Imported solar photovoltaics contributed to health and climate benefits in the United States

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For attribution, please cite this work as: Qiu, Minghao, Gang He, Peter Marcotullio. 2025. Imported solar photovoltaics contributed to health and climate benefits in the United States, *One Earth* 8, 101467, `https://doi.org/10.1016/j.oneear.2025.101467`

eTOC

Global supply chains have helped drive the rapid deployment of solar photovoltaics, but their broader societal benefits are often overlooked. Here we estimate that imported solar capacity in the U.S. displaced 305 TWh of fossil generation, avoided 178 million tons of CO_2, and prevented 595 premature deaths between 2014 and 2022. These findings highlight how international clean energy supply chain delivers substantial climate and health benefits—critical evidence for informing energy policy and supply chain resilience debates.

Highlights

- Imported PV displaced 305 TWh of U.S. fossil generation between 2014–2022
- Avoided 178 Mt CO_2 and 595 premature deaths from air pollution
- $28 billion in total health and climate benefits from imported solar capacity
- Benefits reached 43% of people living outside importing states

Science for Society

Clean energy technologies like solar photovoltaic (PV) are pivotal in reducing emissions, improving air quality, and enhancing public health. In the U.S., solar PV deployment has surged dramatically, with the vast majority of modules imported, highlighting a deepening reliance on global supply chains. However, recent challenges including the pandemic and geopolitical tensions threaten supply chain stability, slowing progress in solar PV adoption. A comprehensive understanding of the broader socio-environmental benefits of solar PVs is vital to crafting policies that stabilize these supply chains and accelerate deployment. However, such an understanding appears absent. Employing system modelling, we reveal that imported solar panels have displaced 305 TWh of fossil fuel generation, avoided 178 million tons of CO , and prevented nearly 600 premature deaths from 2014–2022. The monetized value of these health and climate benefits has already offset about half of the deployment costs. Importantly, nearly half of U.S. residents living outside the solar-importing states have also benefited, underscoring the far-reaching societal value of global clean energy trade. These findings emphasize the critical stakes in international energy policy and supply chain resilience.

Summary

Global supply chains have played a central role in driving down solar photovoltaic (PV) costs and accelerating deployment globally, but their broader societal benefits are underexplored. Here we quantify the climate, air quality, and health impacts of imported solar panels in the United States between 2014 and 2022. We find that 1 kW of imported solar capacity yields an average of $180 in annualized climate and health benefits, offsetting nearly half the PV module cost in 2020. Generation from imported solar PV capacity displaced fossil generation by 305 TWh, avoided 178 million tons of CO , and prevented an estimated 595 premature deaths between 2014 and 2022. While these advantages are unevenly distributed across regions and population groups, residents in non-importing states also benefited from them. These findings provide critical evidence for policy debates on clean energy trade, showing that imported solar capacity delivers substantial public health and climate gains beyond direct cost savings.

Introduction

Achieving carbon neutrality requires deploying renewable energy at unprecedented speed and scale ultimately relying on efficient global clean energy supply chains. According to the International Energy Agency (IEA), solar and wind energy have to reach 20 and 15 times their 2020 generation levels to achieve global net-zero carbon emission by 2050, respectively.[1] The global supply chains for solar and wind, interconnected with critical minerals and storage technologies, play a pivotal role in the success of this transition.[2] The global supply chains and the international collaboration that makes the supply chains work is a key factor that drove the cost decline of renewables such as solar photovoltaic (PV).[3] The levelized cost of electricity of solar PV has dropped by more than 89% from 2010 to 2022, and has become the cheapest source of energy in many parts of the world.[4] The continuous drop of renewable energy costs is needed to achieve the speed and scale of deployment at global scale to keep global temperature warming under 1.5 °C.

However, the pandemic and geopolitical tensions create significant risks to the stability of global clean energy supply chains.[5,6,7] Furthermore, the unequal distribution of costs and benefits along supply chains raises ethical and socio-economic concerns, sometimes leading countries to break from global supply chains to pursuit domestic manufacturing. While some countries benefit economically from the growth of the global renewable energy sector, other countries bear disproportionate environmental and social burdens, such as air quality and health impacts, particularly those in Africa, Southeast Asia, and South America.[8] Understanding the magnitude and distributions of costs and benefits associated with a clean energy supply chain is essential for designing policies to speed up deployment of renewable energy for the low carbon energy transition, while at the same time helping to mitigate the risks and challenges associated with supply chain dynamics and shocks.

Prior studies have quantified the economic benefits of the global supply chains of clean energy and have shown that an efficient and resilient supply chain is crucial for achieving continuous cost reductions in solar, wind, and energy storage technologies — a key factor to scale up deployment. For example, Helveston et al. shows that solar PV costs could be 20–30% higher in 2030 if countries move from global supply chain to manufacturing domestically.[9] In addition to cost reduction, global supply chains also play a pivotal role in carbon emission mitigation, pollution reduction, and the overall improvement of human health.[10] However, compared to the economic benefits associated with clean energy supply chains, less is known about the environmental, climate, and health impacts associated with global clean energy supply chains.

Deployment of renewable energy can displace electricity generation that would otherwise need to be generated by fossil fuel power plants.[11,12] As a result, deployment of renewable energy can reduce emissions of greenhouse gases and air pollutants, lead to improvements in air quality and related human health outcomes.[13,14,15,16] Many studies project substantial air quality and health benefits associated with expansions of renewable energy under net zero scenarios around the world.[17,18,19] As global supply chains of clean energy enable greater deployment of renewable energy, a resilient and efficient global supply chain is essential for the delivery of these climate and health benefits. However, to our knowledge, the climate, air quality, and health effects associated with the global supply chains of clean energy remains underexplored.

Here we focus on solar generation in the U.S., which has expanded rapidly over the last two decades and remains closely connected with the global supply chains. By quantifying the climate, air quality, and health impacts of power generation associated with imported PV panels in the U.S. from 2014–2022, this study reveals the often-overlooked societal benefits of global clean energy supply chains. We find that solar panels imported into the U.S. between 2014 and 2022 displaced 305 TWh of fossil fuel generation, avoided 178 million tons of CO_2 emissions, and prevented an estimated 595 premature deaths due to improved air quality during the same period. These benefits translate into $28 billion in monetized climate and health gains ($180/kW)—equivalent to nearly half the average cost of PV modules in 2020. As policymakers consider reshaping energy trade and manufacturing strategies, our findings demonstrate that global supply chains not only reduce costs but also deliver significant public health and climate dividends that should be incorporated into decision-making.

Results

Methods summary

Starting from nearly zero in 2010, solar power grew to account for 3.4% of total electricity generation by 2022 in the United States.[20] Solar generation accounted for more than 5% of total state-wide generation in 10 states, led by Nevada (21% of state-wide generation) and California (19% of state-wide generation). Similar to the rest of the world, this rapid deployment of solar panels is connected to the global supply chains.[3] The Energy Information Administration (EIA) reports that 88% of PV modules in the U.S. are shipped from other countries in 2022, and only 12% are domestically manufactured.[21] This pattern partly reflects the differences in PV cost – the overnight unit capital costs for solar PV in the U.S. is higher than other major markets such as Europe, India, and China, exceeding twice the cost of solar PV in China.[22] U.S. has imported solar PVs from a variety of countries with the importing source substantially changing over time – the top three countries that the U.S. imported solar PVs from are Thailand, Vietnam, and Malaysia in 2023[21,23] (Figure S1).

We estimate the state-level imported PV capacity by using state-level shipment data (which includes both international and domestic shipping) and a national average ratio between the international and domestic shipping (as this ratio is not reported at individual state).[24] To account for the lag in module shipment, installation, and power generation, we assume a three-year lag between shipments and electricity generation following the average timeline for solar project[25] and further examine how the estimated impacts vary across the choice of lag period (See Figure S2).

To quantify the effects on emissions, air quality, and human health, we first establish a statistical relationship between solar generation and electricity generation from other fuel types, using daily electricity generation data at the grid region level (region definitions derived from the EIA;[26] see Figure 2A). Our analysis directly accounts for the trans-boundary impacts of solar generation on fossil fuel generation in the neighboring region, due to the import/export of electricity across different grid regions. For each grid region, we empirically estimate the influence of an increased unit of solar generation on different types of fossil fuel generation in the same region and neighboring regions. Using such relationships, we calculate the displaced generation and emissions of CO_2, NO_x, and SO_2 from each individual fossil fuel plant due to solar generation associated with imported PV capacity in the U.S. We then estimate the effects on surface $PM_{2.5}$ concentration using a reduced-complexity air quality model, the Intervention Model for Air Pollution (InMAP).[27] Finally, we calculate the monetized benefits (2020 $US) from excess mortality due to estimated $PM_{2.5}$ changes using an empirically derived exposure-response function from a recent meta-analysis[28] and a value of statistical life of $10.95 million (2019 $US) recommended by the U.S. Environmental Protection Agency (EPA).[29] Monetized benefits of avoided CO_2 emissions are calculated using a social cost of carbon value of $120 per ton (2020 $US).[30]

Contribution of imported solar PV

As reported by the EIA, 78% of solar PV capacity in the U.S. were shipped from other countries from 2010 to 2022. After deducting shipments from domestic manufacturing, we estimate that the U.S. has imported 97 GW of PV capacity during 2010–2022, and at least 50 GW of the imported PV capacity were already installed (assuming a three-year lag between shipments and installation) (Figure S2). These imported PV capacity have generated 398 TWh of electricity during 2010-2022, which accounts for 63% of the total solar generation in the U.S. during the same period (Figure 1). Contributions of generation from imported PV capacity to the total solar generation gradually increased from about 20% before 2015 to about 70% in recent years (Figure S3). California leads all states in the amount and percentage of imported solar capacity (30% of total imported PV capacity and 45% of the electricity generated from imported PV capacity from 2010–2022). This underscores California's pivotal role in the nation's clean energy transition and its reliance on global supply chains to meet its renewable energy goals. We estimate that imported PV capacity generated 180 TWh in California, which accounted for 77% of the total state-wide solar generation. Other states that also replied on imported PV capacity for solar power generation include Arizona (35 TWh, 72% of total state-wide solar generation), North Carolina (27 TWh, 50% state-wide solar generation), Nevada (22 TWh, 51% state-wide solar generation), and Texas (18 TWh, 31% state-wide solar generation).

Impacts of solar generation on fossil fuel generation

We find that a marginal increase in solar generation reduces the electricity generation from fossil fuel sources in the same region, when holding the electricity demand constant (Figure 2B). Increased

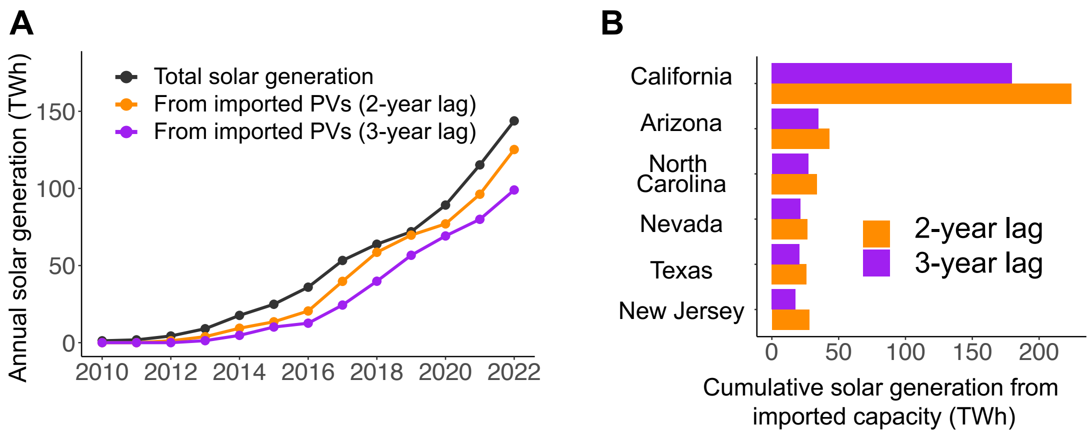

Figure 1: **Solar generation associated with imported PV capacity accounts for about 70% of total solar generation in the U.S in recent years.** Panel A: annual solar generation in the U.S. from all PV capacity (black), from imported PV capacity assuming a 2-year lag (orange) or a 3-year lag (purple) between electricity generation and panel shipments. Panel B: cumulative solar generation associated with imported PV capacity at the state level (2010–2022). Panel B shows the top six states with the largest solar generation associated with imported PV capacity.

solar generation mostly displaces electricity generation from fossil fuel sources, except for in Carolina and Southeast where increases in solar generation are also associated with small declines in hydro generation. This is consistent with the fact that small-scale hydro generation plays an important role in these two regions, and they can be operated to match the solar generation variability.[31] One unit of solar generation can have different effects on different types of fossil fuel generation across grid regions, depending on the underlying energy mix of each region (see Figure S4). For example, we estimate that 1 MWh of solar generation in Texas can reduce generation from natural gas generation plants by 0.70 MWh, and generation from coal power plants by 0.31 MWh. In Florida, however, 1 MWh increase of solar generation reduces natural gas generation by 0.97 MWh and effectively zero generation from coal power plants (see Table S1).

We also find that solar generation in one region reduces electricity generation from fossil fuel power plants in neighboring regions through import/export of electricity, consistent with prior studies.[12,32] These transboundary effects are particularly important in the Western Interconnections (California, Northwest, and Southwest). For these three regions, we find that an increase in solar generation in one region reduces electricity imports from the other two regions. Since most of the electricity import is supplied by fossil fuel power plants, increased solar generation thus reduces electricity generation from fossil fuel plants in the neighboring regions (see Figure 2C and Method).

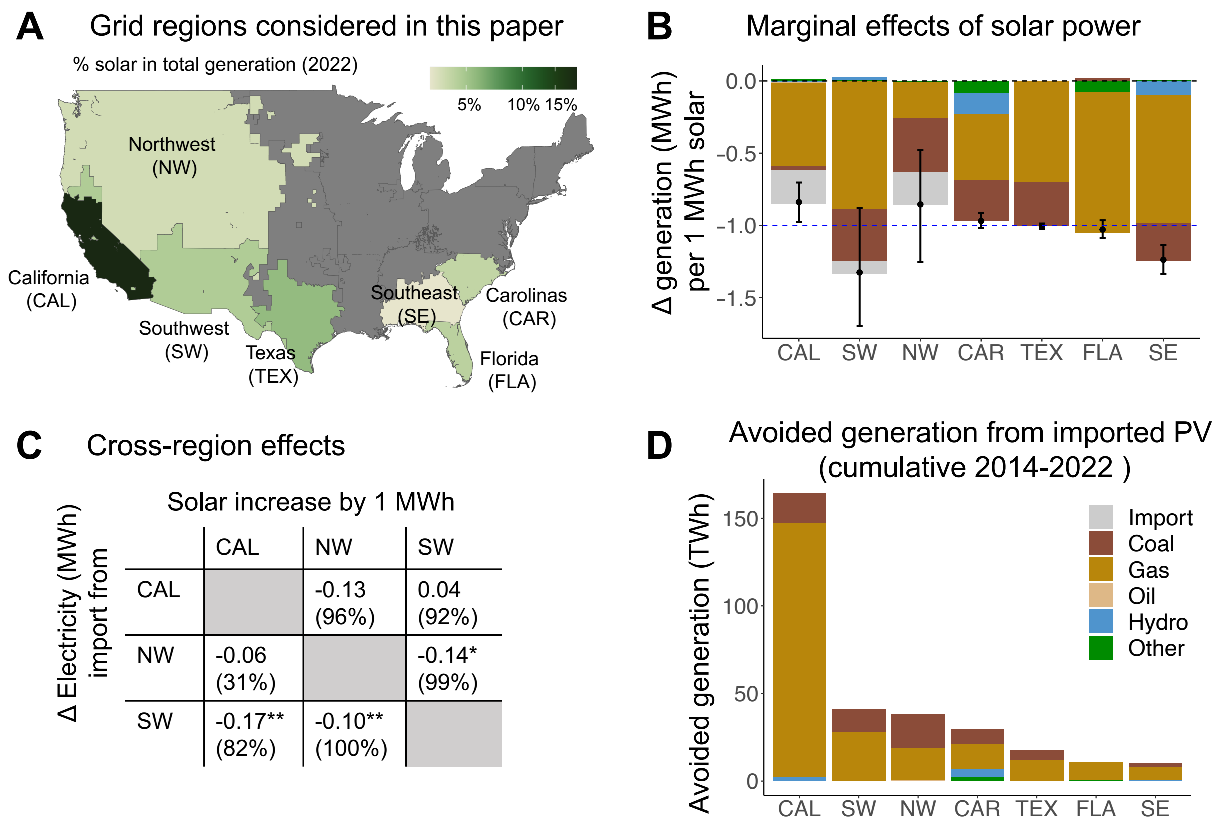

Figure 2: **Solar generation reduces electricity generation from fossil fuel power plants.** Panel A: Grid regions considered in our study. The map shows the percentage of solar generation in the total generation at each region in 2022. We only include the seven regions with solar contribution >1%. Regions not included in the study are shown in grey. Region shape and definition are derived from the Energy Information Administration.[26] Panel B: Estimated marginal changes in electricity generation from power plants of different fuel types due to 1 MWh increase in solar generation in each region. Dashed line in A represents 1MWh/1MWh threshold. The error bar indicates the 95% confidence interval of the aggregated effects, estimated using bootstrap. Panel C: estimated impacts on electricity import from the neighboring regions (rows in the table) due to 1 MWh increases in solar generation in each region in the Western U.S. (columns in the table). Significance: $*$ $p<0.10$, $**$ $p<0.05$. Percentage values in the parenthesis show contributions of fossil fuel plants to the electricity import. Panel D: cumulative avoided electricity generation due to imported solar PV (2014-2022).

For example, we estimate that 1 MWh increase of solar generation in Northwest (NW) can lead to a decrease in electricity import from California (CAL) by 0.13 MWh. We further find that every 1 MWh change in electricity export between NW and CAL is associated with a change of fossil fuel generation in CAL by 0.96 MWh (Figure S5). This suggests that, when NW has more solar generation, NW reduces the net import of electricity from CAL, leading to some fossil fuel plants in CAL to generate less. During the studied period, we estimate that most changes in electricity import/export are associated with changes in fossil fuel generation almost with a 1-1 relationship, except for electricity imported from NW to CAL (Figure S5). There, we estimate that 31% of the electricity exported from NW to CAL came from fossil fuel power plants in NW (with coal and natural gas plants each contributing to 19% and 12%, respectively). This is consistent with the fact that hydropower accounts for over 30% of total electricity generation in NW and is found to be associated with transboundary import/export between NW and CAL.[33]

When combining the estimated solar generation from imported PV capacity with the estimated effects of solar generation on fossil fuel generation, we find that imported PV capacity has avoided electricity generation from fossil fuel sources by 305 TWh during 2014–2022, which is about 14% the size of total electricity consumption in the studied regions in 2022 (Figure 2D). Generation from natural gas plants accounts for 235 TWh (77% of the total avoided generation). Generation from coal power plants accounts for another 66 TWh (22% of the total), with generation from other fossil fuel (including oil and biomass) accounting for the remaining 1% (see Figure S6 for results at region-year level). We find most avoided coal generation comes from coal power plants in Northwest (NW) and Texas (TEX), while most avoided natural gas generation is associated with plants in California (CAL) and Southeast (SE).

Impacts on emissions, air quality, and human health

Figure 3 shows the emission, air quality, and health benefits of electricity generation from imported PV capacity from 2014–2022. Estimated with our statistical model, the imported PV capacity has reduced SO_2 emissions by 88,000 tons (8.2% of the total power sector SO_2 emissions in the U.S. in 2022), NO_x emissions by 153,000 tons (12% of U.S. total in 2022), and CO_2 emissions by 178 million tons (11% of U.S. total in 2022) over 2014–2022. We estimate a total reduction of 595 premature deaths (95% confidence interval: [377, 807]) across the U.S. during 2014–2022 due to decreased $PM_{2.5}$ concentration related to imported PV capacity (see Figure S7 for effects on $PM_{2.5}$ concentration). As shown in Figure 3D, the health benefits of imported PV capacity are distributed across the populous counties in California, Texas, both Carolinas, and Florida. This is because of the large amounts of electricity generation produced from imported PV capacity, alongside high-emitting fossil fuel plants being displaced by solar generation in these regions. Table S2 shows the mortality effects estimated using alternative exposure-response functions between all-

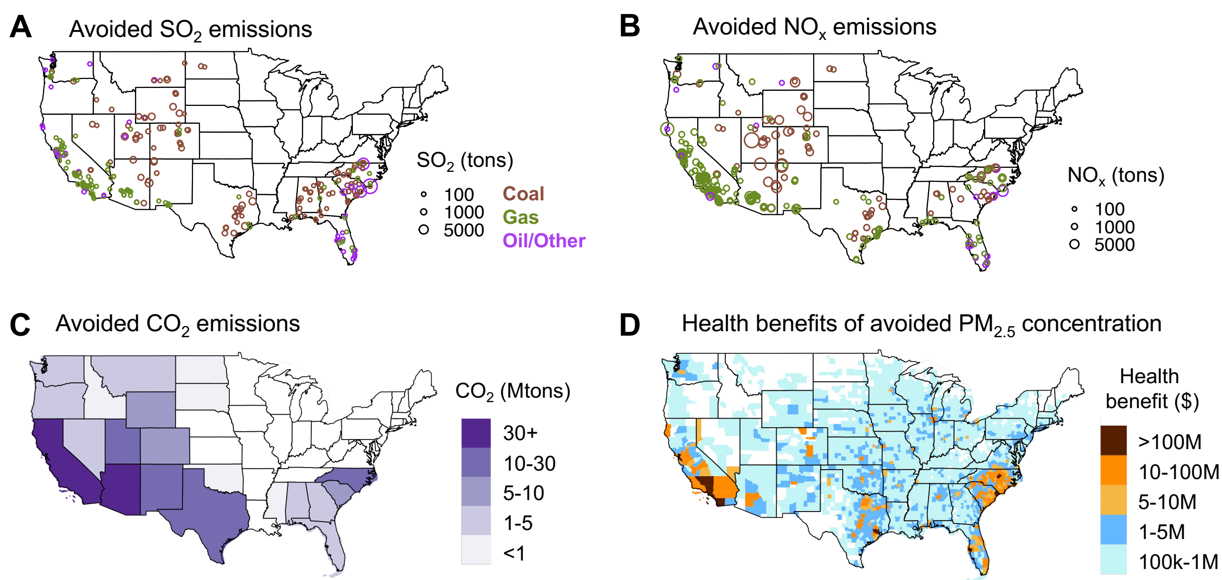

Figure 3: **Avoided emissions and $PM_{2.5}$-related health benefits associated with electricity generation from imported PV capacity.** Panel A and B: avoided SO_2 and NO_x emissions from fossil fuel power plants due to electricity generation from imported PV capacity. Panel C: avoided state-level CO_2 emissions due to electricity generation from imported PV capacity. Panel D: Health benefits at the county level due to avoided premature mortality associated with exposure to $PM_{2.5}$ concentrations. The plots show the total cumulative emission changes and health benefits from 2014 to 2022.

cause mortality and $PM_{2.5}$ exposures. Table S3 shows the estimated mortality by six leading death causes.[34]

We estimate that imported PV capacity has resulted in cumulative monetized climate and health benefits of $28 billion in the U.S. over 2014–2022. Climate benefits associated with carbon emission reductions represent 76% of the total benefits ($21.3 billion), and air pollution-related health benefits account for the rest 24% ($6.7 billion). Averaged across the U.S., 1 kW imported PV capacity created $180 (95%CI: $54-$378) of climate and air pollution-related health benefits during the studied period ($137 from climate benefits and $43 from health benefits). However, as shown in Figure 4, the environmental benefits of importing and installing solar PV are quite different across different regions. Importing solar PV in North and South Carolina generates the largest benefit at $239 due to large health effects. We estimate that solar generation in Carolinas has large effects on three power plants which have high SO_2 emission factors and are close to populous regions. On the other hand, importing solar PV in Florida only generates a marginal benefit that is less than half of the benefits in CAR, TEX, and NW, at $109 per kW. This is because solar generation in FLA mostly displaces generation from natural gas plants, which have relatively lower emission factors of CO_2, SO_2, and NO_x. Note that while the marginal effects of solar generations are likely similar across imported and domestic-manufactured panels, the average benefits of imported PV capacity and domestic PV are slightly different due to the varying emission factors and share of imported solar PV. We have reported the differences in Table S7. Monetized benefits of imported PV capacity increase over time which reflects an increasing trend of imported PVs despite the lower emissions factors from fossil fuel plants in more recent years (Figure S8). Monetized impacts estimated using alternative values of SCC and VSL are reported in Table S4.

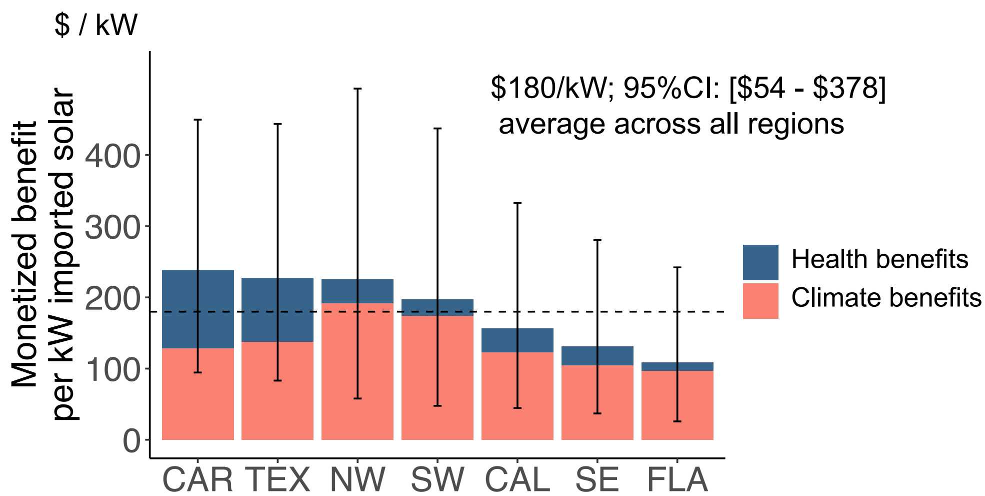

Figure 4: **Average monetized climate and health benefits of importing 1 kW PV capacity.** This plot shows the average monetized benefits associated with the imported PV capacity (1 kW) in each of the corresponding regions over 2014-2022. The results are calculated as the total benefits of solar generation associated with imported PV capacity divided by the total sum of imported PV capacity between 2014-2022. The monetized benefits include climate benefits from avoided CO_2 emissions and health benefits related to avoided $PM_{2.5}$ mortality. Climate benefits are calculated using a social cost of carbon value of 120$ per ton, as recommended by U.S. EPA.[30] Health benefits are monetized using a value of statistical life of 10.95 million dollars (2019 $US), as recommended by U.S. EPA.[29] The error bars represent the 95% confidence intervals of the monetized benefits using the uncertainty of the exposure-response function (for health benefits) and the uncertainty in SCC (for climate benefits). All values are converted to dollars in the year of 2020.

We find that the improved air quality associated with imported PV capacity benefits all population groups with different income and racial/ethnicity backgrounds (Figure 5). The air quality benefits are distributed fairly evenly across different income groups (as the % benefits accrued to each income group is similar to the % of population of each group). The Hispanic population proportionally benefits more from the imported PV capacity (22.8% of the benefit accrued to Hispanic populations which is 17.7% of the total population). The largest air quality benefit is accrued to white populations, despite the lower-than-average proportional benefits. Importantly, we find that importing solar panels substantially benefits the population living outside the importing states. We estimate that 42.8% of the total air quality benefits flowed to populations living outside the importing states, as a result of the import/export of solar generation (Figure 2C) and the spatial transport of $PM_{2.5}$ (Figure S7).

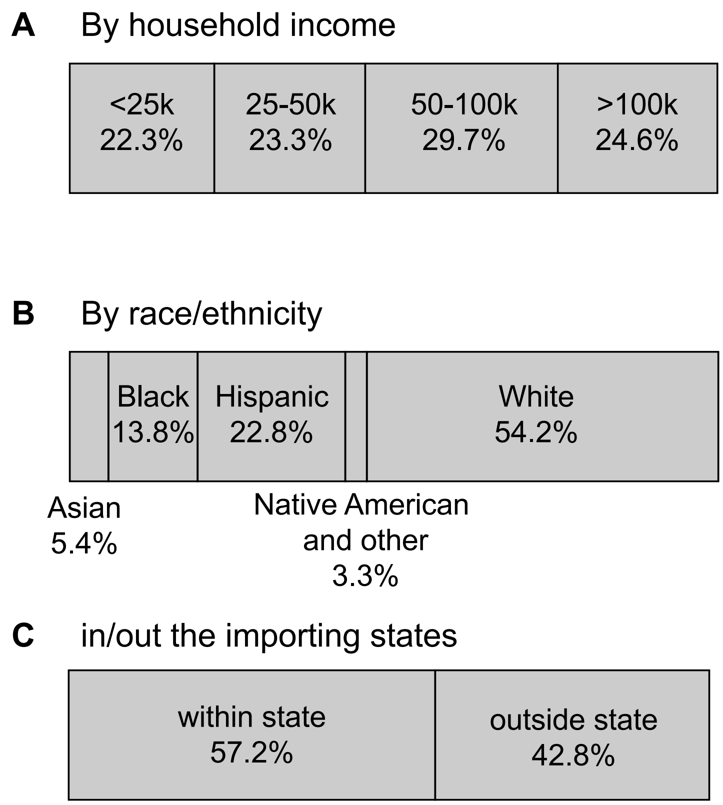

Figure 5: **Who benefits from the improved air quality associated with generation from imported PV capacity?** This plot shows the population subgroups getting the health benefits associated with imported PV capacity, decomposed into different income groups, different racial/ethnic groups, and residents living within/outside the state that imports the solar PV capacity.

Discussion

Our analysis shows that imported PV capacity from global supply chains has created large carbon mitigation, air pollution reduction, and human health benefits in the U.S. We estimate that imported PV capacity has resulted in monetized benefits of $28 billion in total over 2014–2022 in the U.S., a comparable magnitude as the estimated cost savings of $22.6 billion by importing from global supply chains between 2014 and 2020.[9] On average, we estimate that importing and installing a 1 kW solar PV capacity generates a monetized benefit of $180, offsetting almost half of the module cost in 2020.[35] Our results are robust against alternative exposure-response functions for health impacts analysis, alternative plant-level downscaling methods, and alternative choices of lag period between installation and generation (Tables S2, S4, S5, S6).

Our study demonstrates that the benefits of global supply chains of clean energy are much larger than prior estimates that do not account for the environmental and health benefits. Projecting the future impacts related to imported solar PV is challenging due to the underlying uncertainty in the global supply chain and energy sector transition in the U.S. However, these effects identified in our historical analysis likely remain large in the near term as fossil fuel plants remain the "marginal energy source" (i.e. the source that provides additional energy load when there is an additional demand) even under rapid growth of renewable energy, which suggests increasing PVs will keep replacing fossil fuel plants.[36] Considering the benefits of global clean energy supply chains does not imply ignorance of other challenges of global supply chains, especially the disruptions revealed by the pandemic and geopolitics. In fact, our analysis shows the need to enhance the resilience of the supply chains to address those challenges so countries can continue to benefit from global supply chains while reducing other risks. As some countries move away from global clean energy supply chains, costs could be higher therefore impeding the deployment of solar PV which would reduce the environmental and human health benefits from solar deployment.

In this work, we leverage daily electricity generation data to quantify marginal influences of solar power on fossil fuel power plants, accounting for cross-region import/export of electricity. Our approach is similar to the statistical approaches used in earlier work with several modifications.[12,15,32] First, our work leverages more recent data and captures the marginal effects of solar power in a grid where solar power plays an increasingly important role (Figure S4). Second, we use daily (instead of hourly) data to account for the diurnal variability of solar power to capture both the temporary and delayed effects of solar power on fossil plant emissions. Finally, we only use electricity generation data of different fuel types and then estimate the emission impacts based on technology-specific emission factors. Nevertheless, our estimated impacts of solar power on electricity generation and emissions are similar to prior studies (see Figure S9, S10). Consistent with prior work, our results show strong heterogeneity in health benefits from imported solar PV across states due to differences in the underlying energy grid and emissions factors.[12,32] Our results highlight important opportunities to improve air quality and human health through solar import and deployment in these high-benefits regions (e.g., Carolinas and Texas). We also find that solar power does not always displace the most polluting sources (such as high-emitting coal power plants), which highlights an opportunity to design and implement complementary policies to maximize the environmental benefits associated with solar power adoptions.[15,37]

This study has several limitations that could be strengthened by future research. First, EIA does not directly report import data at the state level. Instead, we estimate the state-level imported PV capacity using state-level shipment data (which includes both international shipping (i.e. "imported PV capacity" as focused in our work and domestic shipping). The ratio between international and domestic shipping, however, is not available to us at the state level, and we thus rely on the national share for each year to make the calculation. Second, the effects of solar power on fossil fuel electricity generation are modeled at the ISO scale, and then statistically downscaled to the fossil plant level assuming equal effects among plants of the same fuel type within each ISOs. While we show that our estimated impacts are robust across alternative down-scaling approaches (Table S5), our study does not capture the actual effects at the plant level which may be determined by local marginal prices of electricity and transmission congestion. Third, our analysis focuses on the existing power grid and does not assess long-run marginal emissions, for example, how other renewable energy projects (such as wind) might have been built in the absence of imported solar PV capacity. Fourth, our assumption of a three-year lag between solar PV import and electricity generation is based on industrial practices which may not reflect individual project progress. A three-year lag is likely longer than what it takes for many individual projects, so our estimates are thus a lower bound of the associated benefits, as we underestimate the solar generation associated with the imported PV capacity (Table S6). Fifth, despite the wide use of InMAP in understanding electricity production impacts on air quality,[38,39] it does not account for the inter-annual variability of meteorological conditions or changes in baseline air quality. Future research can leverage alternative air quality models to understand how air quality impacts may vary across different models. Finally, our health benefit estimate should be viewed as a lower bound as it does not account for potential influences through morbidity burden (such as hospitalization and health care costs) or labor productivity.[40,41]

In summary, our study provides quantitative evidence on the climate, environmental, and human health effects of imported solar PV. These findings can inform more comprehensive considerations in supply chain policies and decision-making. Initiatives such as the Coalition of Trade Ministers on Climate aim to promote coordinated trade policies to address climate change. Our research contributes novel evidence to the complex issues and debates over supply chains in global clean energy transitions. Some of the decisions might not always be based on cost considerations, rather on supply chain security, energy security, and other political economic factors. For example, IEA highlighted the need for secure, resilient and sustainable energy technology supply chains,[42] and the U.S. Department of Energy proposed a whole of government approach to chart a course for revitalizing the U.S. economy and domestic manufacturing by securing the country's most critical supply chains.[43] The distributional effects of climate and health benefits by household income, race/ethnicity, and across importing and neighboring states provide nuanced, granular insights into who gains and losses from policy changes, highlighting the need to protect the vulnerable populations and communities. Nonetheless, our evidence shows what's at stake, and what are the trade-offs of such moves that reduce solar imports and deployment. When policy makers desire to decouple from global supply chains, they need to balance the benefits and costs, and create the right incentives and necessary policies to address the unintended impacts.

Methods

Resource availability

Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the lead contact, Gang He, gang.he@baruch.cuny.edu .

Materials availability

This study did not generate new materials.

Data and code availability

The dataset and code to generate the figures are available at `https://zenodo.org/records/16622349`.

Datasets

Solar imports by state

We obtain state-level solar shipment data in the U.S. and its territories during 2010–2022 from the Energy Information Administration (EIA)'s Annual Solar Photovoltaic Module Shipments Report.[21] This state-level dataset includes shipment for both importing, exporting, and manufacturing purposes, but the data for each individual category is only available at the national level. Therefore, we multiply state-level shipment data by the national import ratio (i.e., ratio between imported capacity over total shipment) each year to calculate the imported PV capacity by state from 2010 to 2022. Thus, our estimates of state-level imported PV capacity captures the state-level variations in PV shipments (e.g., a state that imports more will have higher shipment), but is subject to other uncertainty (e.g., if a state is only an intermediate transfer location).

We consider a 2-3 year construction period for solar projects, i.e., the time lag between shipments and power generation, following the average timeline for solar projects.[25] Due to this time lag, we only use shipment data from 2012-2020, although our analysis estimates impacts on climate and health benefits from 2014-2022. Using a lag time of 2-3 years, we estimate that the imported PV capacity during 2010–2022 accounted for 87% (2-year lag) or 69% (3-year lag) of the total installed capacities in 2022 (see Figure S2). We use the three-year lag in our main analysis as a conservative estimate of the imported PV capacity, and report the estimates assuming a 2-year lag in the sensitivity analysis (Table S6). Electricity generation associated with imported PV capacity is calculated using imported solar capacity and annual average capacity factor of solar plants in each state. It should be noted that the EIA data has 'W' (Withheld to protect sensitive data) and 'Q' (Poor data quality) for a few data entries. We treated 'W' as missing value (0), and there is no 'Q' in our analysis. The dataset represents the best available data for state level solar PV shipments and imports.

Regional electricity generation data by fuel types

To estimate the effect of solar generation on electricity generation from other fuel types, we use daily regional electricity generation by different fuel types from 2018-2022 derived from EIA Hourly Electric Grid Monitor dataset.[26] The dataset includes daily generation of different fuel types, electricity demand, and import/export of electricity generation between one region and all other regions. We focus on seven EIA regions in our analysis: California (CAL), Carolinas (CAR), Florida (FLA), Northwest (NW), Southwest (SW), Southeast (SE), and Texas (TEX). The region definitions can be found in Figure 2A. These regions are selected because their solar generation accounts for at least 1% of the total regional electricity generation in 2022, so we can robustly estimate the effects of solar generation on electricity generation from other fuel types.

Plant-level generation and emissions data

To quantify the effects of generation from imported PV capacity on emissions, air quality, and health effects, our analysis focuses on the fossil fuel power plants operating between 2014-2022. Annual electricity generation and emissions (CO_2, SO_2, and NO_x) of major fossil fuel electricity power plants are obtained from EIA.[44] The emissions data of SO_2 and NO_x combines data from the EPA Air Market Program Dataset[45] and EIA estimates (when EPA data is unavailable). Our final sample consists of 1256 fossil fuel power plants – 1189 plants that use natural gas, 140 plants that use coal, 112 plants that use oil, and 21 plants that use biomass or other fuel types (among them, 174 plants have more than one fuel type).

Impacts of solar generation on fossil fuel generation

We use a statistical model to quantify the impacts of daily solar generation on daily electricity generation from different fuel types, following similar methods from prior literature.[16,32,12] For each grid region in our sample, we estimate the following equation:

$$Y^i_{r,ymd} = \beta^i_r Solar_{r,ymd} + \gamma_i X_{r,ymd} + \delta_{r,ym} + \varepsilon^i_{r,ymd} \tag{1}$$

where $Y^i_{r,ymd}$ is the electricity generation from fuel source i in region r at year y, month of year m, and day of month d. We estimate the effects of solar generation on generation from five fuel types: natural gas, coal, oil, hydro, and others. $Solar_{r,ymd}$ denotes the solar generation in region r at year y, month of year m, and day of month d. $X_{r,ymd}$ denotes a set of control variables including electricity demand and generation from other fuel types that are not likely to be displaced by solar generation (wind and nuclear generation). $\delta_{r,ym}$ denotes a set of month-year fixed effects (i.e. separate intercepts for each month in our sample) that accounts for all factors that differ across months. This allows us to control for any factors that differ across month-of-years (e.g. seasonality in electricity generation and weather), as well as any factors that differ across different years (e.g., July 2019 is different from July 2020 for many different reasons). $\epsilon^{i}_{r,ymd}$ represents the error term. The confidence interval of the coefficients is estimated using bootstrap of 500 runs.

The main parameters of interest are β^{r}_{i}, that quantify the impacts of solar generation on electricity generation from fuel type i in region r. In essence, we identify the effect of solar generation on electricity generation of different fuel types using daily variations of solar generation within each month, holding the electricity demand, wind generation, and nuclear generation constant. These parameters measure the causal impacts of solar generation under the identifying assumption that the daily solar generation is uncorrelated with the error term ε after controlling for the control variables and time fixed effects. As suggested by previous literature, this assumption is likely to be satisfied as daily variations in renewable energy production can be viewed as exogenous[46,47]. The exogeneity of solar generation comes from the facts that (1) at the daily scale the solar potential is almost entirely driven by exogenous meteorological variables (such as solar radiation), and (2) real solar generation is very close to the solar potential, as the marginal cost of solar generation is negligible.

Trans-boundary impacts through electricity import and export

For grid regions that are interconnected, solar generation in one region could offset generation from fossil fuel power plants in the neighboring regions due to import and export of electricity. We quantify the transboundary effects in the Western Interconnection (the three grid regions: California, Southwest, and Northwest), where we found that the aggregated impact of 1 MWh of solar generation on fossil fuel plant generation is substantially smaller than 1 MWh, suggesting solar generation likely offset electricity generation from neighboring regions (see Figure 2B). To quantify the trans-boundary impacts of solar generation on fossil power plants in the neighboring regions, we use daily electricity import and export between all region pairs from the same EIA dataset.[26] We estimate the following regression:

$$Export^{i->j}_{ymd} = \beta_{ij} Solar_{j,ymd} + \gamma \boldsymbol{X_{i,ymd}} + \theta_i Export^{i->other}_{ymd} + \delta_{ym} + \epsilon_{ymd}$$

where $\text{Export}_{ymd}^{i->j}$ denotes the net export from grid region i to grid region j on year y, month-of-year m, and day-of-month d. $Solar_{j,ymd}$ denotes the solar generation in region j at year y, month of year m, and day of month d. $\boldsymbol{X_{i,ymd}}$ denotes a set of control variables, including the solar generation, electricity demand, wind, and nuclear generation of region i. $Export_{ymd}^{i->other}$ denotes the export from region i to the other grid region (other than j). δ_{ym} denote year-month fixed effects. ϵ_{ymd} is the error term. Here, the main coefficient of interest is β_{ij}, which quantifies the impacts of solar generation changes in region j on the net export of electricity from region i to j, conditioned on region i's electricity demand, generation, and import/export from the other regions. We estimated six βs in total with $i, j \in \{CAL, NW, SW\}$, excluding the self-pairs.

Air quality impacts analysis

To estimate the effects of imported PV capacity on emissions and air quality, we combine the aggregated estimates of solar generation on different fuel types with plant-level emissions data. We assume that all powerplants of the same fuel type (e.g., natural gas plant) within each region are equally influenced by solar generation at the same proportion. For example, we estimate that 1 MWh of solar generation in Texas can displace generation from natural gas power plants in Texas by 0.70 MWh. We then calculate the generation reductions at each natural gas power plant such that the reduction at each plant is proportional to their total generation while the sum of the total generation reductions equals 0.70 MWh. We further calculate the effects of solar generation on CO_2, SO_2, and NO_x emissions at each plant for each year during 2014–2022, by using plant-specific emission factors for each year, to account for plant-specific technology and facility differences, as well and changes in emissions factors for the same plant over time. To explore the effect of this assumption on the estimated emission and air quality effects, we perform a sensitivity analysis to allow effects of solar generation differ across individual fossil fuel plants (instead of assuming the same proportional effect). More specifically, we construct 5000 plant-level scenarios derived from randomly selecting plants and the amount of generation reductions at each plant due to solar generation in order to match the aggregated effects of solar generation on this fuel type (Table S5).

We use the Intervention Model for Air Pollution (InMAP), a reduced-complexity air quality model to simulate the changes in surface $PM_{2.5}$ concentrations associated with SO_2 and NO_x emissions changes due to solar generation. InMAP is a reduced complexity model that can simulate $PM_{2.5}$ concentrations given emissions inputs[27] and has been widely used to identify air quality impacts of emission changes.[48,39] In this work, we use the InMAP source receptor matrix (ISRM) archived from.[49] The ISRM consists of matrices of dimensions 52411×52411 (as the U.S. is divided into 52411 grid cells) for three heights of emission locations and seven precursor emission species. For a given height and emission species, ISRM calculates the changes in $PM_{2.5}$ for any grid cell in the US due to one unit increase in one of the precursor emissions in any of the 52411 grid cells. We multiply the ISRM of SO_2 and NO_x by the plant-level emission changes (emission heights are determined according to the stack heights of the plant) to calculate the changes in surface $PM_{2.5}$ due to generation from imported PV capacity.

Health impacts analysis

For health benefits, we calculate the changes in premature mortality associated with changes in exposure to $PM_{2.5}$. We use the exposure-response function between $PM_{2.5}$ exposure and all-age, all-cause mortality rates from a recent meta-analysis.[28] Pope et al. estimate a hazard ratio of 1.08 (95% CI: 1.05, 1.11) per 10 $\mu g/m^3$ increase of ambient $PM_{2.5}$ derived from a meta-analysis of 16 studies that estimate the mortality response to $PM_{2.5}$ exposure in North American populations. We calculate the changes in county-level premature mortality due to $PM_{2.5}$ changes using the following equation:[50,51]

$$\Delta \text{Mortality}_c = pop_c \times D_c \times PAF_c \tag{2}$$

where $\Delta\text{Mortality}_c$ estimates the changes in premature mortality at county c due to changes in $PM_{2.5}$, pop_c denotes the population at county c, D_c denotes the baseline mortality rate at county c, and PAF_c is the population attributable fraction (PAF) associated with changes in $PM_{2.5}$ concentrations and is further defined by (given our exposure-response function is log-linear):

$$PAF_c = exp(\beta \times \Delta \text{PM}_{2.5}) - 1 \tag{3}$$

where $\beta = \ln(1.08)/10$ that calculates changes in log mortality rate per 1 $\mu g/m^3$ increase in $PM_{2.5}$ concentration.

We use county-level population and baseline mortality rates from the U.S. Centers for Disease Control and Prevention.[52] We use the county-level average death rate between 2014 to 2019 as the baseline mortality rate for calculations with hazard ratios. Our approach follows a large body of literature that quantifies the mortality impacts of $PM_{2.5}$ change using all-cause mortality rate.[51] To explore the effects of alternative exposure-response functions on the estimated mortality, we also calculate avoided mortality related to $PM_{2.5}$ changes estimated with alternative exposure-response functions;[53,54,55,56] these results can be found in Table S2.

In addition to the estimated all-cause mortality, we estimate the premature mortality due to changes in $PM_{2.5}$, attributable to Chronic Obstructive Pulmonary Disease (COPD), Lower Respiratory Infections (LRI), Ischemic Heart Disease (IHD), Stroke, Diabetes, and Lung Cancer. We focus on these six causes as they account for the majority of death burdens related to $PM_{2.5}$ exposure.[57] We use the relative risks derived from the Global Burden of Disease (GBD) study 2021, which are generated using the MR-BRT meta-regression tool and input data from a rich set of epidemiologic studies of exposure to ambient air pollution.[34] We use the county-level average death rate for each death cause (determined based on ICD-10 codes) between 2014 to 2019 as the baseline mortality rate. The estimated cause-specific mortality can be found in Table S3.

For the distributional analysis of health impacts, we calculate the premature mortality of each demographic group in each county due to changes in $PM_{2.5}$. We combine simulated $PM_{2.5}$ concentrations from ISRM with the county-level demographic information (i.e. population counts of different income and racial/ethnic groups in each county). The demographic data is derived from the American Community Survey (ACS) data from 2013–2017.[58] The county-level demographic data is assumed to be constant across our study period 2014–2022. We also estimate the fraction of health benefits accrued to the population living in and outside the solar importing states. For each state that imported solar PVs, we calculate the avoided emissions and changes in $PM_{2.5}$ and premature mortality that are only associated with the solar generated by the state's imported PV capacity. We then separately estimate the mortality for counties within and outside the importing states.

Monetized climate and health benefits

The health impacts are monetized using a value of statistical life (VSL) of $10.95 million (2019 $US) derived from Carleton et al. 2022.[59] The VSL estimate we use in this paper is based on the value recommended and used by the U.S. EPA's Regulatory Impact Analysis for the Clean Power Plan[29] and is adjusted to the year 2019 dollars. We also use alternative VSL values from the 5th and 95th percentile of a recent meta-analysis of VSL values for sensitivity analysis.[60] VSL represents the monetized values people are willing to pay to reduce the mortality risk by a small margin. VSL estimates are often derived from revealed-preference studies where researchers use observation on human behaviors to quantify the trade-offs between mortality risk and money and stated-preference studies where people are surveyed about their willingness to pay. The VSL approach is widely used to quantify the mortality impacts of air pollution changes as it provides a summary measure for the monetized value of small changes in mortality risk experienced by a large number of people – the exact case for air pollution regulations.

The climate benefit associated with CO_2 emission reduction is monetized using a value of social cost of carbon at $120 per ton (2020 $US) derived using a 2.5% discounting rate.[30] We also use alternative social cost of carbon derived from Rennert et al. 2022[61] — $80 and $195 estimated using 2% and 3% discounting rates for sensitivity analysis.

Acknowledgments

G.H. acknowledges support from the Global Energy Initiative at ClimateWorks Foundation (no. 23–2515). M.Q. acknowledges support from the Minghua Zhang Faculty Career Catalyst Award from Stony Brook University.

Author contributions

G.H. conceived the original research idea. M.Q. and G.H. designed the research and analysis plan. G.H. led solar PV data curation. M.Q. led the modeling on emissions, air quality and human health effects. M.Q. and G.H. drafted the paper with inputs and comments from P.M.. All authors reviewed and edited the paper.

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Supplemental Information

Supplemental Tables

Table S1: Estimated effects of 1 MWh solar generation on electricity generation from different fuel types (including import from neighboring regions, unit: MWh). Values in the parenthesis show the 95% confidence intervals of the coefficients estimated using 500 random bootstrap simulations.

Region	Fuel type	Coefficient	Region	Fuel type	Coefficient
CAL	Coal	-0.03 (-0.05, -0.02)	CAR	Coal	-0.29 (-0.39, -0.17)
	Gas	-0.58 (-0.67, -0.48)		Gas	-0.46 (-0.53, -0.36)
	Oil	0.00 (0.00, 0.00)		Oil	0.00 (-0.01, 0.01)
	Hydro	-0.01 (-0.03, 0.02)		Hydro	-0.15 (-0.19, -0.10)
	Other	0.01 (0.00, 0.02)		Other	-0.08 (-0.10, -0.06)
	Import	-0.23 (-0.34, -0.14)			
NW	Coal	-0.37 (-0.54, -0.20)	FLA	Coal	0.02 (-0.06, 0.11)
	Gas	-0.25 (-0.41, -0.10)		Gas	-0.97 (-1.11, -0.85)
	Oil	0.00 (0.00, 0.00)		Oil	0.00 (0.00, 0.00)
	Other	0.00 (-0.02, 0.01)		Hydro	0.00 (0.00, 0.00)
	Import	-0.23 (-0.62, 0.13)		Other	-0.07 (-0.16, 0.01)
SW	Coal	-0.35 (-0.56, -0.15)	SE	Coal	-0.27 (-0.41, -0.11)
	Gas	-0.89 (-1.13, -0.65)		Gas	-0.88 (-1.04, -0.73)
	Oil	0.00 (0.00, 0.00)		Oil	0.00 (0.00, 0.01)
	Hydro	0.02 (-0.02, 0.06)		Hydro	-0.10 (-0.17, -0.03)
	Other	0.00 (0.00, 0.01)		Other	0.01 (0.00, 0.02)
	Import	-0.09 (-0.42, 0.23)			
TEX	Coal	-0.31 (-0.39, -0.24)			
	Gas	-0.70 (-0.76, -0.62)			
	Hydro	0.00 (0.00, 0.00)			
	Other	0.00 (-0.03, 0.02)			

Table S2: Avoided mortality due to imported PV capacity in 2014–2022 estimated with alternative exposure-response functions. Values in the parenthesis represent 95% confidence intervals.

Scenario	Exposure-response function	Mortality
Imported solar (3 year lag)	Pope et al. 2020[1] (main)	595 [377, 807]
	Krewski et al. 2009[2]	421 [266, 580]
	Lepeule et al. 2012[3]	1013 [523, 1537]
	Hoek et al. 2013[4]	450 [303, 595]
	Di et al. 2017[5]	545 [530, 559]
Imported solar (2 year lag)	Pope et al. 2020 (main)	786 [498, 1066]
	Krewski et al. 2009	556 [351, 767]
	Lepeule et al. 2012	1338 [691, 2031]
	Hoek et al. 2013	595 [400, 786]
	Di et al. 2017	719 [700, 738]

Table S3: Avoided mortality of different causes due to imported PV capacity in 2014–2022. We estimate the premature mortality due to changes in $PM_{2.5}$, attributable to Chronic Obstructive Pulmonary Disease (COPD), Lower Respiratory Infections (LRI), Ischemic Heart Disease (IHD), Stroke, Diabetes, and Lung Cancer. “Total” represents the aggregated estimates across all six causes. Values in the parenthesis represent 95% confidence intervals.

Scenario	Cause	Mortality
Imported solar (3 year lag)	COPD	52 [43, 62]
	IHD	178 [132, 224]
	LRI	27 [3, 49]
	Diabete	27 [16, 38]
	Lung Cancer	50 [31, 69]
	Stroke	49 [38, 60]
	Total	**383 [262, 503]**
Imported solar (2 year lag)	COPD	69 [56, 82]
	IHD	235 [173, 295]
	LRI	35 [3, 64]
	Diabete	35 [21, 49]
	Lung Cancer	66 [41, 91]
	Stroke	65 [50, 80]
	Total	**505 [345, 662]**

Table S4: Estimated monetized benefits of imported PV capacity across different values of value of statistical life (VSL) and social cost of carbon (SCC). The main estimate calculated using SCC of $120 and VSL of 10.95 million dollars are bolded. VSL values are derived from Banzhaf 2022[6] (unit: 2019 $US). SCC values are derived from U.S. Environmental Protection Agency 2023[7] and Rennert et al. 2022[8] (unit: 2020 $US). All values are converted to 2020 $US, except for VSL.

VSL ($million)	SCC ($million)	CO_2 damage ($bn)	mortality damage ($bn)	total damage ($bn)
2.45	80	14.2	1.5	15.7
2.45	120	21.3	1.5	22.8
2.45	195	34.6	1.5	36.1
10.95	80	14.2	6.7	20.9
10.95	**120**	**21.3**	**6.7**	**28.0**
10.95	195	34.6	6.7	41.3
13.97	80	14.2	8.6	22.8
13.97	120	21.3	8.6	29.9
13.97	195	34.6	8.6	43.2

Table S5: Avoided emissions and mortality due to imported PV capacity estimated using an alternative down-scaling approach of generation at the plant level. "Main result" shows results estimated assuming the solar effects on plant-level generation is proportional to the total generation (reported as the main result). "Random at plant level" shows results estimated with random selections of power plants (within each region and fuel type) to respond to solar generation changes while holding the total generation reductions the same. The table shows the average, 2.5 percentile, and 97.5 percentile of the results estimated using 200 random selections.

	Main result	Random at plant level		
		mean	2.5% percentile	97.5% percentile
CO_2 (MT)	178	184	197	172
NO_x (1000 tons)	153	161	238	105
SO_2 (1000 tons)	88	101	148	68
Premature deaths	595	666	421	1099

Table S6: Effects of solar generation associated with imported PV capacity on avoided generation, emissions, and mortality, under 2-year and 3-year lag periods between installation and generation.

	3-year lag	2-year lag
Fossil fuel generation (TWh)	305	392
CO_2 emissions (M tons)	178	229
SO_2 emissions (1000 tons)	88	118
NO_x emissions (1000 tons)	153	196
Mortality	595	786
Monetized benefits ($ billion)	28	36

Table S7: Comparison of average climate and health benefits created by generation of domestic solar PV and imported solar PV at each grid region (2014–2022). The small differences are due to changes in marginal solar impacts over time (e.g., shifts in emission factors for various fuel types) and varying contributions from imported versus domestic solar PV in each region. For example, in Carolinas, the average benefits from imported solar PV is slightly higher than the domestic PV – because higher-emitting plants generate more electricity within each fossil fuel type in more recent years when imported PV contributed more to the overall installed capacity. Overall, the results across the two categories are quite similar.

	Capacity (MW)		Climate benefits ($/kW)		Health benefits ($/kW)	
	domestic	imported	domestic	imported	domestic	imported
CAL	23655	81042	115.7	123.3	31.0	33.1
CAR	20492	17536	117.6	128.7	100.6	110.1
FLA	13551	5711	93.8	97.2	10.9	11.3
SW	6828	17531	165.7	174.3	21.4	22.6
TEX	21986	9807	138.8	138.2	89.8	89.4
NW	0	18006	NA	192.1	NA	33.3
SE	0	6067	NA	104.6	NA	26.7

Supplemental Figures

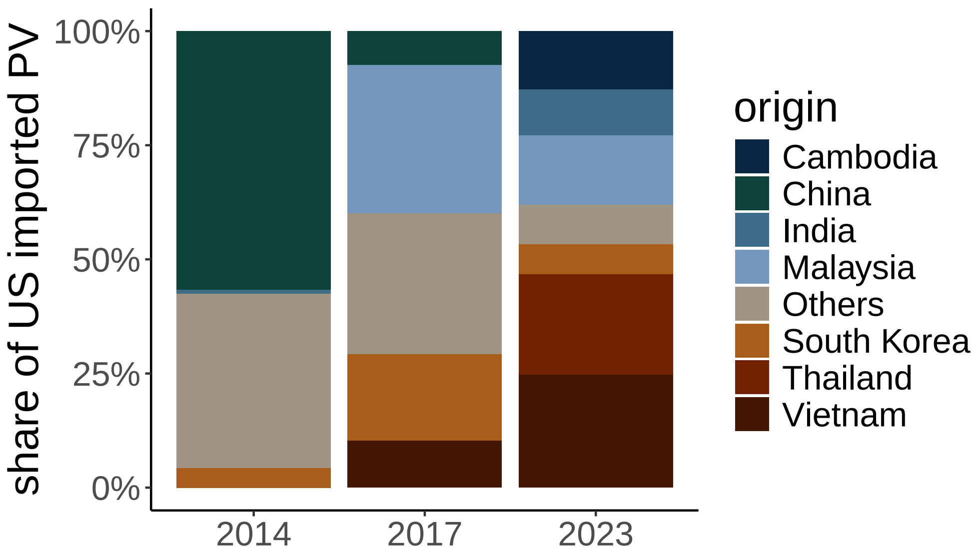

Figure S1: Countries that the U.S. imported solar PVs from.The 2014 and 2017 data are derived from the EIA Annual Solar Photovoltaic Module Shipments Report.[9] While EIA data is available from 2018-2022, there is a major change in the reporting, and multiple countries are often combined in the report since 2018. Therefore, we use the more disaggregated data from the BloombergNEF report of Sustainable Energy in America 2024 Factbook Tracking Market and Policy Trends for 2023.[10]

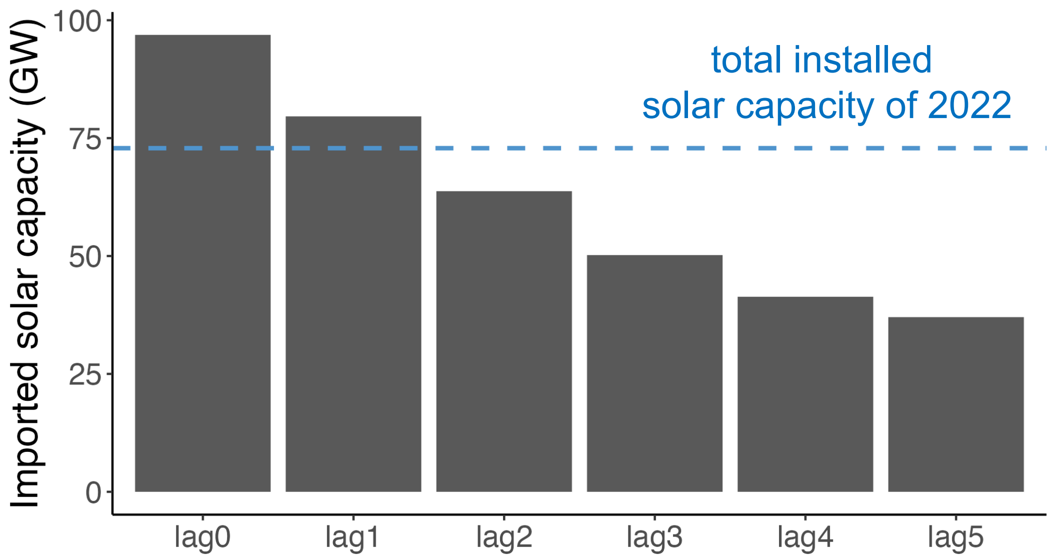

Figure S2: Estimated imported solar PV capacity in the U.S. using different assumptions about the time lags between shipment and installation. The blue dashed line shows total installed solar PV capacity in 2022. Scenarios with no lag or a one-year lag overestimate installed capacity, suggesting they are implausible. The three-year lag assumption aligns most closely with reported import shares and total installations, and is therefore used in the main analysis. The two-year lag is included as a sensitivity case.

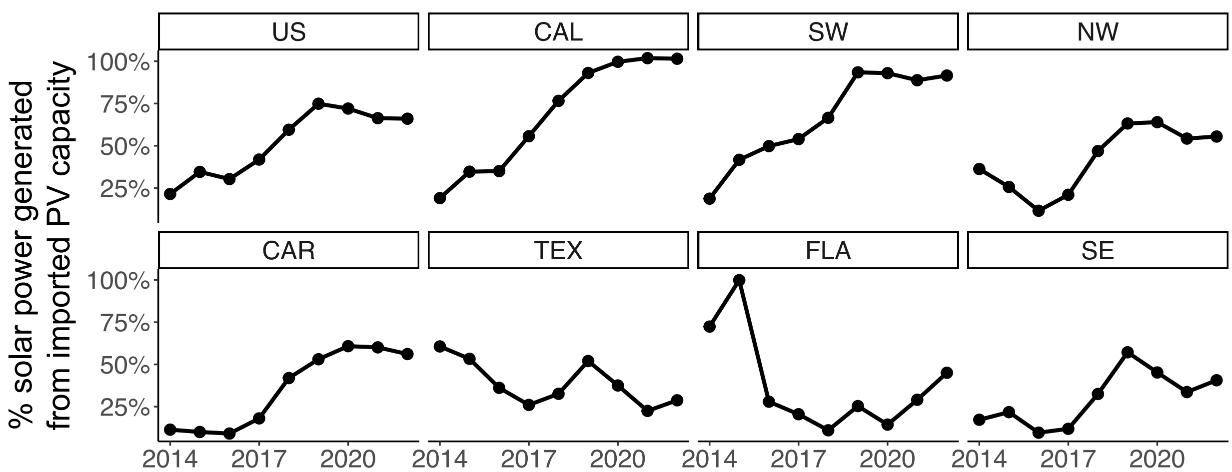

Figure S3: Percentage of electricity generation from imported PVs in total solar generation in the U.S. (the sum of all regions included in our study), and each of the seven regions. The solar power generation from imported PV capacity are calculated using the state-level imported PV capacity and the historical solar capacity factor. This plot shows results assuming a three-year lag between shipment and generation.

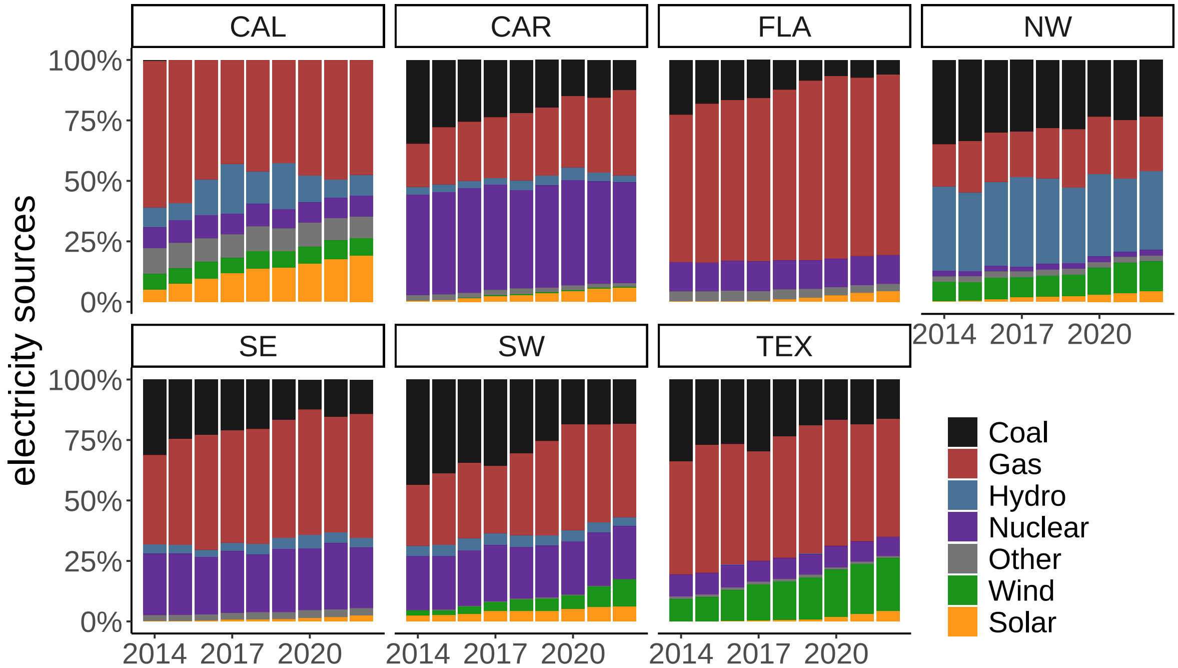

Figure S4: Contributions of different energy types in regional electricity generation by year and region.

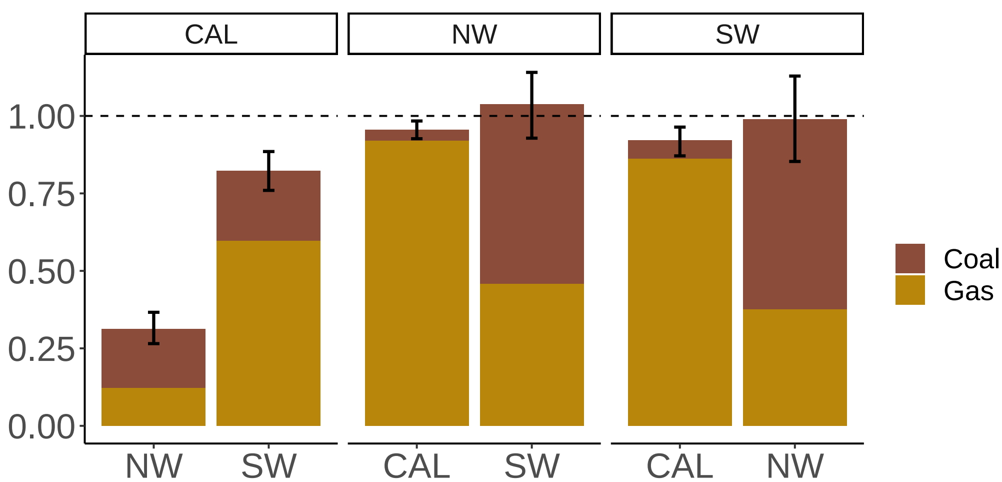

Figure S5: Estimated effects of electricity import/export on electricity generation from different fossil fuel types in the Western United States.

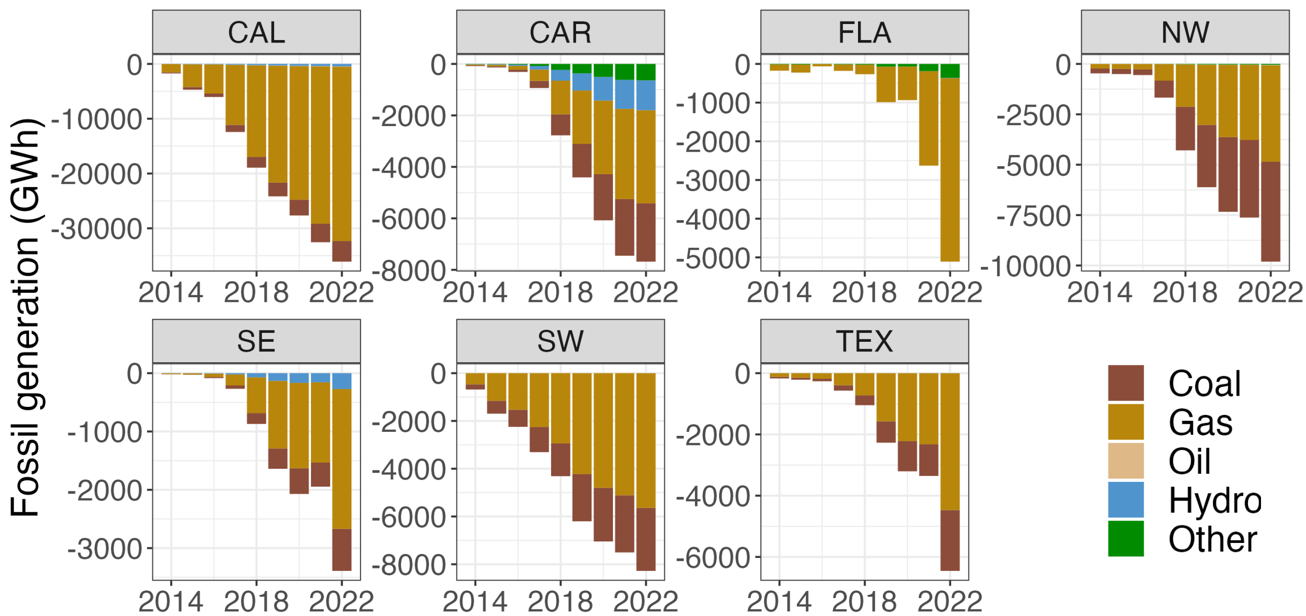

Figure S6: Estimated generation change due to imported PV capacity for each region in each year between 2014–2022.

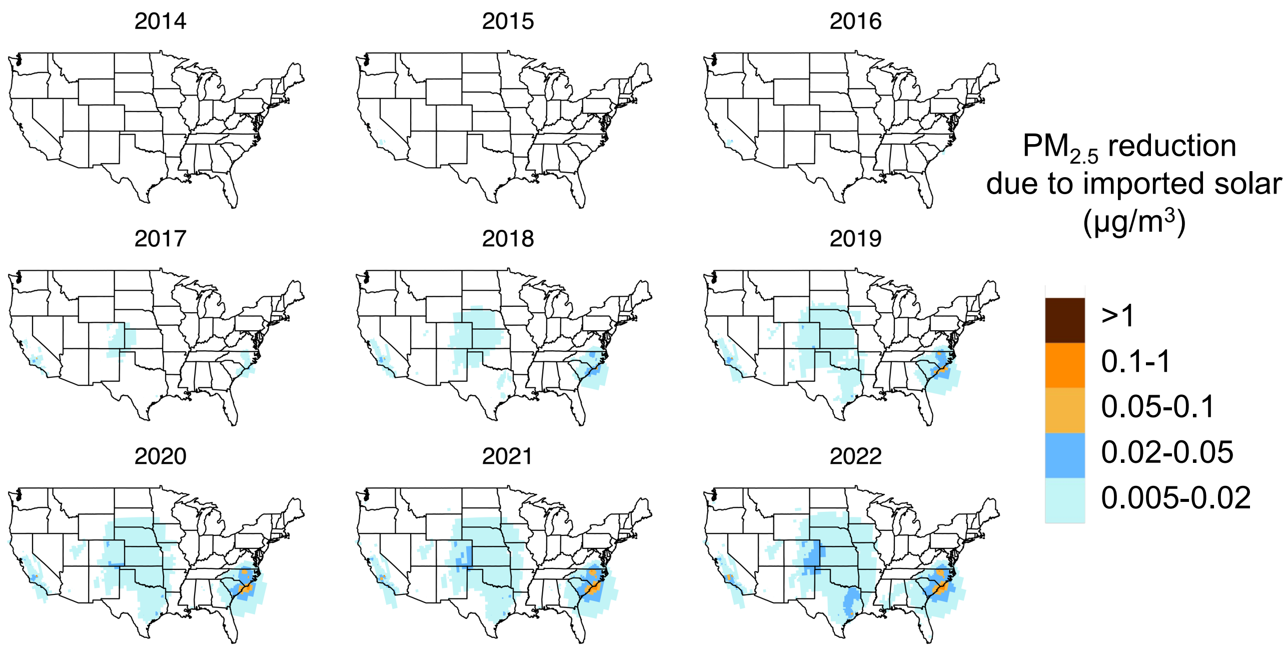

Figure S7: Impacts of imported PV capacity on annual $PM_{2.5}$ concentration from 2014–2022. The plot shows the reduction in annual $PM_{2.5}$ concentration due to reductions of SO_2 and NO_x from power generation associated with imported PV capacity.

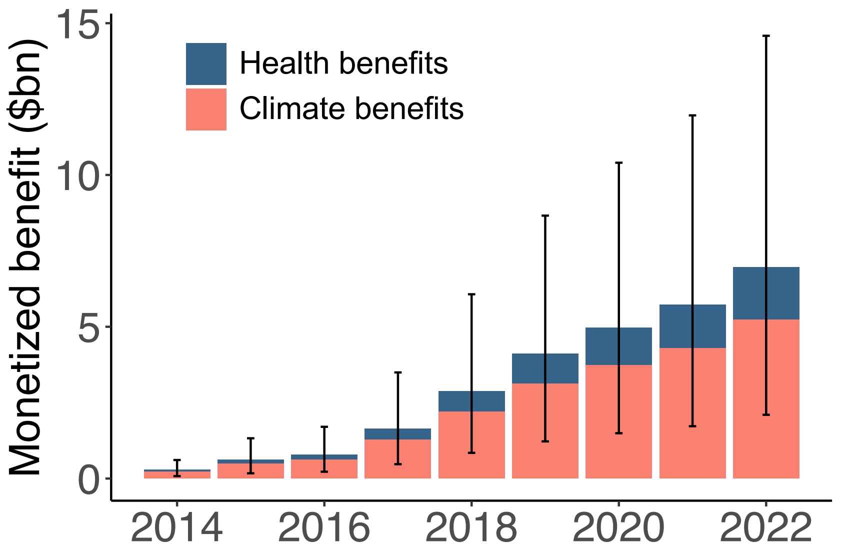

Figure S8: Monetized benefits associated with imported PV capacity in the U.S. over 2014–2022. The error bars represent the 95% confidence intervals of the monetized benefits using the uncertainty of the exposure-response function (for health benefits) and the uncertainty in SCC (for climate benefits).

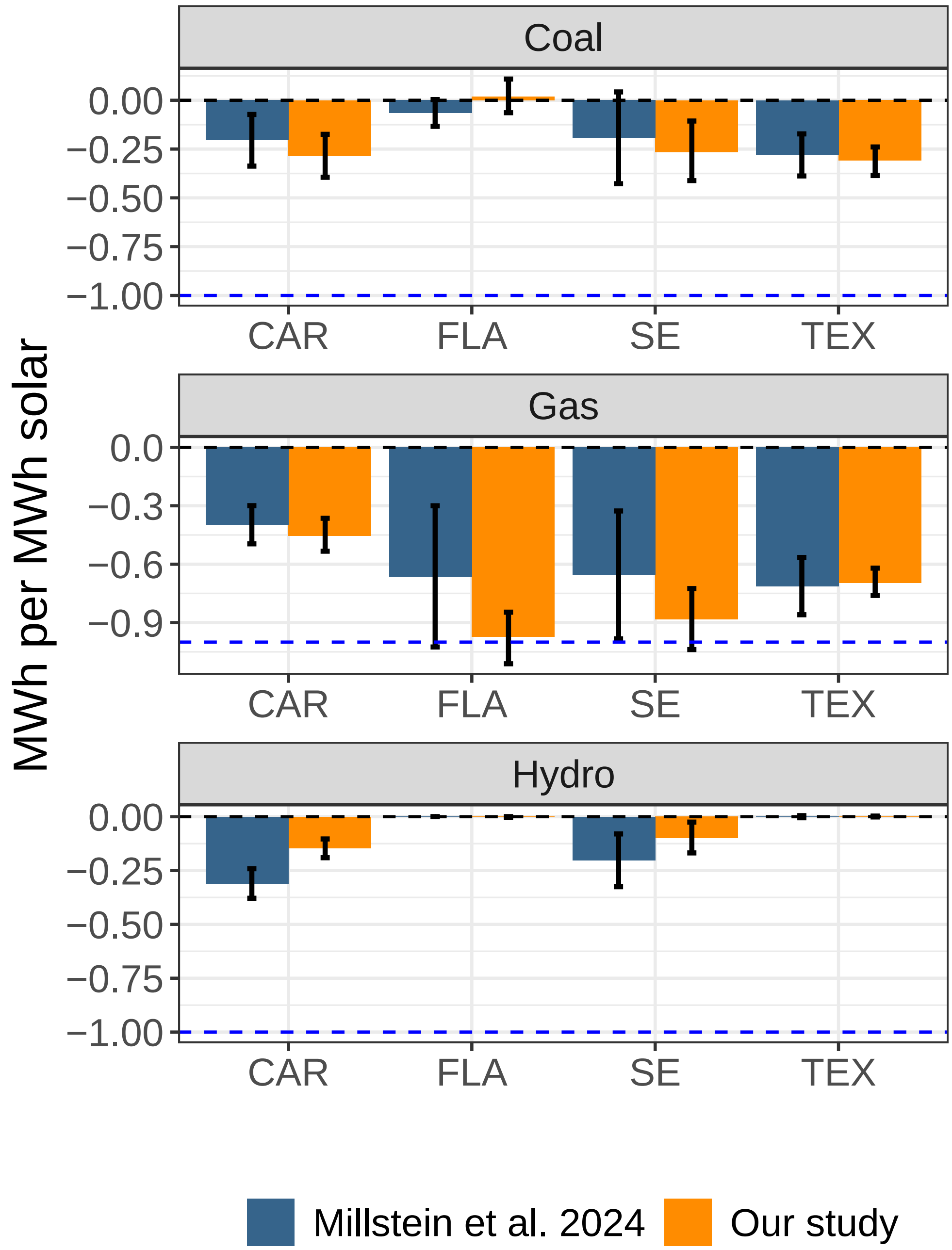

Figure S9: Estimated impacts of solar power on electricity generation from coal, natural gas, and hydro plants. The plot compares the effects estimated in our study with the reported effects in Millstein et al. 2024.[11] Only the four regions that appeared in both papers are shown here. The error bar corresponds to the 95% confidence interval.

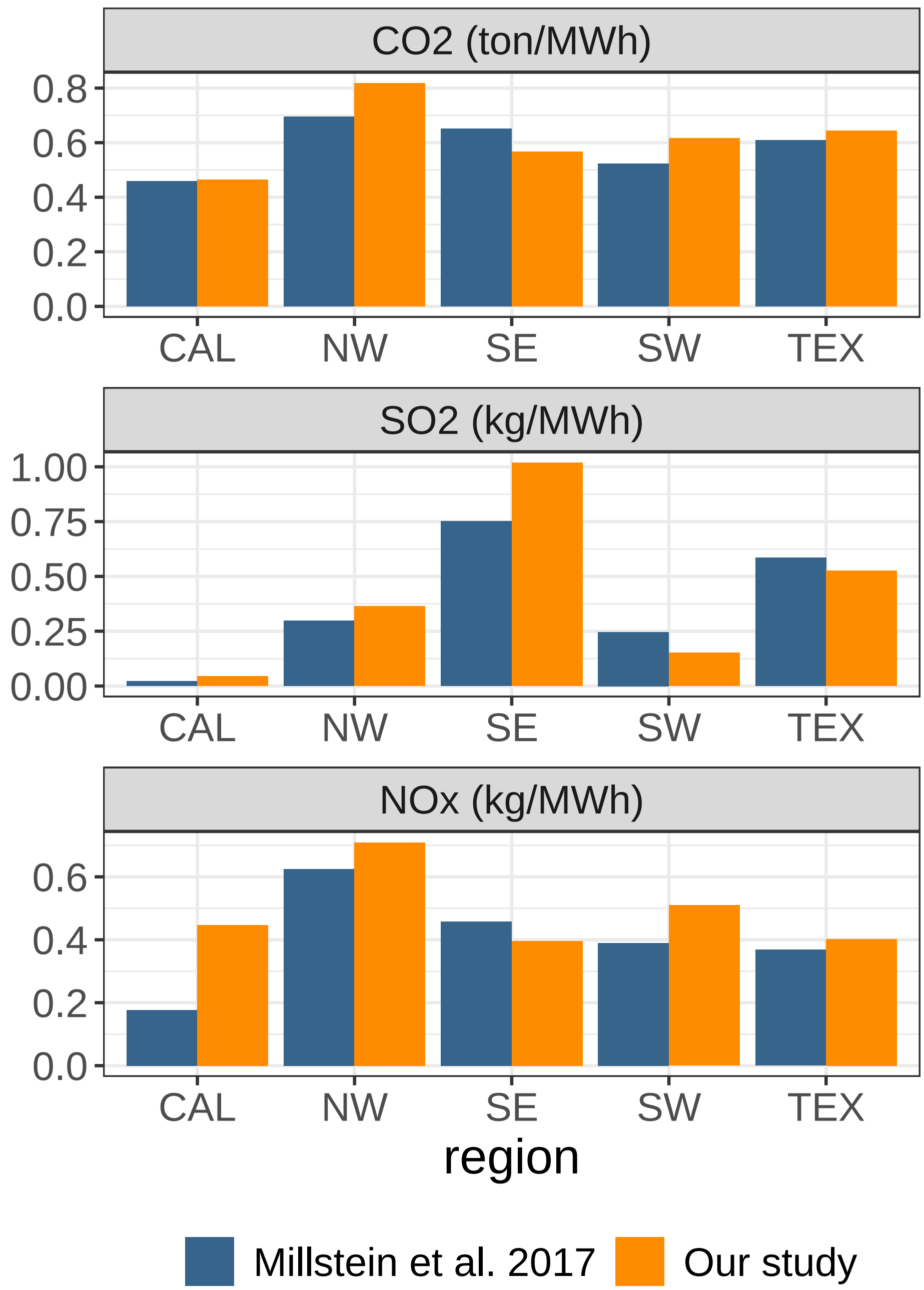

Figure S10: Estimated impacts of solar power on power sector emissions. The plot compares the effects estimated in our study with the reported effects in Millstein et al. 2017.[12] Only the regions that appeared in both papers are shown here. Note the figure shows the estimates for year 2015 from Millstein et al. 2017[12] (the latest year in their reported results) to be more comparable with our study period.

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