C is excluded to align with He and Tanaka's findings and improve the efficiency of our estimates.[8] Columns 1–3 report the results for different age groups—0–19, 20–64, and 65 and above—while Column 4 presents estimate using the age-adjusted mortality rate, accounting for the varying contributions of each age group to the total population. In contrast to the reference temperature bin, our analysis reveals a positive correlation between mortality rate and temperatures both below and above this reference for individuals aged 65 and above, as well as for the age-adjusted mortality rate. However, we find no significant impact for younger cohorts. The stronger effects observed among the elderly suggest that older individuals are more vulnerable to temperature extremes due to a combination of physiological and health-related factors.

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[8] See footnote 3.

Aging weakens the body's ability to regulate temperature, making older adults more susceptible to hypothermia in cold conditions and heat-related illnesses in extreme heat. Additionally, pre-existing health conditions, such as cardiovascular and respiratory diseases, increase the risk of complications when exposed to temperature fluctuations. Certain medications commonly used by older individuals can further impair the body's ability to cope with heat or cold. Moreover, limited mobility and social isolation may prevent timely protective actions, increasing their overall vulnerability. These factors collectively explain why temperature extremes have a stronger impact on elderly mortality rates.

Our preferred empirical model, as presented in Column 4, demonstrates that exposure to an additional day below 15°C increases the mortality rate by 0.16 percent, while an extra day above 30°C results in a 0.45 percent increase. The similarity between the age-adjusted estimates and those for the elderly reflects the dominant contribution of this age group to overall mortality patterns. Figure 2 shows the age-adjusted mortality rate–temperature response function from Column 4, along with 95 percent confidence intervals.

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

	(1) 0–19	(2) 20–64	(3) above 65	(4) age-adjusted
<15℃	-0.0042	0.0011	0.0017***	0.0016***
	(0.0066)	(0.0014)	(0.0004)	(0.0004)
>30℃	-0.0037	0.0055***	0.0045***	0.0045***
	(0.0116)	(0.0015)	(0.0016)	(0.0014)
Obs.	3,115	3,168	3,168	3,168
Num. of prefectures	44	44	44	44
Control var.	Yes	Yes	Yes	Yes
F statistic	0.25	6.89	15.13	12.99
Prob > F	0.7799	0.0025	0.0000	0.0000
R-squared	0.3127	0.8266	0.9675	0.9705

Notes: ***, **, and * denote 1 percent, 5 percent, and 10 percent significant level, respectively. Columns 1–3 present estimates for different age groups, as indicated at the top of each column, while Column 4 reports result for the age-adjusted mortality rate; 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. 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.

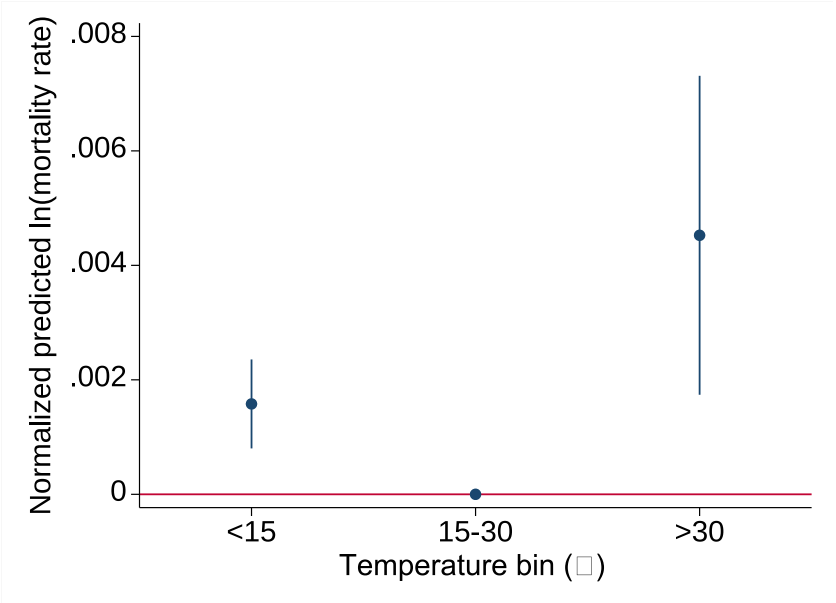

Figure 2: Relationship between temperature and mortality rate

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.

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

Table 3 presents the 2SLS estimation results, examining the impact of residential solar PV installations on the relationship between temperature and mortality. The results show that solar PV installations significantly reduce mortality among the elderly during high temperatures, but this effect is not observed during low temperatures. Specifically, a 10-fold increase in cumulative residential solar PV installations offsets the mortality impact of extreme heat, leading to reduced heat-related mortality rates among individuals aged 65 and above, as well as the age-adjusted mortality rate. As seen in the OLS results in Table 2, no significant impact is found for the younger cohorts.

The greater effectiveness of solar PVs in mitigating the effects of high temperatures is likely due to its role in providing additional electricity for cooling appliances, such as air conditioners and fans. During hot weather, increased solar PV capacity allows households to use these cooling systems more efficiently, reducing heat stress and, consequently, lowering mortality risks. In contrast, during colder months, solar PV's effectiveness is limited by the lower solar radiation, which reduces its electricity generation and makes it less effective in mitigating cold-related mortality. Additionally, households can rely on alternative heating methods, such as oil heaters, to cope with cold temperatures, whereas fewer alternatives exist for managing extreme heat.

The lack of significant impact for younger cohorts can be attributed to their generally lower vulnerability to temperature extremes. Younger individuals have more robust thermoregulatory systems, fewer pre-existing health conditions, and are less susceptible to the health risks associated with extreme temperatures. As a result, the need for additional cooling or heating provided by solar PV installations has no meaningful effect on this group, leading to no impact in the analysis.

These findings highlight the potential of residential solar PV installations to mitigate heat-related mortality, particularly for elderly populations. Given that older individuals are more vulnerable to temperature extremes, expanding access to solar energy could be an effective strategy for reducing climate-related health risks. Policymakers may consider supporting the adoption of solar PV systems, particularly in regions with aging populations, to enhance climate resilience and protect public health.

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

	(1) 0–19	(2) 20–64	(3) above 65	(4) age-adjusted
<15℃	-0.0107	0.0063	-0.0001	-0.0038
	(0.0243)	(0.0095)	(0.0042)	(0.0054)
<15℃ × solar PV	0.0007	-0.0006	0.0002	0.0008
	(0.0032)	(0.0010)	(0.0005)	(0.0006)
>30℃	-0.0880	-0.0072	0.0375**	0.0544*
	(0.1399)	(0.0481)	(0.0168)	(0.0270)
>30℃ × solar PV	0.0087	0.0013	-0.0034*	-0.0050*
	(0.0152)	(0.0048)	(0.0017)	(0.0028)
Obs.	2,985	3,036	3,036	3,036
Num. of prefectures	44	44	44	44
Control var.	Yes	Yes	Yes	Yes
F statistic	0.31	3.33	4.76	5.95
Prob > F	0.9044	0.0125	0.0015	0.0003
First stage SW F >10[9]	Yes	Yes	Yes	Yes

Notes: ***, **, and * denote 1 percent, 5 percent, and 10 percent significant level, respectively. Columns 1–3 present estimates for different age groups, as indicated at the top of each column, while Column 4 reports result for the age-adjusted mortality rate; 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. 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

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[9] The first-stage F-statistics for the instrumental variables (SW F) are all above 10, indicating that the instruments are sufficiently strong and the first-stage regression is not weak. This ensures the validity of the 2SLS estimation and supports the reliability of our findings.

4.3 Heterogeneous Effects: Different Causes of Death

To further explore the heterogeneous effects of residential solar PV installations, we examine their impact on different causes of death, specifically cardiovascular mortality and accident-related mortality. The results, presented in Table 4, reveal that solar PV installations significantly reduce the mortality impact of temperature extremes on cardiovascular deaths, while no significant effect is observed for accident-related deaths. The inclusion of accident-related deaths in the analysis serves as a placebo test, helping us determine whether the effects observed for cardiovascular mortality are truly linked to temperature exposure and solar PV installations.

The significant reduction in cardiovascular mortality can be attributed to the direct relationship between temperature extremes and cardiovascular health. Extreme heat and cold can place substantial stress on the cardiovascular system, increasing the risk of heart attacks, strokes, and other related events. Solar PV installations help mitigate this risk by providing additional electricity for cooling systems, such as air conditioners, which reduce exposure to high temperatures. By alleviating heat stress, solar PV systems significantly reduce the mortality risk for individuals with pre-existing cardiovascular conditions, especially among vulnerable populations.

In contrast, the lack of significant impact on accident-related deaths suggests that temperature extremes have a less direct effect on accidents compared to cardiovascular health. While extreme temperatures may contribute to accidents (e.g., through heat-induced fatigue or cold-related slips), the impact is less pronounced and influenced by a wider range of factors, such as behavior, infrastructure, and safety conditions. These factors are less likely to be directly mitigated by solar PV installations, leading to the absence of a significant effect on accident-related mortality.

Overall, our findings highlight that residential solar PV installations can significantly reduce the mortality impact of temperature extremes, though the effect is not statistically significant for cold temperatures. This is particularly relevant for temperature-related health risks, such as cardiovascular diseases. These results suggest that increasing access to solar energy, particularly in regions with vulnerable populations, could be an effective strategy for reducing temperature-related mortality risks.

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periods in the dataset do not have prior-quarter values available for estimation.

Table 4—Heterogeneous effects on different causes of mortality

	(1) above 65 CVD	(2) above 65 accident	(3) age-adj. CVD	(4) age-adj. accident
<15°C	-0.0054	0.0039	-0.0038	0.0088
	(0.0060)	(0.0176)	(0.0054)	(0.0168)
<15°C × solar PV	0.0010	-0.0005	0.0008	-0.0010
	(0.0007)	(0.0020)	(0.0006)	(0.0019)
>30°C	0.0707**	-0.0268	0.0544*	0.0189
	(0.0307)	(0.0557)	(0.0270)	(0.0460)
>30°C × solar PV	-0.0068**	0.0013	-0.0050*	-0.0030
	(0.0031)	(0.0057)	(0.0028)	(0.0047)
Obs.	3,036	3,036	3,036	3,036
Num. of prefectures	44	44	44	44
Control var.	Yes	Yes	Yes	Yes
F statistic	6.00	2.03	5.95	2.67
Prob > F	0.0003	0.0928	0.0003	0.0344
First stage SW F >10[10]	Yes	Yes	Yes	Yes

Notes: ***, **, and * denote 1 percent, 5 percent, and 10 percent significant level, respectively. CVD refers to cardiovascular. 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. 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.

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[10] See footnote 9.

5. Conclusion

This study investigates the impact of residential solar PV installations on the relationship between temperature extremes and mortality. By examining different age groups and mortality causes, we find that solar PV installations have a significant role in mitigating the adverse effects of high temperatures on mortality, particularly for individuals aged 65 and above. The results suggest that solar PV installations help reduce heat-related mortality by providing additional electricity for cooling, thus lowering heat stress, especially for vulnerable populations. However, the effectiveness of solar PV in reducing cold-related mortality is limited due to insufficient solar radiation in winter.

Furthermore, we observe heterogeneous effects when examining different causes of death. While solar PV installations significantly reduce the temperature-related mortality risk associated with cardiovascular diseases, no significant effect is found for accident-related deaths. This is likely because the relationship between temperature and accidents is more indirect and influenced by a broader set of factors beyond the capacity of solar PV systems to mitigate.

The findings highlight the potential of residential solar PV installations in enhancing climate resilience and reducing health risks associated with extreme temperatures. Policymakers could consider promoting solar energy adoption, especially in regions with aging populations or those vulnerable to temperature extremes. This could be a key strategy in mitigating climate-related health risks, particularly in improving the well-being of elderly individuals and those with pre-existing health conditions.

Future research could explore the role of income and geographical factors—such as regional variations in solar radiation—in contributing to disparities in the effectiveness of solar PV systems in mitigating temperature-related mortality. Understanding how these factors influence the distribution and benefits of solar energy adoption can help target interventions more effectively and reduce social inequalities in climate resilience.

6. References

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