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PAPER

# Synergies between climate mitigation and adaptation: the role of photovoltaics in meeting cooling demand in Italy

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## Abstract

This paper explores the synergies between photovoltaic (PV) adoption as a climate mitigation strategy and the growing need for adaptation through increased cooling demand across Italy. We combine estimates of semi elasticities capturing the effect of residential PV systems on household electricity withdrawals from the grid with high frequency projections of local PV potential, future adoption scenarios and climate projections. This integrated framework allows us to assess two key outcomes: first, the evolution of residential electricity demand for cooling under rising temperatures and second, the extent to which PV diffusion can offset grid electricity consumption. Our nationwide analysis estimates that with rising temperatures, cooling needs will drive significant increases in electricity demand, by 2–3 TWh annually, a 5% increase with respect to residential electricity consumption in 2023. At the same time, expanded PV adoption can partially counterbalance this effect by reducing household reliance on the grid during peak demand periods by almost 50%. The spatial distribution of future PV uptake reveals pronounced heterogeneity across municipalities. Areas in northern Italy and the islands, where installation rates are relatively high, experience sizable benefits from PV generation. In contrast, large and densely populated cities in central and southern Italy, despite being more exposed to frequent and intense heat, capture far smaller gains due to persistently low PV penetration. Overall, our results highlight the importance of jointly considering mitigation and adaptation when designing energy policies. They also underscore the role of targeted measures to promote PV adoption in heat exposed urban areas as part of Italy's ongoing energy transition.

## 1. Introduction

Climate change is amplifying both the urgency of emission reduction efforts and the necessity of effective adaptation strategies. Rising temperatures and the associated increase in cooling demands pose significant challenges for power systems worldwide (Yalew *et al* 2020), especially in regions like the Mediterranean where summers are intensifying rapidly (Cramer *et al* 2018). In Italy, residential electricity consumption is forecast to grow substantially as households install or more frequently use air conditioning to cope with heat extremes (Colelli *et al* 2023). Such intensifying demand risks straining national energy systems, escalating peak loads, and undermining climate objectives if fossil-fuel-intensive electricity is used to meet these needs (Colelli *et al* 2022). If electricity demand will increase significantly in response to rising temperatures households might be trading off self-health protection and higher electricity expenditures (Randazzo *et al* 2020).

While the role of photovoltaics (PV) to address the mitigation challenge is well known (Creutzig *et al* 2017, Victoria *et al* 2021), recent research underscores the capacity of solar PV to tackle both mitigation and adaptation. On the adaptation side, PV systems can help insulate consumers from cost spikes by providing zero-marginal-cost power, especially when air conditioning loads surge in extreme

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temperatures. Moreover, emerging evidence illustrates how these technologies reshape residential load profiles: PV self-production reduces the dependence on the grid, although the'rebound effect' may partially offset these savings, since lower marginal prices could induce greater overall usage (Deng and Newton 2017, Qiu *et al* 2019, Boccard and Gautier 2021, Beppler *et al* 2023). Self-consumption rates can be further optimized through battery storage or a strong alignment between peak household demand and solar output (Khalilpour and Vassallo 2016, Linssen *et al* 2017, Nyholm *et al* 2017). Focusing on Italy, recent work by Piazza *et al* (2025) underscores the value of PV for adaptation, finding that installing rooftop solar panels reduces household grid consumption by 68% precisely during extreme heat events—days when municipal temperatures surpass 30 °C and air conditioning needs spike. This synergy between PV production and peak cooling demand highlights a promising avenue for reconciling climate mitigation (i.e. curbing emissions) with adaptation (i.e. coping with higher temperatures). Despite these complementary benefits, comprehensive, high-resolution assessments that integrate future climate projections with prospective PV uptake scenarios remain limited. Previous research has focused predominantly on either quantifying changes in cooling demands under diverse climate pathways (Wenz *et al* 2017, Colelli *et al* 2023) or estimating the potential for distributed solar power to reduce grid-supplied electricity at a macro-regional level though integrated assessment and energy models (Gupta *et al* 2021, Di Bella and Colelli 2024, Flores *et al* 2024).

Few studies have combined these strands to examine the net effect of scaling up residential PV on mitigating the added electricity demand from air conditioning in a warming climate with a high temporal and geographic resolution. This study bridges this gap by leveraging existing estimates of household-level-PV impacts on grid- electricity uptake (Piazza *et al* 2025), high-frequency climate projections, and spatially-disaggregated scenarios of future PV deployment across Italy. We investigate two outcomes: (i) the incremental electricity demand for cooling driven by rising temperatures, and (ii) the potential reduction in grid reliance achievable through expanded household solar PV adoption. Our nationwide analysis determines the level of PV deployment required to offset the climate- induced increase in cooling needs and quantifies the additional benefits if Italy attains its national mitigation targets. This work highlights the importance of integrating mitigation and adaptation policies to enhance energy security, reduce household costs, and support a just transition in the face of climate change. By providing a comprehensive framework for evaluating the role of solar energy in compensating heat-driven demand, our findings offer valuable insights for policymakers and stakeholders aiming to align Italy's evolving energy landscape with its commitments to climate.

## 2. Methods

This study employs a comprehensive framework to assess the interplay between the adoption of PV technology and the increasing demand for cooling, driven by climate change in Italy. By integrating high-resolution household electricity consumption data, spatially detailed PV ownership statistics, and high-frequency climate projections, we model future scenarios of energy demand and PV impact. Spatially-disaggregated projections of PV deployment and cooling-related electricity consumption are developed to evaluate the potential of PV systems to mitigate the additional electricity consumption from the grid required to adapt to hotter climate conditions. As illustrated in figure 1, our methodological framework integrates the collection and processing of historical data with the development of future projections and scenarios.

### 2.1. Data

We use institutional data from the Autorità di Regolazione per Energia Reti e Ambiente (ARERA) to analyze household electricity consumption in Italy, focusing on monthly and hourly average usage at the NUTS 3 provincial level. The data, sourced from distribution companies and processed via the Integrated Information System (SII), is aggregated across different power classes and distinguishes between weekday and weekend usage patterns. This detailed breakdown facilitates an in-depth examination of consumption trends across provinces. To characterize current and future residential PV system distribution with high spatial resolution, we incorporate data from the Gestore dei Servizi Energetici (GSE). Specifically, we construct a NUTS 3-level prevalence rate using the number of PV installations per province. Additionally, the GSE Solar Atlas database provides municipal-level PV installation counts as of January 2024. To isolate residential installations, we consider only PV systems with a capacity below 20 kW, aligning with regulatory limits for domestic producers. Data sources and characteristics are summarised in table 1.

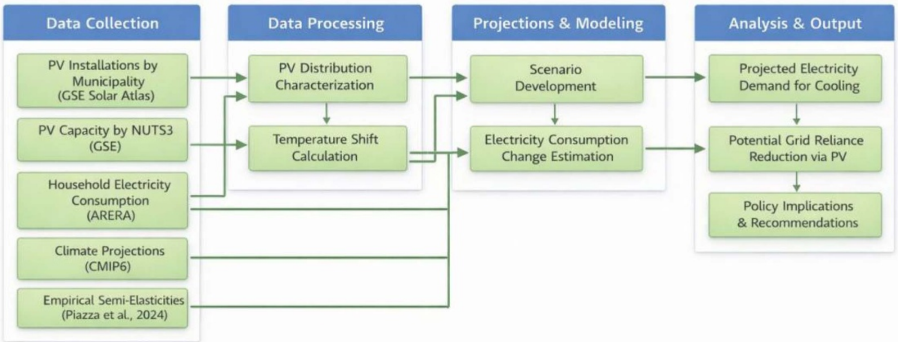


**Figure 1.** Methodological framework for assessing the impact of photovoltaic (PV) adoption on residential cooling demand in Italy under climate change. The workflow integrates data on PV installations, capacity, household electricity consumption, climate projections, and empirical semi-elasticities, with the final goal of developing temporally and spatially-explicit projections of temperature-induced electricity demand and potential reductions in such demand across PV adoption scenarios.

**Table 1.** Data Sources and Characteristics.

| Data input | Geographic level | Time coverage | Source |
|---|---|---|---|
| Household electricity consumption | NUTS 3 | Monthly, hourly | ARERA, SII |
| PV system units | Municipal | January 2024 | GSE, Solar Atlas |
| PV system capacity | NUTS 3 | 2023 | GSE |
| Semi-elasticities of grid consumption | — | — | Piazza *et al* (2025) |
| Historical weather data | 0.25° × 0.25° grid cell | 2001–2020 | ERA5 |
| Future temperature projections | 0.5° × 0.5° grid cell | 1991–2050 | CMIP6 GCMs |

*Notes:* Data sources used for the analysis, including electricity consumption, PV system characteristics, and climate variables. Time coverage varies by dataset, with historical and future projections from different sources.

We adopt the empirically estimated semi-elasticities presented in Piazza *et al* (2025) to characterize the response of grid-based consumption of households without and with a PV systems to outdoor daily mean temperatures. Piazza *et al* (2025) exploit changes in consumption patterns within the household following the PV installation start date of each system. By controlling for seasonal recurrent effects and potential changes at the POD level, they provide estimates that isolate the impact of PV adoption on consumption behavior. Temperature and solar irradiance are included in the regression model to account for the potential influence of weather on household electricity demand with and without PV (see supplementary methods). Figure 2 shows the estimated coefficients of the average daily grid electricity consumption change—reduced by 85%, varying between 75% and 90% depending on the level of daily solar irradiance and by season—with a higher reduction in spring and summer—by 88%—and a minimum reduction in autumn—by 34%.

Grid cell-level weather data, including mean daily temperature and solar irradiance over the historical period of 1991–2020, is obtained from the ERA5 reanalysis products (Hersbach *et al* 2020). To quantify the impact of climate change on cooling demand, we analyze temperature projections from the CMIP6 framework (O'Neill *et al* 2016), incorporating five global climate models (GCMs) to capture uncertainty. We define a representative 20 year historical (1991–2010) and future periods (2021–2030, 2031–2040, 2041–2050) for our analysis.

### 2.2. Projections

*2.2.1.PV ownership*

As a first step, we calculate the municipality-level share of PV installations relative to provincial totals and allocate provincial aggregate residential installations accordingly, assuming one PV system per household and a constant average household size of 2.3 persons (Istat 2023). The estimated number of residential PV installations in municipality $j$ of province $i$ is computed as:

$$M\_ij = (S\_ij/\Sigma\_jS\_ij) \cdot P\_i. \quad (1)$$

Where:

- $M_{ij}$ is the estimated number of residential PV installations in municipality $j$ of province $i$,

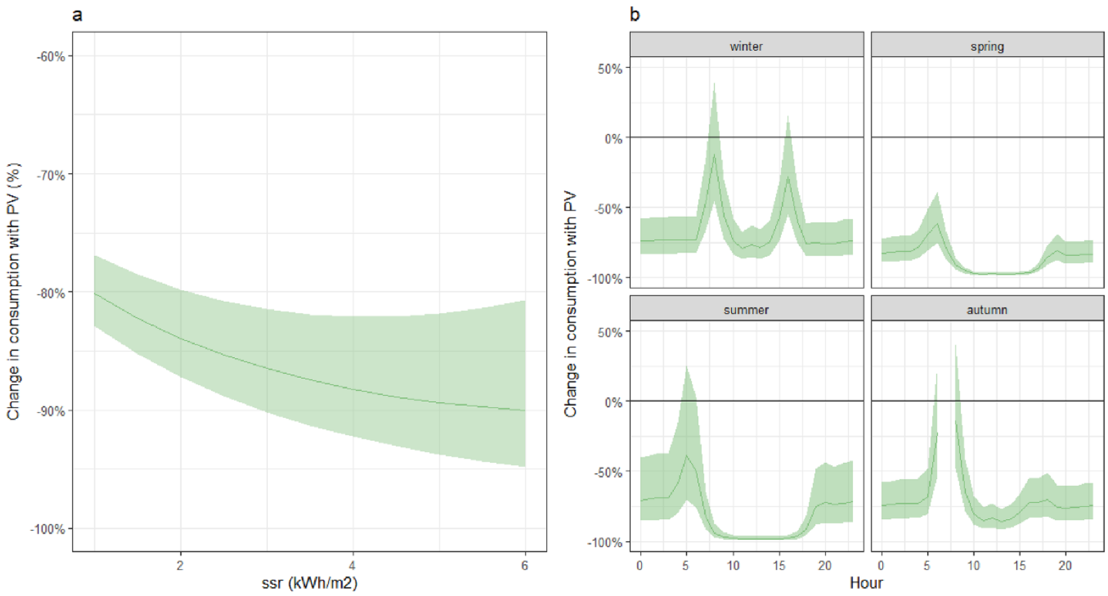


**Figure 2.** Change in grid consumption due to PV adoption by level of solar irradiance and season. Panel (a) shows daily changes depending on temperatures and irradiance levels. Panel (b) shows the effect on hourly demand by season. Shades represent the 95th confidence intervals. Only coefficients statistically significant at the 0.1 level or below are shown. Figure adapted from Piazza *et al* (2025). Adapted from Piazza *et al* (2025). CC BY 4.0.

- $S_{ij}$ is the count of PV installations in municipality $j$ from GSE Solar Atlas,
- Σ_*jS_ij* is the total PV installations in province *i*,
- $P_i$ is the total number of residential PV installations in province $i$ based on GSE statistics.

The difference between the level of AC adoption rate computed at the province level to the one disaggregated at the municipality level is shown in figure 3, panel (a).

As a second step, we project changes in PV prevalence rates using projections from the Italian grid operator (TERNA) up to 2050, extending beyond the provided 2030 and 2040 projections through linear interpolation (TERNA 2024). These projections are applied uniformly across provinces within the same macro region (NUTS 1 level) and encompass both high and low diffusion scenarios to account for uncertainty. Specifically, in the former case, a large portion of the electricity required to meet consumption comes from renewable sources such as solar and wind. This scenario envisions the maximized development of renewable generation in Italy. Conversely, the low scenario is built in alignment with the previous scenario but assumes a delay in implementing the measures outlined to achieve the decarbonization targets, in particular a delayed development of renewable energy sources. Note that we do not account for other differences in the two scenarios outlined by TERNA (2024), such as different patterns in electrification of consumption, wind capacity additions or development of storage capacity and solutions for recovering overgeneration, as our main focus is the trajectories of residential-scale solar PV. Our projections indicate an increase in average PV ownership from 6% in 2023 to 14%–15% by 2030 and 22%–24% by 2050 (see figure 3, panel (b)).

### *2.2.2. Future temperature projections*

Using semi-elasticities from Piazza *et al* (2025), we estimate daily electricity consumption changes due to temperature deviations from the comfort range of 15 °C–21°C. The semi-elasticities $\beta_k$ quantify consumption changes for households without PV, while $\gamma_k$ account for additional changes in PV-equipped households. The coefficients $\delta_1$, $\delta_2$, and $\delta_3$, estimated in Piazza *et al* (2025), model the non-linear relationship between consumption changes and daily solar irradiance levels. Because the semi-elasticities are estimated from observed household electricity consumption, they implicitly capture the net effect of all mechanisms affecting grid demand in PV-equipped households, including irradiance-driven efficiency losses, thermal interactions during PV operation, and natural heat dissipation processes, to the extent that these influence observed consumption (see for instance Elbakheit *et al* (2022)).

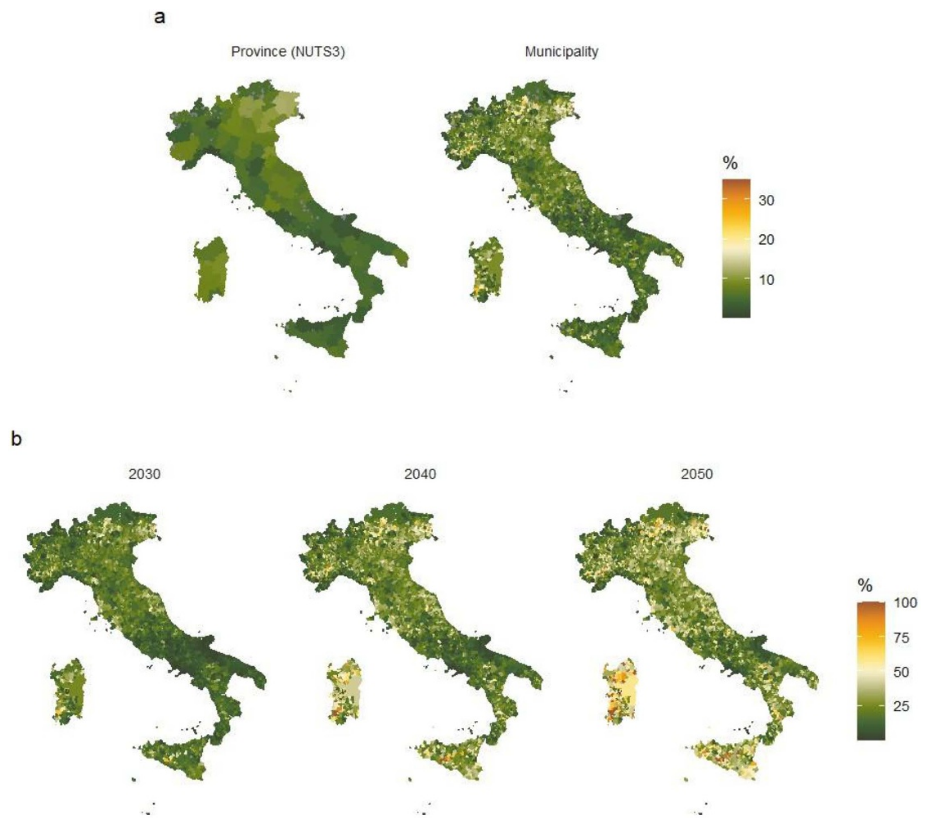


**Figure 3.** Residential photovoltaic ownership rates across Italy. Panel (a) shows observed rates in 2023 at the provincial and municipal level. Panel (b) shows projected municipal-level rates from 2030 to 2050 under a high diffusion scenario.

To quantify the impact of climate change on cooling demand, we use daily temperature projections from the Coupled Model Intercomparison Project Phase 6 (CMIP6; O'Neill *et al* (2016)), a state-of-the-art framework for GCM. In our modeling protocol, we used climate projections from four GCMs: GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1-2-HR, and UKESM1-0-LL. We adopt an ensemble approach for a more robust representation of climate variability and uncertainty in simulating future climate conditions Abramowitz *et al* (2019). Some GCMs project higher-than-average temperature increases by mid- and end-of-century (e.g. UKESM1-0-LL), while others project lower-than-average warming (e.g. MPI-ESM1-2-HR; see supplementary figure 9). This ensemble approach allows us to capture structural uncertainty arising from differences in model physics, parameterizations, and numerical schemes.

The spread of projections across the four GCMs is used to quantify uncertainty in future cooling demand, reflecting structural differences among models. In combination with varying assumptions on future PV adoption rates, this approach allows us to propagate both climatic and technological uncertainties through our estimates.

While the CMIP6 ensemble provides a systematic way to explore plausible climate futures, it does not encompass all possible outcomes. Limitations include: (i) the finite number of models in the ensemble, (ii) potential biases in regional temperature patterns due to model resolution and parameterizations, and (iii) uncertainties associated with emission scenarios beyond SSP2-4.5. Consequently, our projections should be interpreted as indicative of plausible trends of cooling demand induced by projected future temperature shifts, rather than precise forecasts.

*2.2.3. Temperature-induced power grid consumption*

We define a 20 year historical baseline period (1991–2010) and three future decades (2021–2030, 2031–2040, 2041–2050) under the SSP2-4.5 scenario, representing a moderate emissions pathway (Meinshausen *et al* 2020). To evaluate the impact of temperature changes on electricity consumption, we calculate the shift in average daily temperatures ($\Delta T_{c,t,d,g}$) for each grid cell $c$, day $t$, decade $d$, and GCM $g$. This shift represents the difference between future ($T^{\mathrm{F}}_{c,t,d,g}$) temperatures and historical ($T^{\mathrm{H}}_{c,t,d,g}$) temperatures:

$$\Delta T_{c,t,d,g} = T^{\mathrm{F}}_{c,t,d,g} - T^{\mathrm{H}}_{c,t,d,g}. \tag{2}$$

Using this temperature shift, we calculate the projected future temperature ($T^{\mathrm{Fut}}_{c,t,d,g}$) by adding the temperature anomaly to the historical average temperature ($\overline{\overline{T^{\mathrm{Hist}}_{c,t,d,g}}}$):

$$T^{\mathrm{Fut}}_{c,t,d,g} = \overline{\overline{T^{\mathrm{Hist}}_{c,t,d,g}}} + \Delta T_{c,t,d,g}. \tag{3}$$

The resulting temperature projections are then used to estimate gridcell-level changes in electricity consumption for thermal comfort. For households without PV systems, the change in consumption ($\Delta C^{\mathrm{no\,PV}}$) is calculated as a function of the average daily baseline consumption ($C$) and the temperature exposure within specific intervals. Each interval is characterized by a semi-elasticity coefficient ($\beta_k$) that maps the sensitivity of consumption to temperature deviations:

$$\Delta C^{\mathrm{No\,PV}} = \bar{C} * \sum_k \beta_k * T_k. \tag{4}$$

Here, $T_k$ is a dummy variable indicating whether the temperature falls within the $k$-th interval. This formulation captures the temperature-dependent variation in energy use for households without PV systems.

For households equipped with PV systems, the change in consumption ($\Delta C_{\mathrm{PV}}$) is modified to account for the additional effects of solar irradiance ($i$) on the effect pf PV on grid power consumption. This relationship is modeled through a nonlinear function of irradiance coefficients ($\delta_1$, $\delta_2$, and $\delta_3$) and the semi-elasticity ($\gamma_k$) for each temperature interval:

$$\Delta C^{\mathrm{PV}} = \bar{C} * \left(\delta_1 + \delta_2 i + \delta_3 i^2\right) * \sum_k \gamma_k * T_k. \tag{5}$$

This approach captures the dynamic interplay between temperature-driven energy demand and the mitigating effects of PV systems, particularly during high-irradiance periods.

Finally, the total change in electricity consumption for thermal comfort within a grid cell ($\Delta C_{\mathrm{tot}}$) combines the contributions from both non-PV and PV households. This weighted sum accounts for the prevalence of PV systems ($\phi$), the total population ($P$), and the average household size ($Z$):

$$\Delta C^{\mathrm{Tot}} = P/Z * \left[(1-\phi) * \Delta C^{\mathrm{No\,PV}} + \phi * \Delta C^{\mathrm{PV}}\right]. \tag{6}$$

This formulation provides a comprehensive representation of electricity consumption changes in response to temperature variations, considering the mitigating role of PV adoption and the distribution of households with and without PV systems.

### 2.3. Scenario development

To assess the implications of varying PV adoption rates on electricity consumption driven by thermal comfort, we consider three distinct scenarios. The first scenario reconstructs electricity consumption under historical climate conditions and the current prevalence of PV systems. This baseline allows us to understand the status quo and serves as a reference point for the other scenarios. The relationship between electricity demand and these conditions can be expressed as follows:

$$\Delta C^{\mathrm{Hist\,T,Hist\,PV}}_{\mathrm{tot}} = f\left(T^{\mathrm{Hist}} + \phi^{\mathrm{Hist}}\right). \tag{7}$$

In the second scenario, we project changes in electricity consumption under future climate conditions, assuming that the prevalence of PV systems remains unchanged. By keeping the PV adoption rate constant, this scenario isolates the impact of climate change on electricity demand, particularly for thermal comfort. The associated relationship is given by:

$$\Delta C^{\mathrm{Fut\,T,Hist\,PV}}_{\mathrm{tot}} = f\left(T^{\mathrm{Fut}} + \phi^{\mathrm{Hist}}\right). \tag{8}$$

The third scenario incorporates both future climate conditions and an increased prevalence of PV systems, reflecting a transition to higher rates of PV adoption over time. This scenario evaluates the combined effect of climate change and enhanced PV deployment on electricity consumption, highlighting the potential of increased solar energy adoption to mitigate the additional demand for thermal comfort. The mathematical representation of this scenario is:

$$\Delta C^{\mathrm{Fut\,T,Fut\,PV}}_{\mathrm{tot}} = f\left(T^{\mathrm{Fut}} + \phi^{\mathrm{Fut}}\right). \tag{9}$$

These scenarios collectively provide a comprehensive framework for evaluating the interplay between climate change, PV adoption rates, and electricity demand, offering insights into the role of renewable energy in addressing climate-driven increases in energy consumption.

**Table 2.** Projected National Residential Electricity Consumption by Scenario (TWh).

| | Historical | | Thermal Future | | Reductions |
|---|---|---|---|---|---|
| Decade | Total | Thermal | Current PV | Additional PV | from Additional PV |
| 2030 | 69 | 6.0 | 7.6 (+26%) | 7.3 (+18%) | −0.5 |
| 2040 | 69 | 6.0 | 8.3 (+37%) | 7.5 (+24%) | −0.8 |
| 2050 | 69 | 6.0 | 8.8 (+44%) | 7.5 (+25%) | −1.2 |

*Notes:* Projected electricity consumption under different scenarios. Future estimates include variations in photovoltaic (PV) deployment. Percentage increases represent the change from historical thermal consumption.

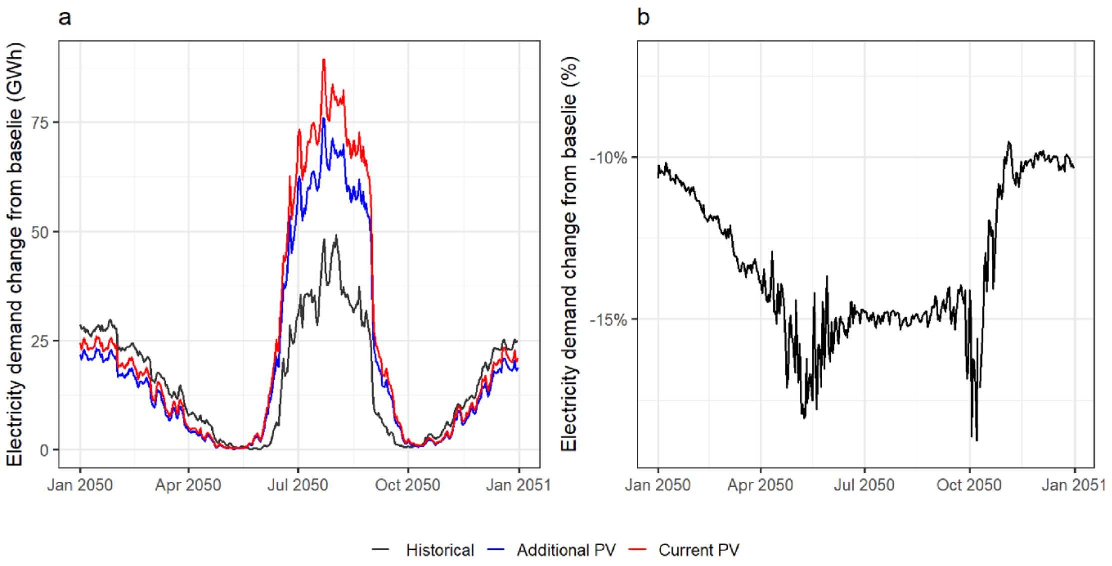


**Figure 4.** Daily country-level electricity consumption for thermal comfort. Panel (a) shows the simulated demand under historical (1991–2010) and future climate around 2050 under two scenarios: constant PV at today's level (Current PV) and increased PV adoption (Additional PV). Panel (b) shows the daily change in consumption attributable to the additional PV deployment relative to the Current PV scenario around 2050.

## 3. Results

The residential sector's grid-supplied electricity consumption (hereafter, electricity consumption) in Italy is projected to rise significantly due to increasing daily mean temperatures. In the absence of accelerated PV adoption, annual residential electricity consumption is expected to increase by approximately 1.6 TWh by 2030 and 2.8 TWh by 2050 as a result of climate change. This growth corresponds to a 26% (44%) rise in electricity demand for thermal comfort by 2030 (2050), equating to 2% (4%) of the residential sector's total electricity use in 2023 (69 TWh). However, as summarized in table 2, expanding PV deployment partially mitigates this increase: under higher PV adoption trajectories, the net rise in electricity consumption is reduced to 1.3 TWh by 2030 and 1.5 TWh by 2050.

Although both colder and hotter days drive the use of electricity for heating and cooling, rising winter temperatures lead to only modest decreases in winter consumption, while summer consumption increases, particularly on peak cooling days (see figure 4, panels (a) and (b)). PV systems help to offset these summer peaks, as their output varies with seasonal irradiance and is closely aligned with air conditioning loads. In a high-adoption scenario, this alignment results in a notable net reduction in grid-supplied electricity consumption for cooling, ranging from −15% to −18% during the summer.

Examining regional patterns of daily cooling demand across Italian NUTS 2 regions (see figure 5, panels (a) and (b), we find that PV adoption effectively alleviates demand spikes in areas with higher deployment rates, such as Sicily and Veneto. However, in key high-demand regions like Lombardy and Lazio, PV contributions remain limited. Comparing all regions based on their annual reduction in additional cooling demand due to increased PV adoption further reinforces this pattern. With the exception of Sicily, which combines high cooling needs with significant relative reductions, the regions that benefit

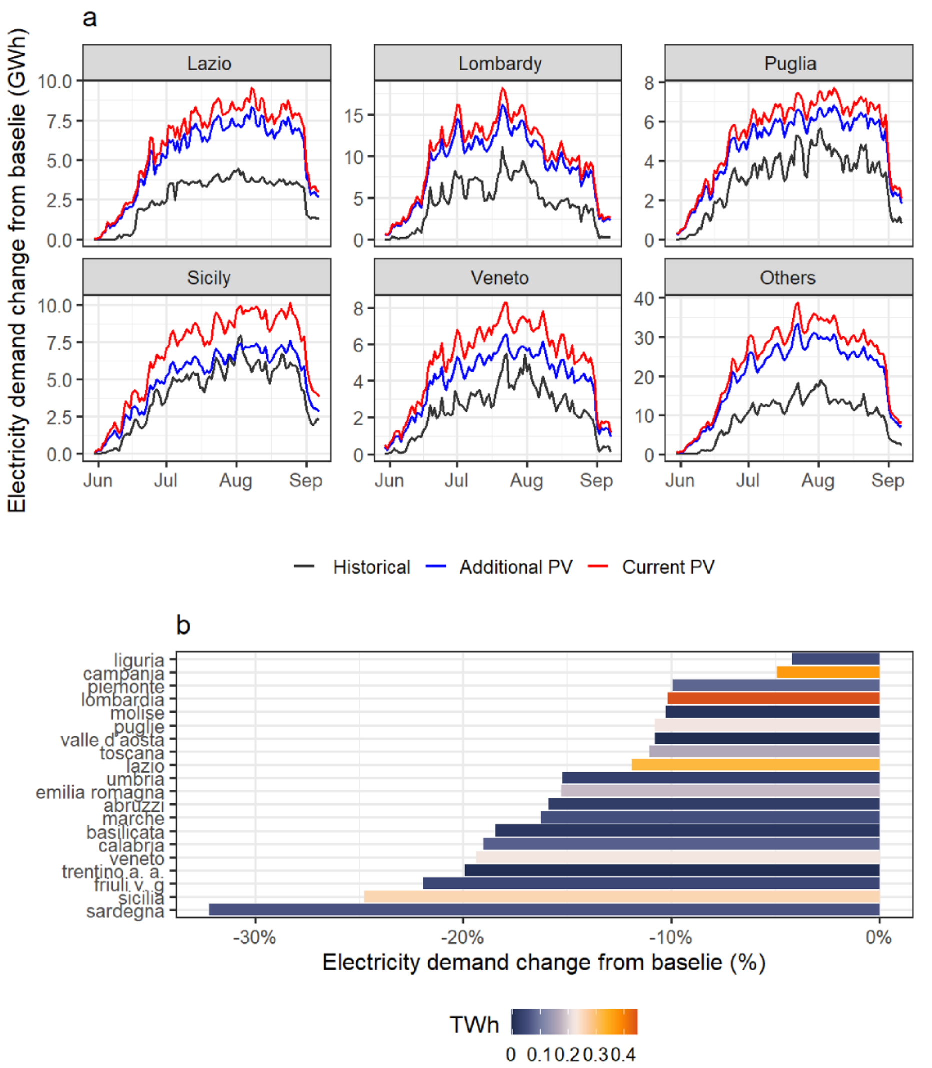


**Figure 5.** Municipal- and regional-level changes in electricity consumption for thermal comfort induced by climate change. Panel (a) reports absolute changes in consumption measured in GWh under the three modeled scenarios. Panel (b) reports percentage changes in consumption relative to baseline demand under the scenario with additional photovoltaic deployment.

most in relative terms (with reductions exceeding 15%) tend to have lower absolute cooling demand, including Sardegna, Trentino, and Friuli. In contrast, major demand centers such as Campania and Lombardy experience only marginal benefits due to limited PV adoption growth.

The largest relative increases in cooling-related electricity demand occur along the western coast of central Italy, particularly in Rome and Naples, highlighting the vulnerability of large, populous cities in hot regions. These urban centers—Rome, Milan, Naples, and Palermo—lead the surge in additional cooling demand.

Future PV adoption will further amplify spatial disparities in cooling-related electricity demand. Without expanded PV uptake, the percentage increase in grid-based consumption remains relatively uniform across Italy (see figure 6, panel (a)). However, when projected PV ownership rates are incorporated, municipalities in northern regions and the islands—where installation rates are higher—experience larger reductions in additional electricity demand (see figure 6, panel (b)). Conversely, many areas in central and southern Italy, despite facing more frequent and intense heat, benefit less from PV due to lower adoption rates. This trend is particularly pronounced in major cities such as Rome, Naples, and Palermo (see figure 7).

The interplay between climate-induced electricity demand and uneven PV deployment underscores the need for targeted policies that integrate mitigation and adaptation strategies. Ensuring that PV adoption keeps pace with increasing cooling needs in high-demand regions will be critical for maintaining energy system stability and reducing climate vulnerability.

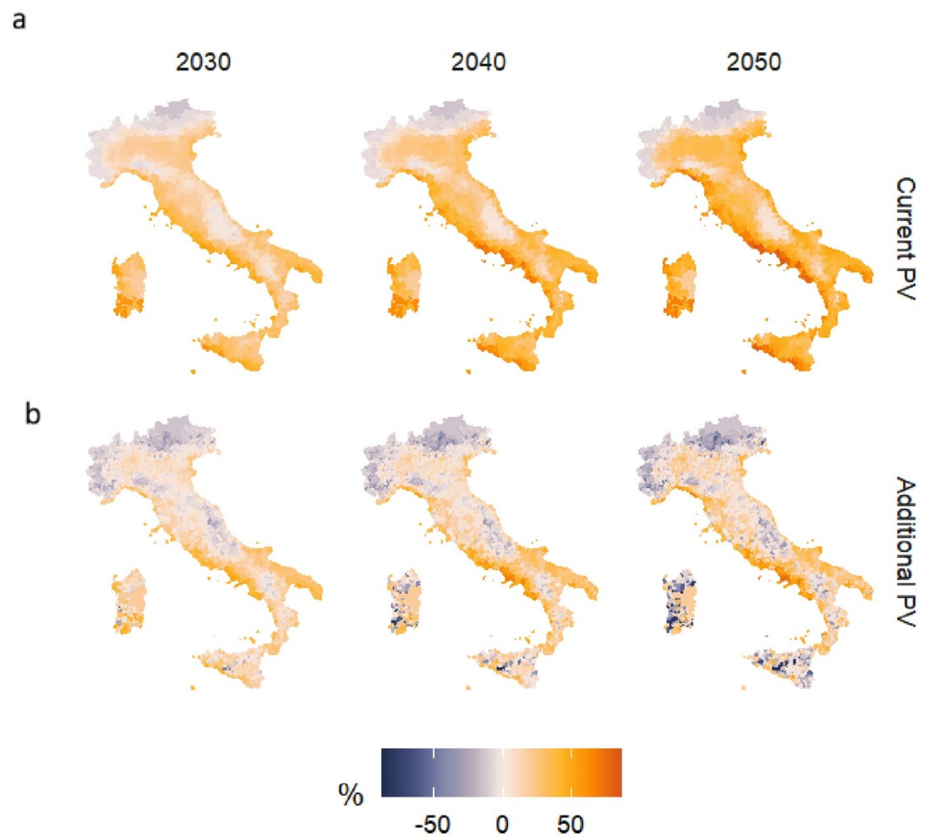


**Figure 6.** Panel (a): annual municipal-level change in consumption for thermal comfort due to climate change, in the scenario with current PV. Panel (b): annual municipal-level change in consumption for thermal comfort due to climate change, in the scenario with additional PV.

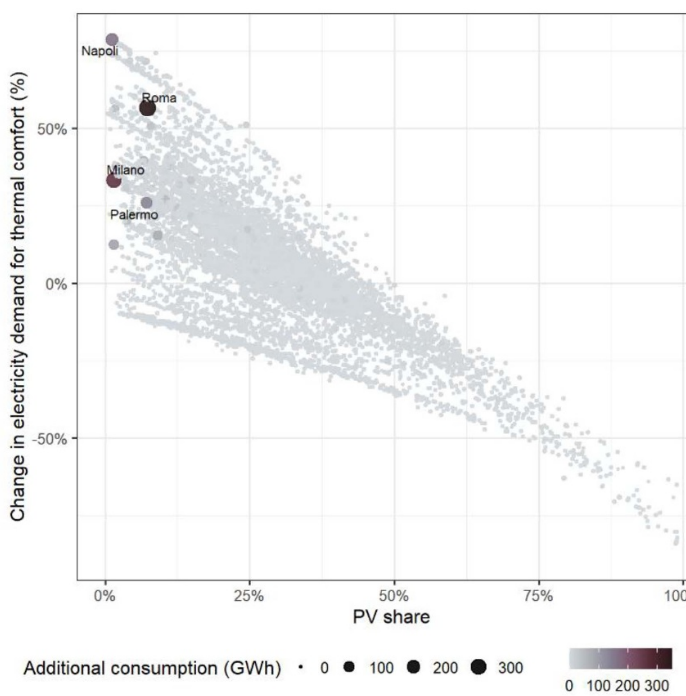


**Figure 7.** Projected change in electricity consumption and PV prevalence shares, in the scenario with additional PV and 2050. The size and color of the scatters represents the additional consumption in the scenario with no PV expansion.

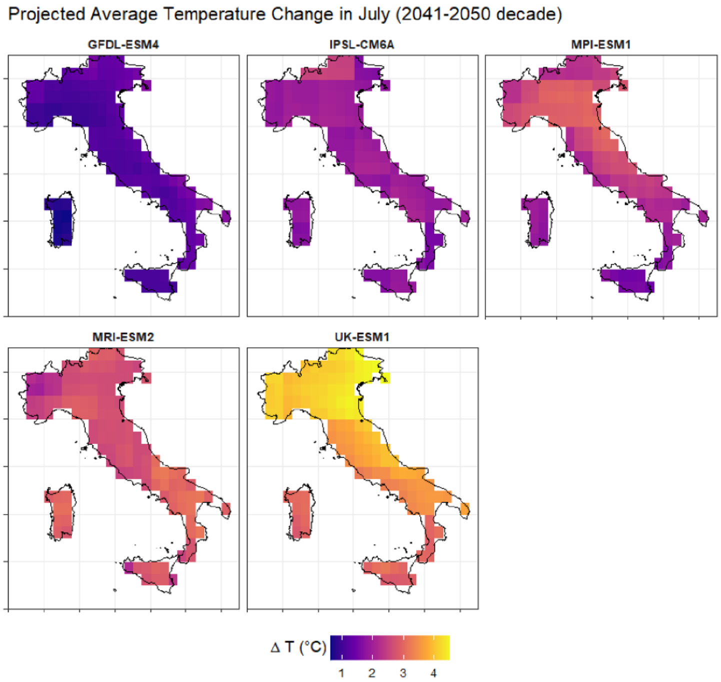


**Figure 8.** Gridded average temperature change ($\Delta T$) in Italy for July for the decade 2041–2050 relative to the historicalbaseline (1991–2010), with color intensity indicating the magnitude of temperature change. Italy's national boundaries are overlaid for geographic reference. Facets separate the results by GCM, allowing comparison of the spatial patterns and highlighting differences among models.

### 3.1. Climate models uncertainty

Projections of electricity demand for cooling, as well as the potential mitigating role of PV adoption, depend critically on the range of future climate conditions considered. We characterize uncertainty in the climate inputs by comparing spatial and temporal patterns across an ensemble of five CMIP6 GCMs (GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1-2-HR, MRI-ESM2, andUK-ESM1), and assess how structural differences across models propagate into projected temperature changes and associated electricity demand. A first dimension of uncertainty arises in the spatial distribution of projected summer warming across Italy. In July, all models indicate stronger temperature increases in northern regions, but the magnitude and spatial gradient vary across projections. In particular, UK-ESM1 consistently projects higher increases throughout most of the country, whereas GFDL-ESM4 produces more moderate warming. The remaining models (IPSL-CM6A-LR, MPI-ESM1-2-HR, and MRI-ESM2) exhibit greater agreement, both in spatial patterns and in average warming. These differences extend to the temporal distribution of daily temperatures, highlighting how model structure shapes not only average changes but also short-term variability. The spatial patterns described here are summarized in figure 8, with daily temperature distributions shown in supplementary figure 11. Figure 9 turns to the implications of these climate projections for electricity demand, illustrating the projected annual change in national power grid consumption under alternative PV ownership scenarios over the study period. Panels (a) and (b) report the total change in electricity consumption required to maintain thermal comfort in a scenario with additional PV deployment, while panels (c) and (d) isolate the incremental effect of this additional PV relative to the historical PV ownership baseline. The figure is structured to distinguish between aggregate outcomes and model specific realizations: in particular, panels (b) and (d) present results separately for each GCM, making it possible to directly assess the extent to which uncertainty in climate projections propagates into uncertainty in electricity demand estimates. Across models, the total increase in grid consumption is of the order of 6–8 TWh, with dispersion widening in later decades, especially approaching 2050. This pattern closely mirrors the divergence in projected temperature changes documented in figures 8–11. In line with its relatively lower warming projections, GFDL-ESM4 yields the smallest increase in consumption (approximately 5.9 TWh), whereas UK-ESM1 produces the highest estimates (reaching up to about 8.5 TWh). The estimated contribution of additional PV follows a similar pattern: by 2050, reductions in grid consumption attributable to PV range from roughly −0.9 TWh to −1.4 TWh across models. Overall, both the magnitude and temporal evolution of projected temperature changes, and the resulting

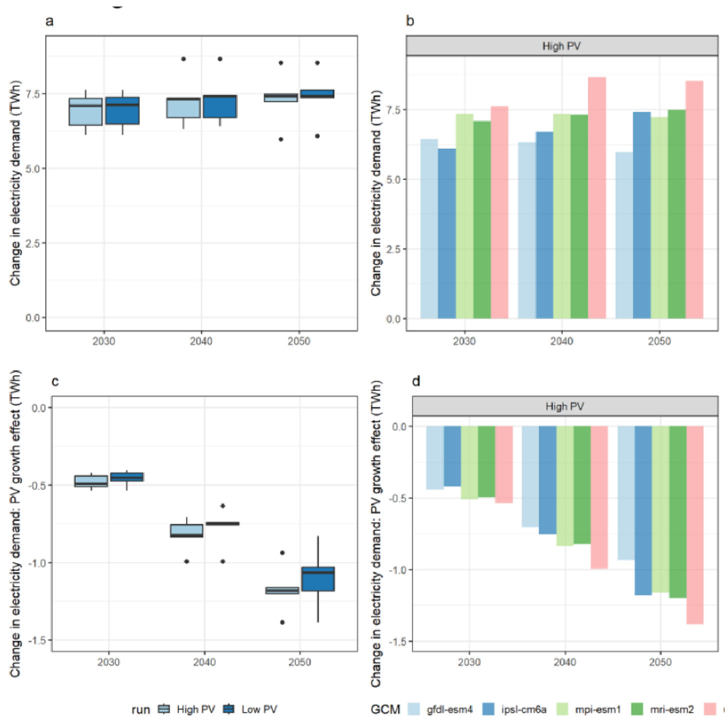


**Figure 9.** Projected changes in national electricity consumption from the power grid under different residential PV ownership scenarios. Panel (a) shows boxplots of total projected consumption changes across all scenarios, capturing variability across GCMs and simulation runs. Panel (b) shows total changes for the High PV scenario, with contributions from individual GCMs displayed as bar plots. Panel (c) shows the impact of additional PV on reducing grid consumption across all scenarios, with negative values indicating reduced reliance on the grid. Panel (d) shows the same effect for the High PV scenario, with contributions from individual GCMs distinguished in bar plots.

electricity demand response, are broadly consistent across the ensemble. Mean estimates align closely with those from three of the five models, indicating that the central findings are not driven by outlier model behavior.

## 4. Discussion and conclusions

This study highlights the significant impact of climate change on residential grid electricity consumption in Italy, particularly due to rising cooling demands in summer. In line with previous research (Colelli *et al* 2023, De Cian *et al* 2023), we find that without increased PV adoption, electricity consumption for cooling is projected to rise substantially. However, we elucidate that expanded PV deployment offers a crucial mitigation-adaptation synergy, alleviating peak cooling loads and reducing reliance on grid-supplied electricity. PV systems provide on-site power generation that naturally meets high cooling demand periods, allowing households equipped with PV to utilize their own solar production rather than draw from the grid. We find that this self-consumption effect reduces peak daily demand in the summer, potentially reducing grid stress that may result from rising summer temperatures. Consequently, the expansion of PV represents a dual benefit strategy, serving both as a mitigation measure that reduces emissions and as an adaptation mechanism that alleviates the burden of the power system in a warming climate. Contrary to purely descriptive assessments of energy trends, this study provides a novel methodological integration by coupling household-level semi-elasticities with high-resolution climate ensembles. This approach addresses a significant gap in the literature regarding the spatial granularity of climate-energy synergies. By utilizing an ensemble of four CMIP6 GCMs, we move beyond deterministic projections to a robust, multi-model probabilistic framework. This allows for a statistically grounded quantification of uncertainty, which is essential for resilient infrastructure planning under the Shared Socioeconomic Pathways (O'Neill *et al* 2016).

We also find that regional disparities in PV adoption rates influence the extent to which different areas benefit from solar energy. While northern regions and islands with higher PV penetration see substantial reductions in additional cooling-related demand, major urban centers in central and southern Italy, such as Rome, Naples, and Palermo, remain particularly vulnerable due to slower adoption rates. Our results quantify the disadvantage that these areas might face if such scenario would prove true, as these would be areas where cooling needs rise the most while benefits of PV are not exploited fully. These underscores the need for possible policy levers—such as subsidies or building codes—that could enhance PV uptake in the regions where PV could provide most benefits to households and the power grid. This seems particularly relevant for avoiding an emerging equity gap in the energy transition in the areas with the large temperature increases and high population density, such as Naples. Our work underscores the necessity of targeted policies to enhance PV adoption, especially in high-demand regions. Aligning mitigation efforts with adaptive needs will be essential for ensuring energy resilience and managing the increasing electricity demand in a warming climate. By leveraging PV as both a mitigation and adaptation tool, policymakers can help stabilize the grid and reduce climate vulnerability across Italy.

The findings of this paper resonate with the broader European Union goals to accelerate the energy transition, as outlined in the 'Fit for 55' package and Italy's National Energy and Climate Plan, both of which emphasize rapid decarbonization and resilience against extreme weather events. Similar model-based analyses corroborate the link between intensifying heat, surging air-conditioning loads, and the mitigating role of distributed solar power Di Bella and Colelli (2024). However, while modeling studies have so far informed on the potential grid demand reductions that can be achieved through decentralized solar PV at the macro-regional level, our spatially granular assessment highlights the necessity of targeted, region-specific strategies—particularly in southern Italy's urban centers. By providing these nuanced, high-resolution insights, our work underscores the importance of aligning local policy frameworks with overarching European objectives for a climate-resilient and low-carbon future.

This analysis is not without caveats. A first set of caveats relates to the empirical estimations of the electricity consumption response to weather conditional on PV adoption. While we rely on econometric estimates from Piazza *et al* (2025), that account for household-level heterogeneity and weather exposure, several caveats remain that could influence the generalizability of the results. First, the estimates rely on data from a single municipality, Brescia, and although its climate, PV performance, and consumption patterns closely mirror national averages (see supplementary methods), we cannot fully rule out municipality- or region-specific effects that may influence electricity demand responses elsewhere. That said, the within-household identification strategy employed by Piazza *et al* (2025)—comparing consumption before and after PV installation while controlling for seasonal and pod-level effects—isolates behavioral responses to PV adoption in a way that is unlikely to be fundamentally different across Italian municipalities sharing broadly similar climatic and regulatory conditions. The primary source of remaining uncertainty is therefore not the identification approach itself, but rather whether the magnitude of the estimated response is transferable; given that Brescia sits close to the national median on key determinants of cooling demand and PV yield, we expect any resulting bias to be modest and unlikely to alter the direction of our findings.

Second, factors such as household wealth, building characteristics, or occupancy patterns, which are not fully observed in our data, may modulate the behavioral response to PV adoption. These unobserved factors are partially absorbed by the household fixed effects in Piazza *et al* (2025), and to the extent that their distribution across Italian provinces does not systematically diverge from Brescia, their influence on national-level projections should be limited. Where such divergence does exist. for instance, in southern regions with older building stock or lower average incomes, our projections should be interpreted with additional caution.

Third, interactions between PV adoption and local grid management, tariff structures, or incentives may vary across regions, potentially affecting the magnitude of grid consumption reductions. Italy's net metering framework (Scambio sul Posto) has been broadly uniform across provinces over our study period, which reduces—though does not eliminate—the concern that spatially varying tariff structures confound our projections. Taken together, these caveats could lead to either slight under- or overestimation of national-level effects, but we have no strong prior reason to expect systematic bias in a single direction, and the overall direction and qualitative magnitude of our projections are therefore likely to be robust. Furthermore, through our approach, we assume that households will respond to a hotter climate as done in the past—e.g. with a more intensive use of energy-intensive cooling stock. This is a standard assumption in reduced-form climate-energy studies (Auffhammer and Mansur, 2014), and is reasonable over the near-term horizon (2021–2040) where major structural shifts in cooling technology are unlikely; over longer horizons toward 2050, improvements in appliance efficiency or building insulation could attenuate the demand response, meaning our projections for that period may represent an upper bound on cooling-related grid consumption.

A second group of caveats relates to the projections of PV technology adoption. The composition of future PV capacity as predicted by national energy plans (e.g. PNIEC) anticipate that the majority of future PV installations will be nonresidential in nature, as ground-mounted systems are more cost-effective than rooftop systems. This structural shift has the potential to exert a considerable influence on the system-level resilience to peak summer loads. We use solely data regarding residential-level distributed PV. This implies that our estimates of PV-driven grid demand reductions should be understood as an upper bound on the contribution of the residential sector specifically, rather than of solar generation more broadly. To the extent that nonresidential PV also generates during peak cooling hours, system-level mitigation could be even greater than we project, but this falls outside the scope of our household-level framework. Our model does not account for the potential change in the underlying relation between load and weather exposure—which could for instance become more higher under an expansion of AC cooling extensive margin or become less prominent with improved appliances' energy efficiency and insulation of buildings. These two forces operate in opposite directions: greater AC penetration would amplify the temperature-consumption relationship beyond what our fixed semi-elasticities capture, while efficiency gains would dampen it. In the absence of reliable projections of how these factors will evolve jointly across Italian provinces, we treat the semi-elasticities as stable, but flag that this assumption introduces increasing uncertainty at longer time horizons.

Furthermore, our results on the regional heterogeneity of the solar PV benefits depend on the official national projections of regional growth in adoption by the Italian grid operator (TERNA 2024). While we follow these official projections as the most authoritative available source, we note that past adoption rates in Italy have been sensitive to policy incentives; should future subsidy schemes or building regulations specifically target regions where adoption is currently low, distributed PV diffusion could accelerate beyond the TERNA baseline, which would reduce the equity gap we identify. Incorporating the endogenous effects of climate change on PV adoption rates, alongside socio-economic dynamics at a finer spatial resolution, would enrich our understanding of the complex, interwoven social and environmental factors that underpin the mitigation–adaptation co-benefits identified in this study. Although we do not directly quantify shifts in daily peak loads, our day-level analysis indicates that rising cooling demand could significantly amplify peak periods. Coupling our projections with energy system models, particularly capacity expansion models, would allow to quantify the infrastructural implications of our key results, particularly on the benefits in terms of avoided emissions from lower power grid consumption and reduced pressures on future generation capacity and grid investments.

Finally, our analysis does not explicitly incorporate battery storage. Integrating such systems with rooftop PV could significantly enhance the mitigation benefits described here (Di Bella and Colelli 2024). By storing surplus daytime solar generation for use during evening hours—when cooling requirements may remain high despite waning solar output—battery storage can further flatten peak demand and reduce households' reliance on the electricity grid. This potential synergy between PV and storage highlights the dynamic interplay between mitigation and adaptation strategies, suggesting that our current estimates of PV's benefits may underestimate the full potential achievable through integrated PV–storage systems. At the same time, the deployment of batteries is not without important caveats. Existing evidence shows that adding battery storage to residential PV systems can increase life-cycle energy use and greenhouse gas emissions relative to PV-only systems, with outcomes that depend critically on battery chemistry, system sizing, lifetime assumptions, and recycling options (Hoppmann *et al* 2014, Schmidt *et al* 2019). From an economic perspective, the profitability of residential PV–battery systems remains highly sensitive to battery costs, degradation rates, electricity tariffs, and policy incentives, implying that storage may not yet be welfare-improving in all contexts (Hoppmann *et al* 2014, Parra *et al* 2016). Technical constraints related to efficiency losses and finite cycle life further complicate large-scale deployment, particularly when batteries are used primarily for peak shaving rather than system-wide flexibility (Schmidt *et al* 2019). For these reasons, we do not frame battery storage as an unqualified complement to PV adoption, but rather as a promising avenue for future research. Rigorous assessments integrating consumption behavior, climate-driven cooling demand, and the full environmental and economic trade-offs of storage technologies are needed to determine under which conditions PV–battery systems can effectively enhance both mitigation and adaptation outcomes.

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## Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

Supplementary Material 1 available at https://doi.org/10.1088/2753-3751/ae6dc0/data1.

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## References

Abramowitz G, Herger N, Gutmann E, Hammerling D, Knutti R, Leduc M, Lorenz R, Pincus R and Schmidt G A 2019 Model dependence in multi-model climate ensembles: weighting, sub-selection and out-of-sample testing *Earth Syst. Dyn.* **10** 91–105

Auffhammer M and Mansur E T 2014 Measuring climatic impacts on energy consumption: a review of the empirical literature *Energy Econ.* **46** 522–30

Beppler R C, Matisoff D C and Oliver M E 2023 Electricity consumption changes following solar adoption: testing for a solar rebound *Econ. Inq.* **61** 58–81

Boccard N and Gautier A 2021 Solar rebound: the unintended consequences of subsidies *Energy Econ.* **100** 105334

Colelli F P, Emmerling J, Marangoni G, Mistry M N and De Cian E 2022 Increased energy use for adaptation significantly impacts mitigation pathways *Nat. Commun.* **13** 4964

Colelli F P, Wing I S and De Cian E 2023 Air-conditioning adoption and electricity demand highlight climate change mitigation–adaptation tradeoffs *Sci. Rep.* **13** 4413

Cramer W *et al* 2018 Climate change and interconnected risks to sustainable development in the Mediterranean *Nat. Clim. Change* **8** 972–80

Creutzig F, Agoston P, Goldschmidt J C, Luderer G, Nemet G and Pietzcker R C 2017 The underestimated potential of solar energy to mitigate climate change *Nat. Energy* **2** 1–9

De Cian E, Falchetta G, Pavanello F, Wing I S and Romitti Y 2023 The impact of air-conditioning on residential electricity demand across world countries *SSRN* (2023) (https://doi.org/10.2139/ssrn.4604871)

Deng G and Newton P 2017 Assessing the impact of solar PV on domestic electricity consumption: exploring the prospect of rebound effects *Energy Policy* **110** 313–24

Di Bella A and Colelli F P 2024 Mitigation strategies can alleviate the power system's vulnerability to climate change and extreme weather: a case study on the Italian power grid *Environ. Res.* **5** 015003

Elbakheit A R, Waheeb S and Mahmoud A 2022 A ducted photovoltaic façade unit with forced convection cooling *Sustainability* **14** 12875

Flores F, Feijoo F, DeStephano P, Herc L, Pfeifer A and Duić N 2024 Assessment of the impacts of renewable energy variability in long-term decarbonization strategies *Appl. Energy* **368** 123464

Gupta A, Davis M and Kumar A 2021 An integrated assessment framework for the decarbonization of the electricity generation sector *Appl. Energy* **288** 116634

Hersbach H *et al* 2020 The ERA5 global reanalysis. *Q. J. R. Meteorol. Soc.* **146** 1999–2049

Hoppmann J, Volland J, Schmidt T S and Hoffmann V H 2014 The economic viability of battery storage for residential solar photovoltaic systems *Renew. Sustain. Energy Rev.* **39** 1101–18

ISTAT 2023 *Statistical Yearbook* (Istituto Nazionale di Statistica - Istat)

Khalilpour K R and Vassallo A 2016 Technoeconomic parametric analysis of PV-battery systems *Renew. Energy* **97** 757–68

Linssen J, Stenzel P and Fleer J 2017 Techno-economic analysis of photovoltaic battery systems and the influence of different consumer load profiles *Appl. Energy* **185** 2019–25

Meinshausen M *et al* 2020 The shared socio-economic pathway (SSP) greenhouse gas concentrations and their extensions to 2500 *Geosci. Model Dev.* **13** 3571–605

Nyholm E, Odenberger M and Johnsson F 2017 An economic assessment of distributed solar PV generation in Sweden from a consumer perspective–the impact of demand response *Renew. Energy* **108** 169–78

O'Neill B C *et al* 2016 The scenario model intercomparison project (ScenarioMIP) for CMIP6 *Geosci. Model Dev.* **9** 3461–82

Parra D, Norman S A, Walker G S and Gillott M 2016 Optimum community energy storage system for demand load shifting *Appl. Energy* **174** 130–43

Piazza L, Colelli F P, Pasut W and De Cian E 2025 How do domestic solar PV users respond to price and temperature shocks? evidence from Italy between 2021–2022 *Energy Econ.* **151** 108813

Qiu Y, Kahn M E and Xing B 2019 Quantifying the rebound effects of residential solar panel adoption *J. Environ. Econ. Manage* **96** 310–41

Randazzo T, De Cian E and Mistry M N 2020 Air conditioning and electricity expenditure: the role of climate in temperate countries *Econ. Model.* **90** 273–87

Schmidt O, Melchior S, Hawkes A and Staffell I 2019 The future cost of electrical energy storage based on experience rates *Nat. Energy* **4** 644–53

TERNA 2024 Documento di descrizione degli scenari 2024 (available at: www.terna.it/it/sistema-elettrico/programmazione-territoriale-efficiente/piano-sviluppo-rete/scenari)

Victoria M *et al* 2021 Solar photovoltaics is ready to power a sustainable future *Joule* **5** 1041–56

Wenz L, Levermann A and Auffhammer M 2017 North–south polarization of European electricity consumption under future warming *Proc. Natl Acad. Sci.* **114** E7910–E7918

Yalew S *et al* 2020 Impacts of climate change on energy systems in global and regional scenarios *Nat. Energy* **5** 794–802