# Health and climate benefits of solar photovoltaic in European countries and the role of imports

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# Abstract

Solar photovoltaic (PV) deployment has grown by 300% in European countries over the last decade, yet its aggregated environmental and health implications remain unclear. This study quantifies these benefits from solar PV adoption across eight major European solar adopters–Belgium, France, Germany, Greece, Italy, Netherlands, Spain, and the United Kingdom– between 2015 and 2021. Using a comprehensive analytical framework combining electricity generation statistics, air quality simulation, and electricity trade data analysis, we quantify the $CO_2$ emissions avoided, air quality improvements (i.e., particulate matter), and associated health benefits of solar generation, with a focus on the role of imported solar PV. Our results show that solar generation prevented 12,000 premature deaths from air pollution and avoided 117 thousand tons of $SO_x$, 188 thousand tons of $NO_x$, 1.6 thousand tons of $PM_{2.5}$, and 47 million tons of $CO_2$ emissions from 2015 to 2021 in selected European countries. The monetized value of these benefits amounts to $44 billion, with health benefits accounting for approximately 98% of the total value. Notably, 69% of those benefits are attributable to the generation from the imported solar PV. Cross-border electricity trading further amplifies the benefits, as solar generation in one country reduces fossil fuel use in neighboring countries. However, the distribution of benefits varies significantly across regions, raising environmental justice concerns. This study demonstrates the significant climate and human health benefits of solar PV deployment, while underscoring the crucial role of global supply chains in achieving these outcomes. Our findings provide much-needed evidence to inform policy debates on accelerating clean energy deployment and shaping the future of global clean energy supply chains.

# Introduction

European countries are leading global climate action through ambitious carbon neutrality commitments, as demonstrated by the European Union's (EU) has legally binding commitment to climate neutrality by 2050 (*4*). Some countries have more ambitious or similar neutrality targets, such as Norway targets carbon neutrality by 2030 (*1*), Portugal by 2045 (*2*), and the United Kingdom (UK) by 2050 (*3*). To achieve these goals, countries are actively phasing out fossil fuels - Germany plans to eliminate coal-fired electricity by 2038 (*5*), France aims to end coal use and halve oil consumption by 2030 (*6*), and some nations have already made progress, with Belgium closing its last coal plants in 2016 (*7*) and Portugal ending coal-based generation in 2021 (*8*).

Solar photovoltaic (PV) deployment plays a crucial role in this transition. The EU Solar Energy Strategy targets more than 320 GW of solar PV capacity by 2025 - double the 2021 levels - and nearly 600 GW by 2030 (*9*). Individual countries have set equally ambitious goals: the UK aims for 70 GW by 2035 (*3*), Poland targets 10-16 GW by 2040 (*10*), and Germany plans for 215 GW while aiming to source 80% of electricity from wind and solar by 2030 (*11*, *12*). However, these transitions face significant challenges, as geopolitical turmoil, global health crises, like the COVID-19 pandemic, and extreme weather , such as heatwaves, have strained energy systems and supply stability (*13–15*).

This rapid solar expansion has delivered significant benefits beyond climate mitigation. Research shows that solar generation enhances energy security (*16*), reduces electricity price volatility (*17*), creates local jobs (*18*), and improves public health through reduced air pollution (*19*). Recent studies project substantial health benefits - up to 161,000 life-years saved by 2050 in EU-27 countries just from solar heating and cooling technologies (*20*), and 2.5 million life-years saved by 2050 in England and Wales from renewable energy expansion (low greenhouse gas emission electricity, fuels for transportation, fuels for home energy, etc) (*21*).

Global supply chains have been instrumental in enabling this transition by driving dramatic cost reductions. The average installed cost of solar PV fell by 83% between 2010 and 2022 (*22*), making solar increasingly competitive with conventional energy sources. European solar deployment heavily relies on these global supply chains, with imported modules accounting for 84% of installations over the past five years and reaching an import value of $10 billion in 2021 (*23*). Research indicates that maintaining global supply chains could reduce costs by an additional 20-30% by 2030 (*24*) while supporting job creation (*25*).

This study focuses on eight major European solar markets: Germany, France, the Netherlands, the United Kingdom, Italy, Belgium, Greece, and Spain. They had a population of 361.1 million, 84.1% GDP, 78.6% electricity production of EU in 2023, and these countries represent significant solar PV installations and imports, with solar contributing 6.0% of total electricity generation in 2023 (*26*). Individual countries show even higher shares - 12.3% in Germany and 9.5% in Belgium. These deployments are supported by substantial imports, with Germany and Belgium importing solar PV worth 2.4 billion and 0.2 billion euros in 2021, respectively (*27*). China remains the largest PV exporter to these eight countries, though import ratios vary significantly - from 97% in Greece to 35% in Germany (*27*).

We quantify the climate and human health effects of solar PV generation across these eight countries from 2015-2021, with particular attention to the role of imported solar PV. Our comprehensive analytical framework estimates fossil fuel displacement from solar generation and analyzes how imported solar PV contributes to these benefits. We combine statistical modeling of hourly electricity generation data, air quality simulation ($PM_{2.5}$, $SO_x$, $NO_x$) using the Community Multiscale Air Quality Modeling System (CMAQ), and electricity trade data analysis to provide a detailed assessment of solar PV's climate and health impacts. To accurately attribute climate and health benefits to imported solar panels, we account for the temporal gap between when panels are imported and when they are installed, applying a two-year

lag between trade flows and actual power generation. This research offers valuable insights for policymakers considering both renewable energy deployment and supply chain strategies.

# Literature Review

Solar PV deployment reduces the combustion of fossil fuels in the electricity sector, thereby lowering concentrations of fine particulate matter (PM2.5) and other air pollutants that are causally linked to premature mortality (*59, 60*). Tarín-Carrasco et al. modelled the impact of a scenario in which 80% of EU electricity is supplied by renewables - with solar contributing 23% by 2050 - and found 895,000 reductions in annual excess premature deaths attributable to PM2.5 across the European population (*61*). Millstein et al. quantified air-quality and mortality co-benefits from wind and solar generation, finding that avoided SO2 and NOx emissions from renewables prevent 3,000 to 12,700 premature deaths across the United States (*62*). Chen et al. analyzed 88.8 million deaths across 653 regions in 31 European countries from 2003 to 2019 and found that regions with faster renewable energy adoption showed systematically lower and declining risks of air-pollution-related mortality compared with slower-adopting regions, with the health dividend most pronounced in Western and Northern Europe (*63*). These studies establish a robust evidence base linking solar PV expansion to measurable reductions in air-pollution-related morbidity and mortality, especially across Europe.

The expansion of solar PV in Europe has made a substantial contribution to reducing greenhouse gas emissions. The European Environment Agency reports that the EU electricity sector was estimated to be 62% less GHG-intensive in 2024 than in 1990, with solar and wind identified as the principal drivers of decarbonization since 2010 (*64*). Verlinden modelled the PV capacity trajectory required for the EU to achieve a 55% GHG emissions reduction target by 2030, concluding that cumulative installed capacity would need to reach 455–605 GW, implying compound annual growth rates of 12–15% (*65*). Victoria et al. using an open-source hourly-resolved model of the European energy system, further demonstrated that achieving a 95% CO2 emissions reduction relative to 1990 levels would require solar PV to supply an average of 33% of EU electricity demand, with southern European countries - where irradiation is highest - taking on the largest PV shares (*66*). Osman et al. published in Nature Communications, further showed that full-scale solar expansion in the EU could enable up to 1.8 GtCO2 of cumulative carbon removal by 2050 through direct air capture powered by solar electricity, with Germany, France, Spain, and the Netherlands accounting for the largest national shares (*67*).

Country-level studies further confirm the CO2 reduction role of solar power across Europe. Cabrera-Tobar et al. used daily electricity and emissions data from the ten largest CO2-emitting EU countries, found that solar generation significantly curbed CO2 emissions in Italy, Spain, Romania, and Austria (*68*). In Germany, solar PV has been central to the Energiewende, contributing to a GHG emission reduction target of 55% by 2030 relative to 1990, with the country targeting 215 GW of solar capacity by 2030 (*69*). Life-cycle assessment (LCA) research consistently finds that solar PV generates far lower greenhouse gas (GHG) emissions per unit of electricity than fossil-fuel alternatives. Hsu et al. estimated median lifecycle GHG emissions for crystalline silicon PV of approximately 45 gCO2eq/kWh - roughly twenty times lower than coal-fired generation (*70*). Tawalbeh et al. confirmed this range across PV technologies, reporting carbon footprints of 14–73 gCO2eq/kWh depending on manufacturing conditions, module type, and irradiation (*71*).

Despite the substantial literature on the climate and health benefits of solar PV in general, very few studies have specifically examined those benefits attributable to imported solar panels. Wang et al. constructed a global matrix of PV trade flows and calculated embodied carbon in internationally traded PV products, finding that trade barriers on PV products cause far greater climate damage - by slowing deployment - than the embodied emissions of cross-border supply chains justify (*72*). The only study identified in this literature that directly and jointly quantifies both the health and climate impacts of imported solar panels is Qiu et al. using electricity system modelling linked to air-quality and health impact functions, the authors estimated that solar PV modules imported into the United States between 2014 and 2022 displaced 305 TWh of fossil-fuel generation, avoided 178 million tonnes of CO2 emissions, and prevented approximately 595 premature

deaths from improved air quality, with monetized climate and health benefits totaling roughly USD 28 billion (*73*). Qiu et al. explicitly argue that these broader societal benefits of imported panels - including their public health dividend - must be incorporated into trade and industrial policy deliberations alongside cost and energy security considerations.

While the health and climate benefits of solar PV in Europe are increasingly documented, no study has examined these benefits at the same time across Belgium, Netherland, Spain, Italy, Greece, France, Germany, and United Kingdom across 2015-2021, and specifically through the lens of imported solar panels in a European context. Qiu et al. is the only study to have jointly quantified the health and climate impacts of imported PV - and it is confined to the United States (*73*). This thesis addresses this gap by applying a country-level analysis across selected European countries to quantify both the health benefits - measured through avoided premature mortality, and the climate benefits - measured through avoided GHG emissions, attributable specifically to imported solar PV panels, providing a systematic European assessment of the health and climate value of solar panel and its imported part.

# Results

## Impacts of solar power on fossil fuel generation

The impact of solar generation on fossil fuel electricity generation varies across countries, depending on their energy mix. Our research reveals that increased solar generation affects both domestic fossil fuel generation and electricity imports when controlling for electricity demand. Figure 1 shows the summed displacement effects, while the individual effects with confidence intervals are shown in Figure S2 in the Supplementary Information.

In all countries examined, solar power generation resulted in a reduction in fossil fuel generation and electricity imports, though the effects varied significantly across different fuel types and import levels. For instance, in France, solar generation primarily displaces hydropower, while in Belgium, the largest reduction comes from decreased electricity imports.

For every 1 MWh increase in solar generation, we observe varying displacement patterns that reflect each country's unique energy system. In Belgium, the displacement is distributed across multiple sources, with 1 MWh of solar power reducing natural gas by 0.33 MWh, hydro by 0.04 MWh, and electricity imports by 0.43 MWh, totaling approximately 0.8 MWh. This distribution demonstrates Belgium's high interconnection with neighboring countries and its reliance on both domestic gas generation and imported electricity. Similarly, other countries show displacement effects that align with their generation portfolios, with coal-heavy systems like Germany seeing more coal displacement and import-dependent systems showing greater reductions in electricity imports. The import displacement effects shown in Figure 1 represent the aggregated cross-border electricity trading impacts that are detailed at the country-pair level in Figure 2.

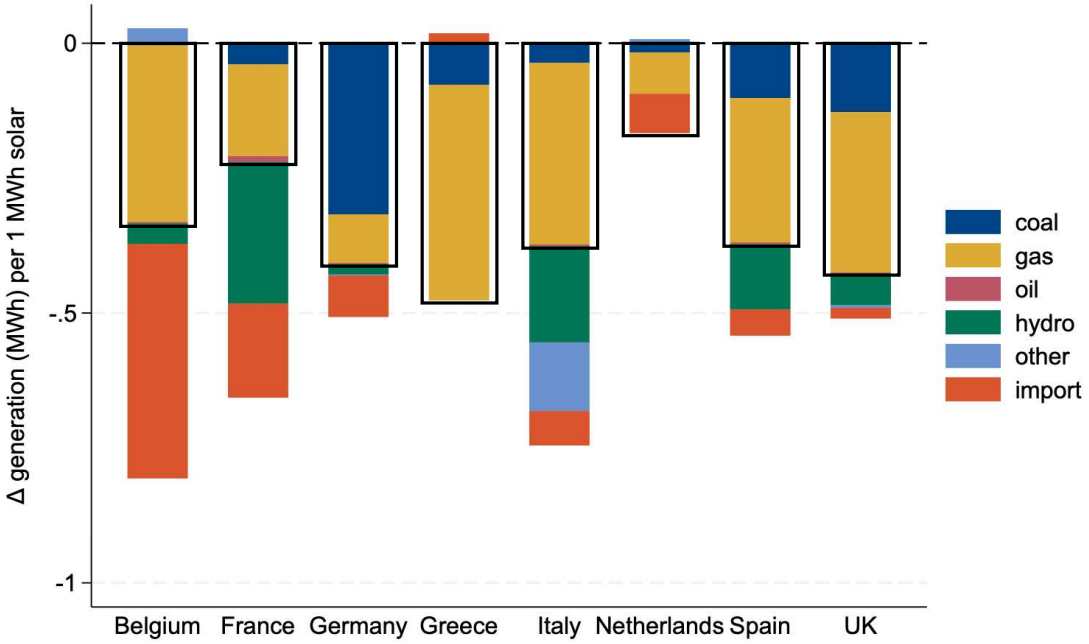



Figure 1: Solar generation reduces electricity generation from fossil fuel and other generations. Note: This figure shows the displacement of generation from different sources for each unit increase in solar generation across eight European countries (2015-2021). Negative values indicate reduced generation from that source. Coal includes lignite, coal-derived gas, and hard coal; Oil includes oil and oil shale; Wind includes both offshore and onshore generation. Import reflects changes in the electricity imports

from neighboring countries.

We also find that solar electricity generation in one country reduces electricity generation from fossil fuels in neighboring countries through import/export of electricity, consistent with prior studies from Fell and Johnson (*28*). These transboundary effects are important in European interconnections, as we observe all significant negative coefficients of the impact of solar generation on electricity import flow. Since most of the electricity imports are supplied by fossil fuel power plants, increased solar generation thus reduces electricity generation from fossil fuel plants in neighboring countries. For example, we estimate that an increase of 1 MWh in solar generation in Belgium can lead to a decrease in electricity import from Germany by 0.07 MWh. This suggests that when Belgium has more solar generation, Belgium reduces the import of electricity from Germany, leading to some fossil fuel plants in Germany generating less. As shown in Figure 2, the magnitude of this effect varies by country pair. For example, our results show that a 1 MWh increase in Belgian solar generation reduces electricity imports from France by 0.38 MWh, while similar generation increases in Germany reduce imports from France by 0.06 MWh. However, the relationship between changes in cross-border electricity flows and fossil fuel generation is not proportional. Historical data show that two-thirds of changes in electricity imports/exports result in relatively modest adjustments to fossil fuel generation, as shown in Figure 2, half of these cases show less than 10% change, and the other half show less than 1% change in fossil fuel power production.

When combining the estimated solar generation from imported capacity with the estimated effects of solar power on fossil fuel generation, we find that imported solar capacity has avoided electricity generation from fossil fuel sources by approximately 92 TWh during 2015-2021, which represents 4% of the total electricity generation across eight focused countries in 2021(*26*) and 22% of total solar-induced fossil fuel displacement during this period.

# Impacts on emissions, air quality, and human health

Our analysis quantifies how solar PV deployment reduced emissions, improved air quality, and benefited human health across the eight European countries from 2015 to 2021. As shown in Table 1, solar generation during this period reduced emissions significantly: 117 thousand tons of $SO_x$, 188 thousand tons of $NO_x$, 1.6 thousand tons of $PM_{2.5}$, and 46.92 million tons of $CO_2$.

These emission reductions led to improvements in air quality that varied considerably by region. Using the CMAQ model, we mapped $PM_{2.5}$ reductions across Europe (Figure 3). The greatest improvements occurred in western Germany, particularly around Bremen, Cologne, and Karlsruhe, with another significant reduction near Berlin. The benefits extended into neighboring countries - the eastern regions of the Netherlands, Belgium, and France saw larger $PM_{2.5}$ reductions due to their proximity to Germany. Substantial improvements also appeared in the London metropolitan area, northern Spain, and northern Italy.

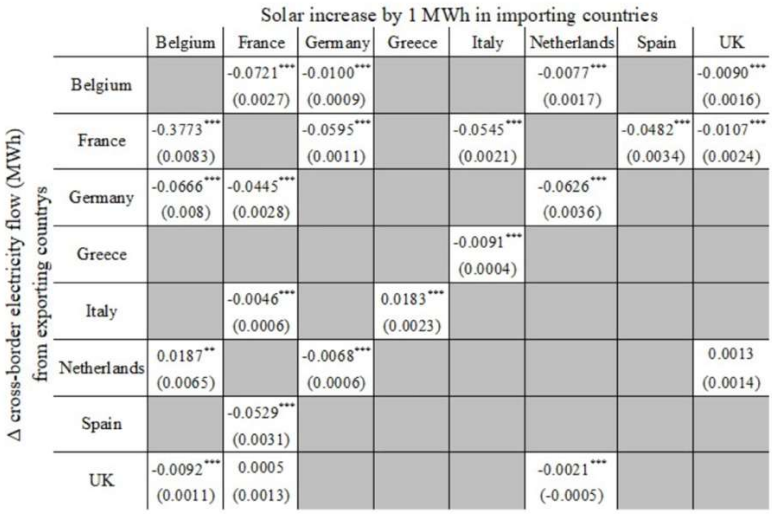



Figure 2: Impact of solar generation increases on cross-border electricity trading. Note: Values show how 1 MWh increase in solar generation in a country (columns) affects electricity imports from neighboring countries (rows). Negative values indicate reduced electricity imports. Grey cells indicate no direct grid connection. Analysis based on hourly data from 2015-2021, with significance levels: $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.

These air quality improvements prevented an estimated 12,236 premature deaths (95% confidence interval: [6293, 18776]) across the eight countries between 2015 and 2021. As detailed in Table 2, Germany experienced the largest reduction in premature deaths (8,792), while Greece saw the smallest (70). This distribution of health benefits aligns with the geographic pattern of $PM_{2.5}$ reductions shown in Figure 3. To verify these findings, we tested alternative dose-response functions, with results presented in Table S5.

When monetized, the combined climate and health benefits of solar PV generation amount to $44.4 billion between 2015 and 2021. Table 3 shows the distribution across countries, with Germany receiving the highest benefits ($31.7 billion) and Greece the lowest ($0.3 billion). Health benefits dominate the total, accounting for 97.9% of the monetized value across all eight countries.

Table 1: Emission reductions, annual premature deaths avoided, and monetized climate and health benefits from solar PV deployment by country.

| Country | Belgium | France | Germany | Greece | Italy | Netherlands | Spain | UK |
|---|---|---|---|---|---|---|---|---|
| Pollutions (ton) | | | | | | | | |
| $SO_x$ | 23 | 2,121 | 98,639 | 3,372 | 3,003 | 509 | 8,867 | 115 |
| $NO_x$ | 1,300 | 3,035 | 142,808 | 7,197 | 12,951 | 1,097 | 14,588 | 4,749 |
| $PM_{2.5}$ | 7 | 59 | 1,128 | 49 | 163 | 7 | 131 | 24 |
| $CO_2$ | 772,244 | 1,834,093 | 27,030,792 | 2,282,346 | 7,545,842 | 392,119 | 4,297,670 | 2,764,694 |
| Avoided Death | 367 | 650 | 9565 | 69 | 662 | 664 | 281 | 424 |
| Financial Benefit (million $) | | | | | | | | |
| Climate | 17 | 39 | 527 | 45 | 138 | 11 | 102 | 51 |
| Health | 1,305 | 3,458 | 31,216 | 247 | 2,352 | 2,358 | 999 | 1,506 |

Note: This table shows avoided emissions of major pollutants ($SO_x$, $NO_x$, $PM_{2.5}$) and $CO_2$ due to displacement of fossil fuel generation. Values account for both direct displacement and cross-border effects through electricity trading. Estimates based on reduced $PM_{2.5}$ exposure from decreased fossil fuel generation. Values in- corporate both direct domestic benefits and cross-border effects through reduced electricity imports. Calculations use country-specific mortality rates and validated dose-response functions. Climate benefits calculated using EU ETS carbon prices and avoided $CO_2$ emissions. Health benefits based on avoided premature deaths valued at $3.55 million value of statistical life (VSL). All values in million dollars (2021). Benefits include both direct domestic impacts and cross-border effects through electricity trading.

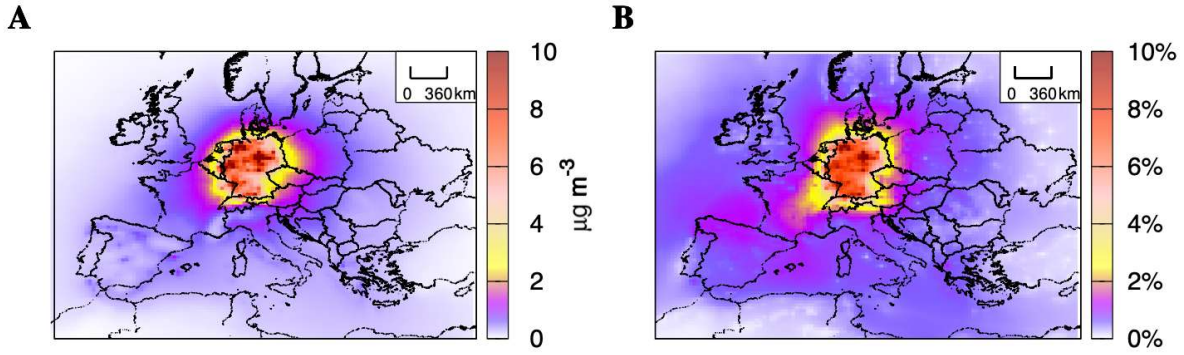



Figure 3: Spatial distribution of $PM_{2.5}$ changes due to solar PV deployment from 2015 to 2021. Note: Panel A shows absolute changes in $PM_{2.5}$ concentrations ($\mu g/m^3$). Panel B shows the changing ratio. Darker red colors indicate larger reductions. Results from CMAQ model simulations covering the eight study countries and surrounding regions at 36 km resolution.

# Contribution of imported solar PV to environmental and health benefits

To accurately attribute climate and health benefits to imported solar panels, we first account for the temporal gap between when panels are imported and when they are installed. Solar projects typically require a construction period before commissioning and power generation. Following the average timeline for utility-scale solar projects (*29*), we apply a two-year lag between trade flows and actual power generation.

Figure 4 confirms our use of a two-year lag. It illustrates our lag analysis across eight European countries. The gray bars represent the net imported capacity at different lag periods (from immediate use to five-year delays), while the red dashed lines show the total installed capacity in 2021. By applying a two-year lag, which aligns with typical project development timelines, we estimate that imported solar capacity during 2015-2021 accounted for approximately 69% of the total installed capacities in 2021, averaged across all eight European countries in our analysis.

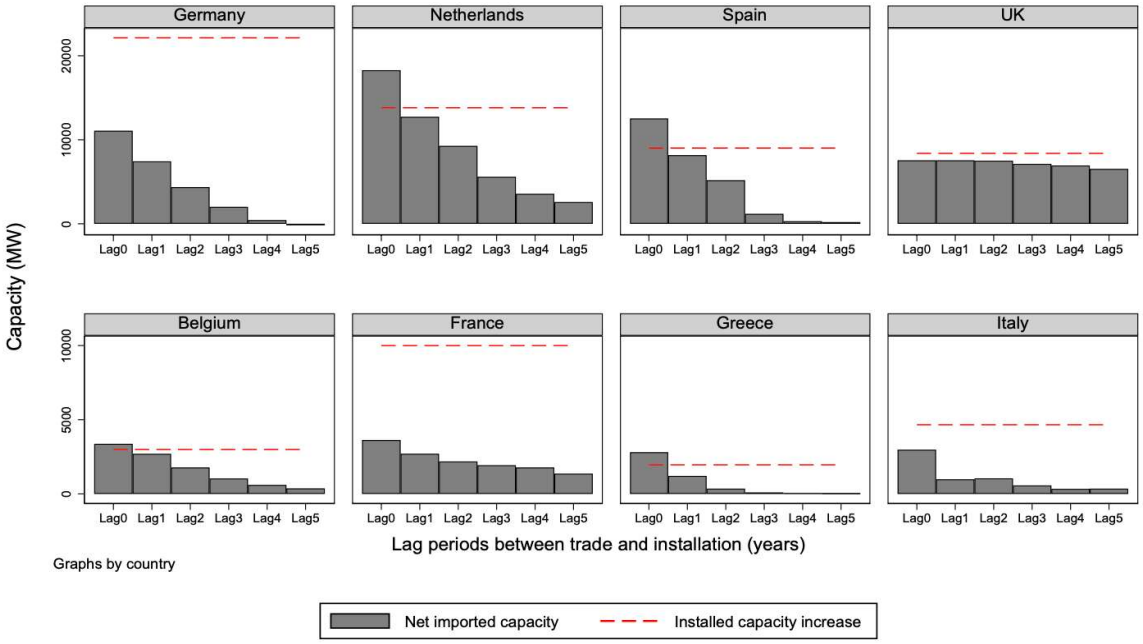



Figure 4: Lag analysis of solar PV imports and installations across eight European countries for 2021. Gray bars represent net imported capacity (imports minus exports) at different lag periods (Lag0 = same-year installation, Lag1 = one-year delay, etc.). Red dashed lines indicate the total installed capacity in 2021. The analysis reveals that a two-year lag (Lag2) provides the best match between import patterns and installation volumes across most countries, accounting for typical project development timelines.

Table 4: Emission reductions attributable to imported solar PV by country, 2015-2021.

| Country | $SO_x$ (ton) | $NO_x$ (ton) | $PM_{2.5}$ (ton) | $CO_2$ (ton) |
|---|---|---|---|---|
| Belgium | 16 | 897 | 5 | 532,848 |
| France | 1,463 | 2,094 | 61 | 1,265,524 |
| Germany | 68,061 | 98,538 | 785 | 18,651,247 |
| Greece | 2,327 | 4,966 | 34 | 1,574,819 |
| Italy | 2,072 | 8,936 | 112 | 5,206,631 |
| Netherlands | 351 | 757 | 5 | 270,562 |
| Spain | 6,118 | 10,066 | 90 | 2,965,392 |
| UK | 79 | 3,277 | 17 | 1,907,639 |
| Total | 80,488 | 129,529 | 1,108 | 32,374,661 |

Note: This table shows avoided emissions attributable to imported solar PV (69% of total solar deployment). Values account for both direct displacement and cross-border effects through electricity trading.

Applying this 69% import contribution to the total climate and health benefits of solar deployment reveals the substantial impact of imported solar PV systems. As shown in Table 4, from 2015 to 2021, imported solar panels across the eight countries reduce approximately 80 thousand tons of $SO_x$, 130 thousand tons

of $NO_x$, 1.1 thousand tons of $PM_{2.5}$, and 32.4 million tons of $CO_2$. Germany accounts for the largest share of these import-driven emission reductions (68 thousand tons of $SO_x$, 99 thousand tons of $NO_x$, 785 tons of $PM_{2.5}$, and 18.7 million tons of $CO_2$).

Table 5 details the health impacts attributable to imported solar panels. Of the estimated 12,236 premature deaths prevented across the eight countries between 2015 and 2021, approximately 8,443 (95% confidence interval: [4,342, 12,955]) can be attributed to imported solar panels, with Germany experiencing the largest share (6,067 avoided premature deaths from imports) and Greece the smallest (48 deaths avoided).

Table 5: Annual premature deaths avoided through imported solar PV by country.

| Year | Belgium | France | Germany | Greece | Italy | Netherlands | Spain | UK |
|---|---|---|---|---|---|---|---|---|
| 2015 | 32 | 84 | 780 | 6 | 63 | 50 | 23 | 31 |
| 2016 | 35 | 84 | 751 | 6 | 45 | 62 | 19 | 32 |
| 2017 | 30 | 72 | 791 | 7 | 62 | 55 | 20 | 33 |
| 2018 | 39 | 94 | 762 | 5 | 48 | 70 | 20 | 46 |
| 2019 | 32 | 81 | 800 | 6 | 54 | 61 | 20 | 44 |
| 2020 | 48 | 130 | 1241 | 9 | 104 | 95 | 48 | 70 |
| 2021 | 36 | 124 | 940 | 8 | 77 | 63 | 41 | 35 |
| Total | 253 | 672 | 6067 | 48 | 457 | 458 | 194 | 293 |

Note: Estimates represent 69% of total avoided premature deaths, attributable to imported solar PV based on our lag analysis. Values incorporate both direct domestic benefits and cross-border effects through reduced electricity imports.

Table 6: Monetized climate and health benefits from imported solar PV by country.

| Country | Climate benefit (million $) | Health benefits (million $) |
|---|---|---|
| Belgium | 12 | 900 |
| France | 27 | 2,386 |
| Germany | 364 | 21,539 |
| Greece | 31 | 170 |
| Italy | 95 | 1,623 |
| Netherlands | 8 | 1,627 |
| Spain | 70 | 689 |
| UK | 35 | 1,039 |

Note: Values represent 69% of total benefits, attributable to imported solar PV based on our lag analysis. Climate benefits are calculated using EU ETS carbon prices and avoided $CO_2$ emissions. Health benefits based on avoided premature deaths valued at $3.55 million value of statistical life (VSL). All values in million dollars (2021).

Similarly, when we apply the import percentage to the monetized benefits, imported solar PV systems generated substantial economic value, as quantified in Table 6. These installations produced approximately $30.6 billion in combined climate and health benefits over the study period. This includes about $30.0 billion in health benefits and $642 million in climate benefits, with Germany receiving approximately $21.9 billion in total benefits from imported panels, while Greece received about $201 million.

These results highlight that international trade in solar PV technology has been a crucial driver of climate and health benefits across Europe, accounting for more than two-thirds of the total benefits realized from solar energy deployment during this period.

# Discussion

This study provides comprehensive evidence of the substantial climate and health benefits delivered by solar PV deployment in eight major European markets, while also highlighting the crucial role of global supply chains in achieving these outcomes. Our analysis specifically demonstrates that during 2015-2021, total solar generation prevented about 12,000 premature deaths and avoided 47 million tons of $CO_2$ emissions. The total monetized benefits amount to $44 billion. Within these overall benefits, imported solar PV has played a significant role, contributing 69% of these benefits during this period despite higher import ratios. These climate and health benefits add to the documented advantages of European solar deployment while highlighting the crucial role of global supply chains in accelerating the clean energy transition.

## Policy Impacts

Our analysis reflects the environmental and health impacts of solar PV deployment in the context of Europe's stringent emission control policies. As detailed in our supplementary analysis, these benefits would be substantially higher in scenarios with less stringent emissions controls - with potential increases by a factor of 13 for $SO_x$ and 5 for $CO_2$ emissions. These findings suggest that policies promoting solar adoption should be coordinated with emission control regulations to maximize environmental benefits while highlighting how technological advancement and regulatory evolution affect the magnitude of benefits from clean energy transitions. Even within the context of Europe's advanced emissions controls, the substantial benefits documented in this study demonstrate the significant value of solar deployment for both climate and public health outcomes.

The cross-border effects of solar deployment through electricity trading demonstrate the need for coordinated European policies on renewable energy and grid integration. Our analysis reveals that solar generation in one country can lead to the displacement of fossil fuels in neighboring countries through reduced electricity imports, with effects varying significantly by country pair. For example, we found that an increase of 1 MWh in solar generation in Belgium can reduce the imports of electricity from Germany by 0.07 MWh. These findings highlight the importance of considering cross-border effects in policy design and suggest that the benefits of solar deployment extend beyond national boundaries. This interconnected nature of European electricity markets requires coordinated policy approaches to maximize the benefits of renewable energy deployment. The current EU regulatory framework could be enhanced to better account for these cross-border effects in renewable energy planning.

## Environmental Justice Implications

Our analysis reveals significant geographic disparities in the distribution of environmental and health benefits from solar deployment. The $PM_{2.5}$ reductions shown in Figure 3 demonstrate a highly uneven spatial pattern, with western Germany experiencing the largest improvements while other regions see minimal changes. This disparity extends through cross-border effects – our electricity trading analysis shows that eastern regions of neighboring countries benefit from German solar deployment through reduced fossil fuel electricity imports, while more distant regions receive little benefit. The emission reductions in Table 1 further illustrate this inequality: Germany's SOx reductions (98,639 tons) dwarf those of Belgium (23 tons), despite both countries sharing borders and grid connections. These patterns suggest that current solar deployment strategies may be reinforcing existing environmental disparities rather than addressing them. The concentration of benefits in already-industrialized regions raises important questions about equitable access to clean energy benefits across Europe.

## Health Benefits versus Climate Benefits

While the health benefits from reduced air pollution dominate the monetized benefits, accounting for

about 98% of total benefits, this finding raises important questions about how to optimize solar deployment strategies to maximize both climate and health co-benefits. Our analysis shows that health benefits constitute $43.4 billion of the total $44.4 billion in benefits. The dominance of health benefits suggests that current policy frameworks, which often focus primarily on climate benefits, might be undervaluing the health co-benefits of solar deployment. Future policy design should consider both climate and health impacts to optimize the overall societal benefits of renewable energy transitions.

## National Variations in Energy Systems

Our statistical analysis reveals significant variations in how solar power displaces different energy sources across countries. In the UK, each MWh of solar generation displaces 0.80 MWh of natural gas and 0.30 MWh of coal, while in France, solar primarily displaces hydropower. These variations reflect fundamental differences in national energy systems. The cross-border effects are equally varied – our results show that a 1 MWh increase in Belgian solar generation reduces electricity imports from France by 0.38 MWh, while similar generation increases in Germany reduce imports from France by 0.06 MWh. These quantified differences demonstrate how national energy system characteristics fundamentally affect the environmental benefits of solar deployment.

## Study Limitations and Future Research

The limitations of our study highlight important areas for future research and data collection. A primary limitation lies in our methodology for calculating net imported solar capacity. Due to data constraints, we rely on trade values and global average installed costs (*30*, *31*). To address the issue of transit countries with high re-export volumes and delay between trade and installation, we use net imports rather than raw imports, and conduct a lag analysis to identify the lag periods. Future studies could address this by developing more precise tracking of panel installations, establishing country-specific price databases, and creating systems to monitor panel movements across borders. Our analysis also faces limitations in emission factors and health impact assessments. The emission factors used are country-level averages, which may not capture variations in power plant technologies and operations within each country. For health impacts, while we use multiple dose- response functions from different studies (*32*–*35*) to address uncertainties, more research is needed to understand the relationship between air pollution and health outcomes, especially at lower pollution levels. Additionally, our focus on $PM_{2.5}$-related mortality could be expanded in future work to include morbidity impacts and other pollutants for a more comprehensive assessment of health benefits.

# Conclusion

Our findings have important implications for European policy, as countries balance domestic manufacturing ambitions with the benefits of global supply chains to accelerate the deployment of renewable energy. Our analysis shows that solar PV deployment has generated substantial climate and health benefits of $44.4 billion during 2015-2021, with the potential for even higher benefits under a counterfactual scenario, assuming less stringent emission control ($323.3 billion, see Supplementary Information). Health benefits account for about 98% of these total benefits. The scale of these benefits shows the importance of maintaining and accelerating solar PV deployment, while the significant contribution of imports (69% of total installed capacity) demonstrates the role of global supply chains in addressing climate and environmental challenges. However, recent initiatives such as the EU Solar Energy Strategy aim to rebuild domestic manufacturing capacity, citing energy security and industrial policy goals. Our findings suggest that policymakers should carefully weigh the potential trade-offs between supply chain localization and the pace of deployment. Future policies could focus on developing a balanced approach that maintains the cost and scale advantages of global supply chains while strategically building domestic capacity in key segments of the value chain. Additionally, the significant health co-benefits we identified suggest that renewable energy policies should be better integrated with air quality management strategies, particularly in regions with high population density and persistent air quality challenge.

# Experimental procedures

## Datasets

### Hourly electricity generation data by country and fuel types

This study examines the impact of solar generation on electricity generation from various fuel types in eight European countries from 2015 to 2021. We analyze daily electricity generation data obtained from the Entsoe transparency platform (*36*), focusing on eight generation types: coal, gas, oil, solar, wind, nuclear, hydro, and other. For clarity, we explain how we categorized generation types from the Entsoe platform: "Coal" is an aggregate category we created by combining fossil brown coal/lignite, fossil coal-derived gas, fossil hard coal, and fossil peat variables; "Oil" combines fossil oil and fossil oil shale variables; "Wind" comprises both offshore and onshore wind generation variables. The other categories (Gas, Nuclear, Solar, Hydro, and Other) correspond directly to individual variables in the Entsoe database.

Our analysis covers Belgium, France, Germany, Greece, Italy, the Netherlands, Spain, and the United Kingdom. We selected these countries based on their sufficient solar generation ratios and data availability. We also use daily electricity demand information for each country, sourced from the Entsoe transparency platform (*37*) for regression analyses.

### Emission factor and heat rate data

Our study examines five fuel categories: brown coal/lignite, hard coal, coal-derived gas, natural gas, and oil. These categories align with the Entsoe database, which provides hourly generation data for our main model. We gather emission factors for various pollutants from different sources depending on the country. For most countries in our focus, we use the European Environment Agency (EEA)(*38*) for $SO_x$, $NO_x$, $PM_{2.5}$, and NMVOC emission factors, and the Greenhouse Gas Protocol (*39*) for $CO_2$ emission factors.

To ensure consistency across databases with varying fuel categorizations, we made the following adaptations: for coal, we used anthracite data to represent hard coal, lignite for brown coal, and coke oven gas for coal-derived gas. For oil, we consider both gas/diesel oil and fuel oil, basing emission reductions on their proportions in annual oil-based production.

To accurately calculate emissions reductions, we also compile heat rate data for each fuel type. The heat rate (in GJ / MWh), which measures the efficiency of the power plant, indicates the fuel energy needed to generate a MWh of electricity (*40*).

### Solar imports by country

This study investigates solar energy adoption in eight European countries from 2015 to 2021. We focus on Belgium, France, Germany, Greece, Italy, the Netherlands, Spain, and the United Kingdom, analyzing their total installed solar capacity and solar PV imports.

Our research relies on two main data sources: the International Renewable Energy Agency (IRENA)(*31*) for annual total installed solar capacity by country, and Eurostat (*41*) for monthly import and export values of photovoltaic devices. We identify photovoltaic imports using product code 85414090 (Photosensitive semiconductor devices, including photovoltaic cells). The net import values can then be calculated using the import values minus the export values.

To determine the net-imported solar capacity, we combine three key data points: (1) Annual global average solar PV module costs from IRENA (*31*), converted from $/kW to $/MW. This is not ideal but reasonable given solar is a globally traded commodity. (2) Annual exchange rates between US dollars and euros from the OECD (*42*) in euros/$. (3) Annual monetary value of net imported solar PV in euros

from Eurostat (*41*).

Using these data, we calculate the net-imported solar PV capacity in megawatts (MW) through the following steps: First, we convert the installed costs from $/kW to $/MW by multiplying by 1000. Then, we convert the monetary value of net imports (imports minus exports) from euros to capacity in MW using:

$$Net\ Import\ Capacity\ (MW) = \frac{Net\ Import\ Value\ (euros)}{Exchange\ Rates\ (euros/\$) \times Cost(\$/MW)} \quad (1)$$

# Impacts of solar generation on electricity generation from various sources

We use a statistical model to quantify the impacts of daily solar generation on daily electricity generation of different fuel types. For each country in our sample, we estimate the following equation.

$$Y_{ict} = \beta_1 Solar_{ict} + \beta_2 X_{ict} + \mu_{ym} + \varepsilon_{ict} \quad (2)$$

where $Y_{ict}$ is the electricity generation from fuel source $i$ at day $t$ in country $c$. We estimate the effects of solar power on generation from five fuel types: natural gas, coal, oil, hydro, and others. $Solar_{ict}$ denotes the solar power generation day $t$ in country $c$. $X_{ict}$ denotes a set of control variables including electricity demand and generation from other fuel types that are not likely to be displaced by solar power (wind and nuclear power). $\mu_{ym}$ denotes the year-month fixed effects that account for all factors that differ across months and years (e.g. policy changes, economic conditions, major events affecting specific years (like the 2020 pandemic), seasonality in electricity generation, and weather patterns). $\varepsilon_{ict}$ represents the error term. The main parameters of interest are $\beta 1$, which quantify the impacts of solar energy on electricity generation from fuel type $i$ in the country $c$.

# Trans-boundary impacts through electricity import and export

In interconnected electricity regions, solar generation in one country can affect fossil fuel power plant output in neighboring countries through electricity import and export. Our research indicates that the overall impact of 1 MWh of solar power on fossil fuel plant generation is significantly less than 1 MWh (see Figure 1 if excluding import solar), suggesting that solar power likely displaces electricity generation from neighboring countries. To quantify these cross-border effects, we analyze daily electricity import and export data between country pairs using the Entsoe dataset (*43*). We use the following regression to estimate how changes in solar power generation in one country influence the electricity flow between it and its neighbors.

$$Export_t^{i \to j} = \beta_{ij} Solar_{jt} + \gamma X_{it} + \theta_i Export_t^{i \to others} + \mu_{ym} + \varepsilon_t \quad (3)$$

where $Export^{i \to j}$ denotes the net export from exporting country $i$ to importing country $j$ on day $t$. $Solar_{jt}$ denotes the solar power generation in importing country $j$ at day $t$. $X_{it}$ denotes a set of control variables, including the solar generation, electricity demand, wind, and nuclear generation of country $i$. $Export^{i \to others}$ denotes the export from exporting country $i$ to the other importing countries (other than $j$). $\mu_{ym}$ denote year-month fixed effects. $\varepsilon_t$ is the error term. Our key focus is on the coefficient $\beta_{ij}$ that quantifies how solar power changes in an importing country $j$ affect net electricity exports from an exporting country $i$ to that importer, conditioned on exporting country $i$'s electricity demand, generation, and import/export from the other countries.

To estimate the effects of electricity generation by solar panels on emissions and air quality, we combine the aggregated estimates of solar power on different fuel types with emission factor data. We calculate

the generation reductions in each country based on the coefficient we estimate in our main model. We further use emission factors to calculate the effects of net-imported solar power on $CO_2$, $SO_x$, $NO_x$, and PM 2.5 emissions for each year during 2015-2021.

# Air quality modeling

We employed a modified CMAQ model (v5.0.2) with the revised Statewide Air Pollution Research Center (SAPRC-11) chemical mechanism to simulate $PM_{2.5}$ level (*44* , *45*). The simulation domain was set with a 36 km horizontal resolution domain (117 × 97 grids) covering Europe and its sur- rounding regions to capture the differences during 2015-2021. To comprehensively assess air quality impacts, we designed three specific modeling scenarios (Table 7): (1) BASE represents the original emission patterns without adjustment; (2) CASE1 represents a counterfactual scenario with less stringent controls to evaluate potential impacts under alternative policy conditions; and (3) CASE2 models impacts under historical data with stringent emission controls, which is our main analysis. The detailed scenario settings and comparative results of the baseline analysis are presented in Table S4 of the Supplementary Information. For the main analysis presented in this paper, we focus on results under current stringent emission controls. To mitigate the influence of initial conditions, we excluded the first three days of results as a spin-up period.

We use the Weather Research and Forecasting (WRF) model version 4.1.2 to provide the meteorological driving fields, based on the FNL (Final) Operational Global Analysis data from the National Center for Environmental Prediction (NCEP) (*46*). The vertical grids were divided into 18 sigma levels, extending from the surface to the upper troposphere.

The original anthropogenic emission inventory was from the Emissions Database for Global Atmospheric Research (EDGAR) v8.1 (*47*), and emissions of particulate matter and volatile organic compounds were speciated into model species using the US EPA's SPECIATE 4.3 source pro- files(*48*). To simulate the concentrations of pollutants in Europe in different scenarios, we adjusted the original emission inventory according to the estimated emission reduction. Biogenic emissions were generated using the Model of Emissions of Gases and Aerosols from Nature (MEGAN) v2.1(*49*). As for model validation, we collected an air quality database from the European Environment Agency (EEA) (*50*) to validate pollutant levels (see Table S4).

Table 7: Overview of air quality modeling scenarios.

| BASE | Original emission inventory |
|---|---|
| CASE1 | Adjusted emission inventory (Counterfactual scenario) |
| CASE2 | Adjusted emission inventory (Stringent policy scenario) |

Note: BASE represents the original emission patterns. CASE1 represents a counterfactual scenario with less stringent controls. All scenarios use consistent meteorological conditions and model parameters. CASE2 models impacts under historical data with stringent emission controls.

# Health impacts analysis

To assess the health impacts of imported solar PV, we evaluate premature deaths attributed to $PM_{2.5}$ exposure. Based on a meta-analysis of 10 studies examining mortality responses to $PM_{2.5}$ in European populations, Pope et al. report a hazard ratio of 1.12 (95% CI: 1.06–1.19) per 10 $\mu g/m^3$ increase in ambient $PM_{2.5}$ (*32*). To account for variations in dose-response relationships, we also estimate avoided mortalities due to $PM_{2.5}$ changes using alternative dose-response functions (*51*, *52*). The corresponding results are presented in Table S5. For these calculations, we apply country-level annual mortality (*53*,

*54*) in conjunction with the hazard ratios and change of $PM_{2.5}$ to estimate premature death for each country.

## Monetized climate and health damages

We quantify the climate and health damages in monetary terms using standard methods from the literature. Health impacts are based on a value of statistical life (VSL) of $3.55 million (in 2021), following EEA guidelines (*55*). The climate benefits from reduced $CO_2$ emissions are monetized using the annual average carbon price (Figure 5) in the EU ETS (*56*).

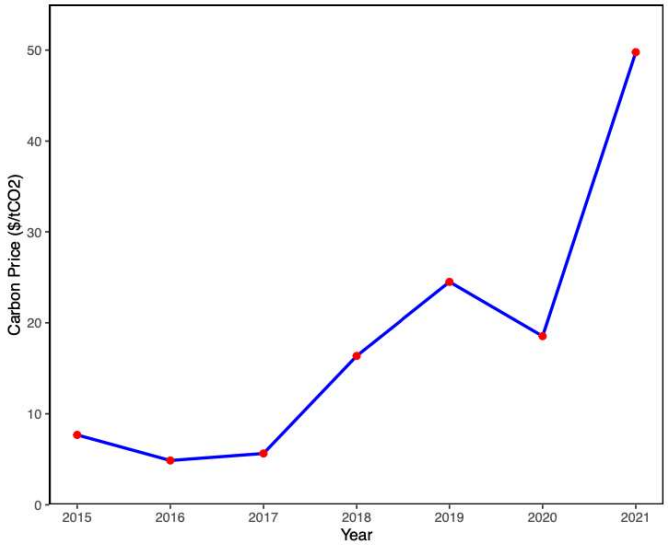



Figure 5: EU annual average carbon price, 2015-2021. Note: This figure shows annual average carbon prices in the EU ETS in dollars per ton of $CO_2$. These prices are used to monetize the climate benefits of avoided emissions from solar PV deployment. The increasing trend reflects strengthening climate policy in the EU.

## Quantifying Solar Import Contributions Through Time-Adjusted Trade Analysis

Many European countries function as transit hubs for solar equipment (*57*), necessitating the use of net imports (imports minus exports) rather than gross imports to prevent double-counting of panels that are imported and subsequently re-exported, especially relevant for transit countries like Greece and Spain where unadjusted import ratios can exceed 500% of annual installations due to significant re-export activities (Figure S1b).

A second challenge arises from the timing mismatch between import and installation dates (*30*). Imported solar panels are not necessarily installed in the same year they enter a country. Using same-year import and installation data would overestimate the import ratio, providing only an upper bound rather than an accurate measure.

To address these timing discrepancies, we conduct a lag analysis examining relationships between net imports and installations across different time periods (from immediate installation to 5-year lags). For each country, we identify the most appropriate lag period and calculate a time-adjusted import ratio:

$$Net\ Import\ Ratio_{c,t} = \frac{Net\ Import\ Capacity_{c,t-l}}{Total\ Installed\ Capacity_{c,t}} \quad (4)$$

where *c* represents the country, *t* is the year of installation, and *l* is the identified lag (in years) between import and installation.

After determining country-specific import ratios, we calculate an EU-wide average import ratio, representing the typical proportion of solar installations sourced from imports across the European market. We then apply this percentage to the total health and climate impacts of EU solar installations from 2015 to 2021, allowing us to quantify what portion of these environmental benefits can be attributed to imported solar PV systems. This methodology provides a more accurate representation of imported solar contributions to domestic capacity by accounting for both trade flow patterns and installation delays across European markets.

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# Supplemental Information

## Counterfactual Scenario Analysis

This analysis presents results from a counterfactual scenario, the baseline scenario, that assumes less stringent emission control technologies in fossil fuel power plants compared to the main analysis presented in the manuscript. The baseline scenario reflects conditions where power plants operate with lower emission control systems, representing a counterfactual case of what emissions would have been without Europe's advanced emissions control regulations. This comparison illustrates the combined effects of renewable energy deployment and stringent emission controls in reducing environmental and health impacts.

Under the baseline scenario with less stringent emission controls, solar PV deployment achieved substantially higher absolute emission reductions during 2015-2021. As shown in Table S1, SOx emissions were reduced by approximately 1.53 million tons, which is 13 times higher than in the stringent scenario. NOx emissions decreased by approximately 417 thousand tons, representing a two-fold increase compared to the stringent scenario. PM2.5 reductions reached approximately 5,686 tons, four times higher than under stringent controls, while CO2 emissions were reduced by approximately 221 million tons, five times higher than the results of the stringent scenario.

The health benefits in the baseline scenario were correspondingly greater, with approximately 90,020 premature deaths avoided (95% confidence interval: [46,383, 137,853]) compared to 12,236 in the stringent scenario. As detailed in Table S2, Germany demonstrated the highest benefits among all countries studied, with about 68,936 premature deaths avoided, while Greece showed the lowest reduction with 483 cases.

The economic valuation of these benefits in the baseline scenario totaled $323.3 billion, as shown in Table S3. The health benefits accounted for $319.7 billion, representing 98.9% of the total value, while the climate benefits contributed $3.6 billion or 1.1% of the total. The distribution of benefits varied significantly by country, with Germany receiving approximately $247 billion in benefits, and other countries ranging from $1.9 billion to $20.5 billion.

The substantial difference between baseline and stringent scenarios demonstrates the significant impact of emission control technologies and regulations on the potential benefits of solar PV deployment. The higher absolute benefits observed in the baseline scenario reflect the greater potential for emission reduction in less regulated environments. These results underscore the complementary environmental and health benefits of solar PV are particularly pronounced in regions with less stringent emissions control.

Table S1: Carbon emission and air pollution reduction under the baseline scenario (unit: ton)

| Country | $SO_x$ (ton) | $NO_x$ (ton) | $PM_{2.5}$ (ton) | $CO_2$ (ton) |
|---|---|---|---|---|
| Belgium | 23 | 5,639 | 57 | 3,556,900 |
| France | 2,598 | 10,978 | 198 | 6,957,802 |
| Germany | 1,373,060 | 276,284 | 3,908 | 135,650,450 |
| Greece | 48,781 | 19,545 | 235 | 12,029,087 |
| Italy | 3,101 | 48,458 | 607 | 30,534,292 |
| Netherlands | 9,059 | 3,999 | 47 | 2,016,974 |
| Spain | 95,681 | 35,733 | 474 | 20,224,329 |
| UK | 72 | 15,988 | 161 | 10,078,605 |
| Total | 1,532,374 | 416,625 | 5,686 | 221,048,440 |

Table S2: Avoided premature death under the baseline scenario

| Avoided Death | Belgium | France | Germany | Greece | Italy | Netherlands | Spain | UK |
|---|---|---|---|---|---|---|---|---|
| 2015 | 256 | 595 | 7,449 | 50 | 393 | 451 | 177 | 214 |
| 2016 | 309 | 631 | 8,099 | 48 | 324 | 620 | 161 | 233 |
| 2017 | 270 | 531 | 8,421 | 64 | 432 | 552 | 164 | 251 |
| 2018 | 379 | 844 | 8,967 | 48 | 378 | 760 | 202 | 384 |
| 2019 | 266 | 647 | 8,958 | 61 | 413 | 587 | 185 | 331 |
| 2020 | 378 | 1,044 | 12,271 | 91 | 836 | 869 | 426 | 547 |
| 2021 | 457 | 1,443 | 14,768 | 118 | 799 | 910 | 539 | 391 |
| Total | 2,318 | 5,740 | 68,936 | 483 | 3,578 | 4,751 | 1,857 | 2,354 |

# Model Validation and Performance

This section details the validation and performance assessment of our modified CMAQ model across the study period (2015-2021). We evaluated model performance using multiple statistical metrics recommended by the EPA, including Mean Fractional Error (MFE), Mean Normalized Bias (MNB), and Mean Normalized Error (MNE). These metrics provide complementary information about model accuracy and precision.

Table S3: Total climate and environmental benefits under the counterfactual scenario (unit: million dollars)

| Country | Climate benefits | Health benefits |
|---|---|---|
| Belgium | 63 | 8,231 |
| France | 116 | 20,379 |
| Germany | 2,206 | 244,746 |
| Greece | 192 | 1,716 |
| Italy | 479 | 12,704 |
| Netherlands | 37 | 16,870 |
| Spain | 399 | 6,594 |
| UK | 186 | 8,359 |

The model performance metrics are calculated as follows. Mean Fractional Error (MFE) measures the average absolute difference between modeled and observed values, normalized by their mean. Mean Normalized Bias (MNB) indicates systematic over- or under-prediction. Mean Normalized Error (MNE) quantifies the absolute magnitude of prediction errors.

As shown in Table S4, our model demonstrates consistent performance across all years, with metrics falling within EPA-recommended criteria. The MFB values range from -0.24 to 0.01, well within the recommended threshold of ±0.6, indicating minimal systematic bias. MFE values re- main below 0.75 throughout the study period, suggesting good overall accuracy. The model shows particularly strong performance in later years (2019-2021), with MFB values closer to zero.

# Alternative Health Impact Assessments

To ensure robust health impact estimates, we evaluated mortality impacts using multiple dose- response functions from recent epidemiological studies. While our main analysis uses the dose- response function from Pope *et al.* (*32*), we also applied alternative functions from Hoffmann, Bert, Zorana, Francesco, and Hanna (*51*) and Beelen *et al.* (*52*) to test the sensitivity of our results to different epidemiological assumptions.

These alternative functions were selected based on their methodological rigor and relevance to European populations. Our main analysis uses (*32*), which is based on a meta-analysis of 10 European cohort studies and provides a comprehensive synthesis of available evidence. Hoffmann et al. (*51*) offers additional validation through its analysis of a large-scale European cohort study with extended follow-up, while Beelen et al. (*52*) contributes insights from the ESCAPE project covering multiple European cohorts. Each of these studies brings unique methodological strengths and together they provide a robust foundation for our health impact assessment.

Table S4: Model performance metrics for $PM_{2.5}$ predictions across the study period (2015-2021).

| $PM_{2.5}$ ($\mu g \cdot m^3$) | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | Criteria |
|---|---|---|---|---|---|---|---|---|
| OBS | 16.18 | 17.39 | 18.19 | 17.02 | 15.27 | 14.21 | 14.78 | |
| PRE | 15.18 | 16.30 | 21.05 | 15.62 | 14.66 | 15.83 | 16.71 | |
| MNB | 0.04 | 0.11 | 0.38 | 0.05 | 0.07 | 0.27 | 0.32 | |
| MNE | 0.61 | 0.67 | 0.76 | 0.62 | 0.62 | 0.70 | 0.73 | |
| MFB | -0.24 | -0.21 | 0.01 | -0.23 | -0.21 | -0.05 | -0.03 | $\leq \pm 0.6$ |
| MFE | 0.59 | 0.61 | 0.55 | 0.59 | 0.58 | 0.56 | 0.56 | $\leq 0.75$ |

Note: OBS and PRE represent observed and predicted $PM_{2.5}$ concentrations, respectively, in $\mu g \cdot m^3$. MFE (Mean Fractional Error) and MFB (Mean Fractional Bias) are dimensionless metrics used to evaluate model performance, with EPA-recommended criteria shown in the rightmost column. The model demonstrates consistent performance within acceptable ranges across all years. MFE measures the aver- age absolute difference between modeled and observed values, normalized by their mean. MNB indicates systematic over- or under-prediction. MNE quantifies the absolute magnitude of prediction errors. Performance criteria are based on EPA guidance for $PM_{2.5}$ modeling (*58*).

As shown in Table S5, the mortality estimates remain consistent across different dose-response functions, with substantial overlap in their confidence intervals. This consistency supports the robustness of our health impact assessment.

# Sensitivity Analysis Results and Methodology

We conducted comprehensive sensitivity analyses to evaluate the robustness of our climate and health benefit calculations. Our analysis uses a sequential change approach, where each year's values are calculated relative to adjacent years, with 2018 as the baseline year. This method better captures the year-to-year evolution of key parameters and their impacts on benefit calculations.

Table S5: Comparison of mortality estimates using alternative dose-response functions for $PM_{2.5}$ exposure during 2015-2021.

| Dose-response function | Mortality (main estimate) | Mortality (lower bound) | Mortality (higher bound) |
|---|---|---|---|
| Pope et al. 2020 (main) | 12,236 | 6,293 | 18,776 |
| Hofffmann et al. 2022 | 12,043 | 6,293 | 17,775 |
| Beelen et al. 2014 | 14,609 | 4,278 | 26,376 |

Note: The main estimate from Pope *et al.* (*32*) is based on a meta-analysis of European studies, while alternative estimates from Hoffmann, Bert, Zorana, Francesco, and Hanna (*51*) and Beelen *et al.* (*52*) provide additional validation. All three approaches yield consistent results, with overlapping confidence intervals, supporting the robustness of our health impact assessment.

## Climate Benefits Sensitivity

For climate benefits, we use Italy's 2018 carbon price ($16/tCO2) and $CO_2$ reduction (1,050,839 ton) as the baseline reference point. We apply a 15% sequential change in carbon prices and a 10% sequential change in $CO_2$ reductions. For example, starting from the 2018 baseline, 2019 values increase by the specified percentage compared to 2018, while 2017 values decrease by the same

percentage compared to 2018. Sequential change means that 2016 values decrease by the same percentage compared to 2017. This pattern continues sequentially in both directions from the baseline year. These ranges were selected based on historical volatility in EU ETS prices and typical uncertainties in emission calculations.

As shown in Table S6, the analysis demonstrates that while benefit estimates are sensitive to carbon pricing and $CO_2$ reduction assumptions, the relative magnitude of benefits across years remains consistent. For instance, despite varying carbon prices from \$10 to \$25/t$CO_2$, the proportional relationship between yearly benefits maintains a similar pattern, with 2021 values consistently about 2.8 times higher than 2015 values across different price scenarios. This consistency in relative patterns suggests that our main findings about the temporal distribution of climate benefits are robust to parameter uncertainties.

## Health Benefits Sensitivity

For health benefits, we use Germany's 2018 premature death estimates (1,105 deaths) and the EEA-recommended VSL (\$3.6 million) as baseline values. Following the same sequential approach, we apply an 8% change in VSL values and a 5% change in mortality estimates relative to adjacent years from the 2018 baseline. These ranges were selected to reflect typical uncertainties in VSL studies and epidemiological estimates.

Table S6: Sensitivity analysis of climate benefits under varying carbon prices.

| Carbon price (\$/t$CO_2$) | $CO_2$ reduction (thousand tons) | | | | | | |
|---|---|---|---|---|---|---|---|
| | 766.1 | 851.2 | 945.8 | 1,050.8 | 1,155.9 | 1,271.5 | 1,398.7 |
| | Climate benefits (million \$) | | | | | | |
| 10 | 7.66 | 8.51 | 9.46 | 10.51 | 11.56 | 12.72 | 13.99 |
| 12 | 9.19 | 10.21 | 11.35 | 12.61 | 13.87 | 15.26 | 16.78 |
| 14 | 10.72 | 11.92 | 13.24 | 14.71 | 16.18 | 17.80 | 19.58 |
| 16 | 12.26 | 13.62 | 15.13 | 16.81 | 18.49 | 20.34 | 22.38 |
| 19 | 14.56 | 16.17 | 17.97 | 19.97 | 21.96 | 24.16 | 26.57 |
| 22 | 16.85 | 18.73 | 20.81 | 23.12 | 25.43 | 27.97 | 30.77 |
| 25 | 19.15 | 21.28 | 23.64 | 26.27 | 28.90 | 31.79 | 34.97 |

Note: This table shows how climate benefits (in million dollars) vary as both variables change annually from 2015 to 2021. The rows show increasing carbon prices starting from \$10/t$CO_2$ in 2015 to \$25/t$CO_2$ in 2021. The columns show increasing $CO_2$ reductions from 766.1 thousand tons in 2015 to 1,398.7 thousand tons in 2021. Negative values indicate avoided costs. Using 2018 as the baseline year, carbon prices change by ±15% and $CO_2$ reductions by ±10% annually.

Table S7 shows that while absolute benefit values are sensitive to VSL assumptions and mortality estimates, the relative distribution of benefits across years remains stable. The ratio of benefits between any two years stays relatively constant across different VSL scenarios. For example, 2021 benefits are consistently about 1.7 times higher than 2015 benefits, regardless of the VSL value used. This stability in relative patterns provides confidence in our conclusions about the temporal trends in health benefits, even while acknowledging uncertainty in absolute values.

Table S7: Sensitivity analysis of health benefits under varying VSL values.

| VSL (million $) | Premature deaths | | | | | | |
|---|---|---|---|---|---|---|---|
| | 947 | 997 | 1,049 | 1,105 | 1,160 | 1,218 | 1,279 |
| | Health benefits (million $) | | | | | | |
| 2.8 | 2,652 | 2,792 | 2,937 | 3,094 | 3,248 | 3,410 | 3,581 |
| 3.0 | 2,841 | 2,991 | 3,147 | 3,315 | 3,480 | 3,654 | 3,837 |
| 3.3 | 3,125 | 3,290 | 3,462 | 3,647 | 3,828 | 4,019 | 4,221 |
| 3.6 | 3,409 | 3,589 | 3,776 | 3,978 | 4,176 | 4,385 | 4,604 |
| 3.8 | 3,599 | 3,789 | 3,986 | 4,199 | 4,408 | 4,628 | 4,860 |
| 4.1 | 3,883 | 4,088 | 4,301 | 4,531 | 4,756 | 4,994 | 5,244 |
| 4.5 | 4,262 | 4,487 | 4,721 | 4,973 | 5,220 | 5,481 | 5,756 |
| Year | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 |

Note: This table shows how health benefits (in million dollars) vary as both variables change annually from 2015 to 2021. The rows show increasing VSL values starting from $2.8 million in 2015 to $4.5 million in 2021. The columns show increasing mortality estimates from 947 deaths in 2015 to 1,279 deaths in 2021. Using 2018 as the baseline year, VSL values change by ±8% and mortality estimates by ±5% annually.

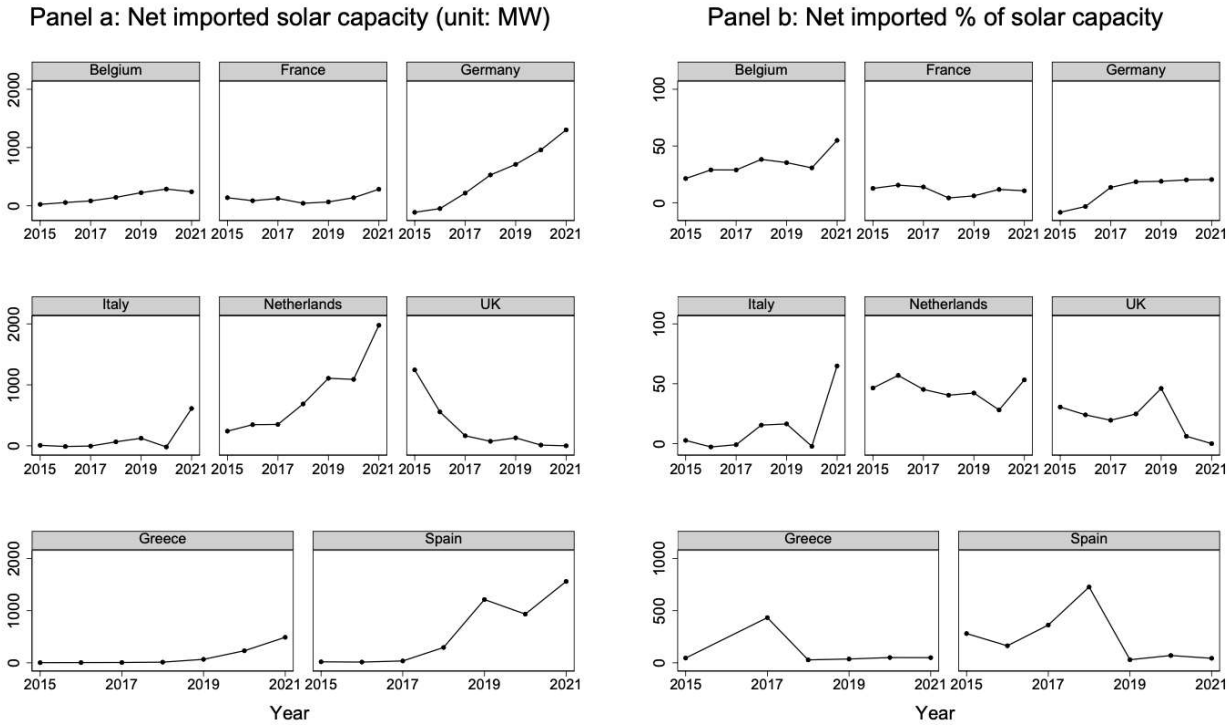



Figure S1: Evolution of net-imported solar PV capacity and its share in total installations without lag adjustment, 2015-2021. Panel a shows the absolute net imported solar capacity in megawatts (MW),

calculated as imports minus exports. Panel b shows the unadjusted ratio of net imported solar capacity to total installed capacity in the same year. Note: These figures represent preliminary estimates before accounting for installation delays, demonstrating why transit countries like Greece and Spain show import ratios exceeding 100% due to re-export patterns and timing mismatches.

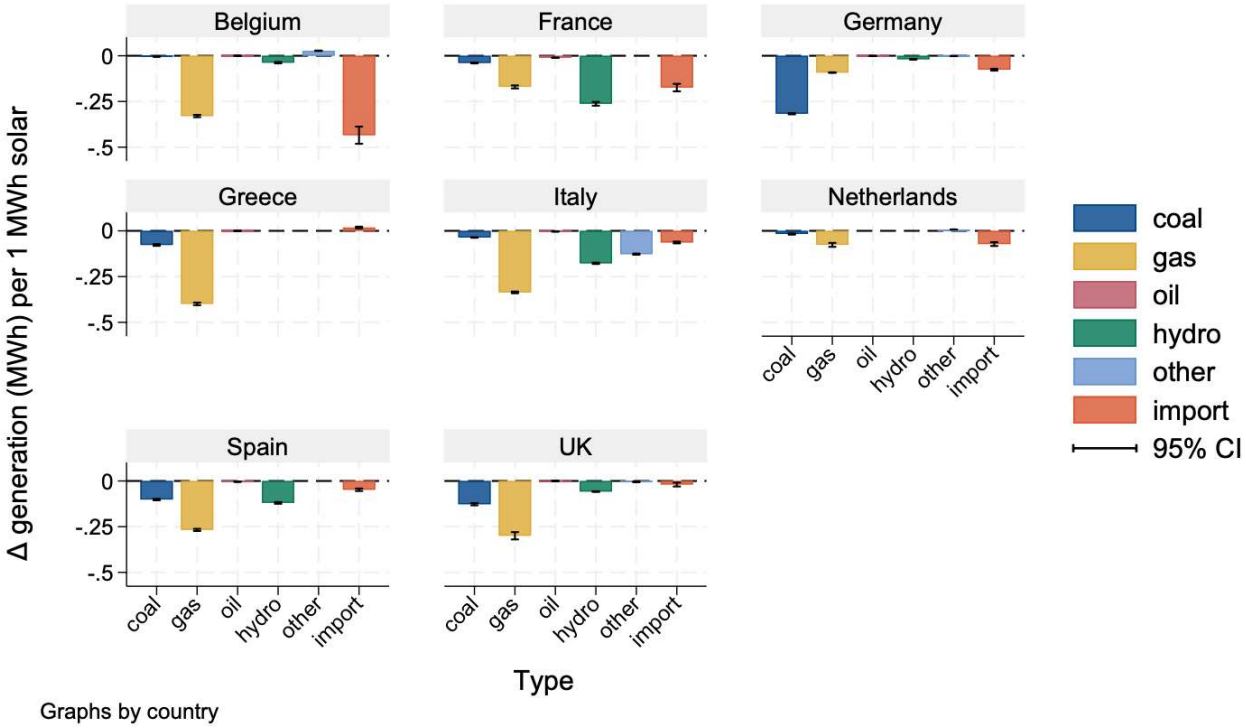



Figure S2: Estimated displacement effects of solar generation on different electricity generation types by country, with 95% confidence intervals. The effects indicate how much each generation source decreases (negative values) or increases (positive values) for each megawatt-hour increase in solar generation. Error bars represent 95% confidence intervals derived from the regression model. Results are based on hourly generation data from 2015-2021, controlling for electricity demand and other relevant factors.