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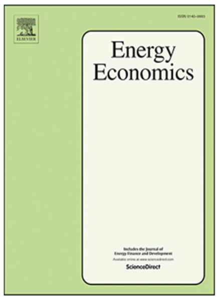

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Street green space and electricity demand: evidence from metered consumption data

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ABSTRACT

Growing climate change impacts call for increased efforts to adapt and to reduce its adverse consequences on society. Adaptation responses can themselves be a source of climate risk, generating negative environmental externalities while entailing budgetary costs for both governments and private citizens. A key example is the private use of air-conditioning for indoor air temperature regulation in the face of rising urban heat. In this paper, we empirically evaluate the impact of street green spaces (SGS) on residential electricity demand through their urban temperature regulation effect. We exploit a monthly panel of household metered electricity demand data from 129,524 households located in 2,181 municipalities distributed across Italy, in the period between 2020 and 2022. We find evidence of a significant non-linear mediating role of SGS on the impact of temperature on household electricity demand. The most salient effect is a reduction in electricity consumption when hot temperatures occur - lowering monthly average electricity consumption by up to 11-25% (for monthly maximum temperatures of 30 and 35° C, respectively). The observed moderating effects of SGS are heterogeneous across municipalities, as they depend on contextual factors such as the degree of urbanization, baseline heat and SGS levels, and average income level. To dissipate across-municipality sorting concerns, we conduct propensity score weighting on a range of potentially confounding observables, and find our results remain consistent. We estimate that a policy increasing the average Green View Index (GVI) level across all municipalities to a value comparable to the median of the current distribution would reduce the growth in residential electricity consumption driven by climate change by more than two thirds (under Representative Concentration Pathway 8.5 climate conditions around 2050). This corresponds to a gross national-level private saving in energy bills of €150 million yearly in 2050. This is a noticeable benefit that represents about 7.3% of our estimated costs to implement such policy, and informs on a potentially substantial social and economic benefit of urban green spaces. Our results provide new quantitative evidence of the role of street green spaces for both energy demand reduction, and therefore climate change mitigation, and in terms of outdoor temperature reduction, supporting climate change adaptation.

Keywords

Street green space; energy demand; public-private adaptation; urban heat islands; nature-based solutions; climate change impacts

JEL classifications:

D12, O13, Q41, Q5

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1 Introduction

Growing climate change impacts call for increased effort on adaptation plans capable of achieving multiple benefits (IPCC, 2023). Adaptation responses can themselves be a source of climate risk, generating negative environmental externalities while entailing budgetary costs for both governments and private citizens. A key example is urban heat adaptation, and specifically air conditioning (AC), including mechanical ventilation systems based on heat-pumps. These technologies are considered effective forms of private adaptation, capable of regulating indoor temperature and reducing the impact of heat on mortality (Barreca et al., 2016; Sera et al., 2020) and other health-related outcomes (Park et al., 2020). However, AC significantly increases households' expenditure (De Cian et al., 2025; Randazzo, De Cian and Mistry, 2020). It is also considered a form of maladaptation (Magnan et al., 2016; Viguié et al., 2020) due to its high energy intensity (De Cian et al., 2025; Falchetta et al., 2024), its adverse impacts on local urban outdoor temperatures (Jin et al., 2020; Salamanca et al., 2014), and its contribution to global greenhouse gas emissions (Byers et al., 2024). Finally, access to private means of heat adaptation is unequally distributed across citizens due to economic barriers and inequalities in adaptive capacity (Kianmehr A and Li, 2023; Romitti et al., 2022).

Urban green infrastructures represent another set of potentially effective adaptation strategies to tackle extreme heat (Li et al., 2024). Among those, street green spaces (SGS) are vegetation-covered areas located along roads within urban boundaries and in the proximity of buildings (Russo and Cirella, 2018). SGS provide a broad range of ecosystem services in terms of human health (Iungman et al., 2023; Jabbar, Yusoff and Shafie, 2021; Liu et al., 2024; Tan, 2022; van den Berg et al., 2015*a*) and well-being (Kwon et al., 2021; Olszewska-Guizzo et al., 2022). They contribute to flood control (Kim, Lee and Sung, 2016; Staccione et al., 2024), carbon sequestration (Fryd, Pauleit and Bühler, 2012; Sun, Xie and Zhao, 2019), and urban biodiversity (Belaire et al., 2022; Uchida et al., 2021; Wooster et al., 2022). SGS are mostly public in nature and they provide a stream of benefits to the general population that are non-excludable and non-rivalrous (Tompkins and Eakin, 2012). On the other hand, nature-based adaptation is not without risks and trade-offs, as it also implies monetary costs, such as the need for recurrent maintenance (Tate et al., 2024), and it might entail unintended risks, such as the increase in local disease-spreading vectors (Mercat et al., 2025).

This paper evaluates the effectiveness of the availability of SGS as a public adaptation option for regulating outdoor and indoor local temperatures and hence indirectly reducing the need for using energy-consuming cooling appliances in households. It primarily contributes to advancing the understanding of the relationship between SGS, the local microclimate within cities, and the consequent role of SGS for energy consumption in buildings. While both topics have been investigated in the literature, existing studies rely on bottom-up, engineering-based approaches applied to specific cities or neighborhoods. Large-scale, empirically grounded assessments of the role of SGS in shaping electricity demand remain missing, in part due to the lack of high-resolution, large-area electricity consumption data and to limitations in the availability of harmonized, spatio-temporal SGS datasets. A recent exception is Han et al. (2024), who exploit an exogenous shock to urban green space in Toronto to identify its causal effect on electricity consumption.

Here we provide an empirical contribution linking SGS and the energy use dimension, with a specific focus on the role of hot temperatures at a national scale. We quantify the benefits of SGS by appraising its temperature regulation effect - measured through the street-based Green View Index (GVI) - and its relevance for household electricity demand. To achieve this goal, we build a monthly panel of household metered electricity demand data from $n = 129,524$ households located in 2,181 municipalities distributed across Italy over the 2020-2022 period augmented with monthly weather characteristics and GVI data and use a household-level fixed effects regression model to estimate how households' electricity-temperature response function is mediated by the extent of SGS. To explore the underlying temperature regulation mechanism through which SGS can affect temperature-related energy

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use in buildings, we develop an auxiliary regression model linking SGS and local temperature at the spatial resolution of 100 meters within a subset of large municipalities where urban microclimate data are available. We then use the estimated relations to assess the private benefits of a public policy targeted at increasing SGS. We characterize SGS provision as a public good generating positive externalities for households, which we quantify in terms of private electricity expenditure and welfare. As a guide for the empirical analysis, we develop a simple theoretical model in which a social planner chooses the socially optimal amount of green spaces and private households adapt to weather conditions through an intensive adjustment in the use of electricity. When maximizing their utility, private households' choices are influenced by the experienced temperature and therefore by the extent of surrounding green spaces.

Our paper contributes to advancing the understanding of the relationship between SGS and local microclimates within cities. Street trees are a key solution for mitigating urban heat islands, primarily by providing shade and enhancing evapotranspiration (Aram et al., 2019; Du et al., 2017; Massaro et al., 2023; Meili et al., 2021, 2025; Turner, Middel and Vanos, 2023; Wong et al., 2021; Yin et al., 2023; Zhang et al., 2014). The concept of *cooling efficiency* is widely used to describe the slope of the relationship between urban green space and air temperature (Li et al., 2024). A growing body of empirical contributions has quantified this parameter using different metrics and modeling approaches (Chan et al., 2024; Yang et al., 2022; Zhan et al., 2024), showing that cooling efficiency varies substantially across geographical, infrastructural, and climatic contexts and is better represented as a non-linear function rather than a constant (Liu et al., 2022; Ouyang et al., 2020). For example, based on a large sample of European cities, Marando et al. (2022) estimate that a minimum tree-cover fraction of approximately 16% is required to achieve a 1°C reduction in urban temperatures. Complementing this, Zawadzka, Harris and Corstanje (2021) demonstrate the importance of using high spatial resolution data, as well as accounting for additional landscape features such as water bodies, to accurately detect the cooling effect of urban green space. The magnitude of the cooling benefit from SGS has also been shown to decline with distance from the tree canopy, underscoring the importance of trees' proximity to buildings for maximizing temperature-reduction benefits (Park et al., 2021). Overall, a comprehensive review by Wong et al. (2021) concludes that urban green infrastructure is an effective strategy for mitigating urban heat, but that its cooling potential is highly context-dependent, varying with the spatial scale of analysis, the extent of greenery, and plant selection and placement. We find that areas of cities with higher GVI warm less in relation to the average warming experienced throughout the city. Moreover, we find evidence of non-linearity in the effect of GVI on local temperature.

Our second contribution relates to the understanding of the consequent role of SGS for energy consumption in buildings. Existing work on the benefits of SGS is dominated by context-specific case studies, both in the Mediterranean region (Aboelata, 2021; Karachaliou, Santamouris and Pangalou, 2016; Napoli et al., 2022; Olivieri et al., 2013; Vurro et al., 2024; Zinzi and Agnoli, 2012) and in other climatic settings (Kim, Yi and Lee, 2019; Moss et al., 2019; Quaranta, Dorati and Pistocchi, 2021; Zhang et al., 2014). For instance, in Athens, Olivieri et al. (2013) estimate that installing a green roof can reduce the annual cooling load of the host building by about 19%, while in Cairo, Zinzi and Agnoli (2012) find that green roofs implemented on 12-meter high buildings can lower cooling energy use by 3.2–4% on a typical summer day. In Beijing, Zhang et al. (2014) quantify the cooling effect and associated environmental benefits of SGS and estimate that air-conditioning demand is reduced by roughly 0.3 TWh (terawatt-hour)/yr. A simulation study for Miami (USA) by McPherson, Herrington and Heisler (1988) shows that dense SGS can decrease annual cooling electricity expenditures by $249 (61%) and reduce local peak cooling loads by 31–49%. Methodologically, Zhu et al. (2022) emphasize the importance of relying on air temperature metrics, rather than land surface temperature, when assessing the potential of urban greenery to curb building energy consumption. Synthesizing evidence across case studies, Seyam (2019) concludes that greenery systems generally contribute to building energy savings, but cannot fully substitute air-conditioning systems for maintaining indoor thermal comfort; instead, their performance depends critically on appropriate management conditions, including adequate watering, to fully realize trees' cooling capacity (Gao, Feng and Santamouris, 2024). This evidence suggests that SGS should be viewed as a form of public adaptation that can lower, but not entirely replace, private adaptation efforts such as mechanical cooling, thus giving rise to public–private synergies in adaptation

(Tompkins and Eakin, 2012). We find that SGS levels - as measured by GVI - significantly and non-linearly affect how temperatures influence household electricity demand. SGS limits the increase in electricity consumption as temperatures rise, with the effect being stronger when temperatures reach the hottest levels ($\geq 30°$ C of monthly average of daily maximum temperatures). The identified moderating effects of SGS are heterogeneous across municipalities, as they depend on contextual factors such as the degree of urbanization, baseline heat and SGS levels, and average income level. A policy aimed at bringing the municipality-level average GVI to at least 21 - a value at around the median of the current distribution across the municipalities covered by our analysis - would reduce by more than two thirds the temperature-induced residential electricity consumption growth driven by climate change.

Since green spaces also require maintenance, our third contribution is to provide a back-of-the-envelope calculation of the public budgetary implications of nature-based solutions such as SGS in relation to the private savings they can generate. A systematic review of the literature on the costs of nature-based solutions, including green spaces (Panduro et al., 2021), found that the establishment cost of green spaces has a mean value of of €60/m2, but with a wide range between €323/m2 and €1.7/m2, though costs in general are not well-documented. Maintenance costs have a mean value of €1.8/m2, but again are characterized by a big spread, between €12.5/m2 and €0.05/m2. Costs vary across space, over time, and with the extent of future warming. For six cities in Austria, annual average costs for new investments in green spaces as well as their maintenance and operation until 2030 have been quantified to lie in the range between €108 and €166 million (Loibl et al., 2015). EU-wide assessments based on geospatial implementation of the meta-models (Quaranta, Dorati and Pistocchi, 2021) have quantified the costs of green roofs and their benefits, in terms of reduced energy demand and CO2 emissions. Specifically, the cost of turning 26,450 squared kilometers of impervious urban areas in Europe into green surfaces is estimated at €60/year per urban resident with a total Net Present Value (NPV) of costs over €1,323 billion. In our paper, we use open public budget data on the yearly costs of maintenance of public green spaces and enhancement of the natural environment for Italian municipalities to estimate investments required to support policies that expand green areas. We then relate these cost estimates to the estimated private benefits in terms of reduced electricity expenditure. National-level private savings in terms of energy bills represent about 7.3% of the costs to implement and maintain the policy. The already significant private benefits of SGS underline the important role of urban green spaces as a form of public adaptation that can reduce the risk of private maladaptation from unregulated active cooling energy use.

The remainder of the paper is organized as follows: Section 2 introduces a theoretical framework for describing the role of SGS for residential energy use from the perspectives of both the social planner and the private household; Sections 3 and 4 illustrate the sources of data and econometric approach used for empirically evaluating the relations described in theoretical framework; Section 5 presents the results of the empirical analysis; Section 6 discusses heterogeneity and robustness checks, while Section 7 derives a set of policy and climate change impacts simulations and their economic implications. To conclude, Section 8 discusses the relevance of the empirical and simulation results and lays out implications for policy and future research.

2 Theoretical framework

To guide our empirical analysis, we develop a simple model in which a social planner decides on the intensity of provision of SGS, G, as a public good while private households maximize their individual utility subject to a standard budget constraint taking the provision of the public good G as exogenous.

The social planner. For each year t, let $G_{a,t}$ be the density of SGS in each administrative area, a. The provision of the public good G is a function of the social planner's decision to implement policies (POL) and invest (INV) in the expansion and maintenance of SGS, for instance through the plantation of trees along roads or through the conversion of land use to create new urban parks. At the same time, G is exogenously affected by inter-yearly variations in temperature, rainfall, and other weather events (c), such as the frequency and intensity of outdoor chronic and acute heat:

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$$G_{a,t} = f(POL_{a,t}, INV_{a,t}, c_{a,t}) \tag{1}$$

The public good G hence generates a stream of positive externality value accruing to an array of private individuals. Each household i in a given administrative area a adjusts the use of electricity, q_E. We assume that the intensity of such energy use is a function of income y, relative prices (p_e, p_x, see private household model below), the meteorological climatic conditions experienced by each household, c; a set of household-specific factors B affecting the behavioral reaction to H in relation to c; and Z, which captures characteristics (different from G) that determine the vulnerability to heat, such as the average characteristics of the building stock and the local demographic structure:

$$q_{E,i\in a,t} = f(p_{E,a,t}, p_{x,a,t}, y_{i\in a,t}; G_{a,t}, c_{a,t}, B_{i\in a,t}, Z_{a,t}) \tag{2}$$

The objective of the public decision-maker taking decisions related to G is to maximize discounted social welfare such that the costs function of expanding and maintaining G ($COST^G$) is balanced against its total public and private benefits. We assume these benefits mainly consist of two components. First, the net reduction in private electricity use $\Delta q_{E,i\in a,t}$ (private positive externality value). Second, the additional set of benefits due to ecosystem services provision ($\Delta q_{ECO,i\in a,t}$):

$$BENEFIT^G = f(\sum_i \Delta q_{E,i\in a,t}, \sum_i \Delta q_{ECO,i\in a,t}) \tag{3}$$

In each municipality, assuming a planning horizon of 20 years, the social planner solves the following intertemporal maximization problem:

$$\max W = \sum_{t=0}^{20} \beta^t NB^G_{a,t} = \sum_{t=0}^{20} \beta^t BENEFIT^G_{a,t} - \beta^t \sum_{t=0}^{20} COST^G_{a,t} \tag{4}$$

subject to the intertemporal budget constraint:

$$\sum_{t=1}^{20} \frac{COST^G_{a,t}}{(1+r)^{t-1}} \leq \sum_{t=1}^{20} \frac{PB_{a,t}}{(1+r)^{t-1}} \tag{5}$$

where:

NB^G_t : net benefits from G in period t

$PB_{a,t}$: public budget available at each time period t

β : Discount factor

r : Discount rate

The first-order conditions identify the optimal level of G, inclusive of private externality benefit:

$$\frac{\partial \mathscr{L}}{\partial NB^G} : \beta^{t-1} W'(NB^G) - \frac{\lambda}{(1+r)^{t-1}} = 0, \quad \text{for } t = 1, 2, \ldots, T, \tag{6}$$

$$\frac{\partial \mathscr{L}}{\partial \lambda} : \sum_{t=1}^{T} \frac{NB^G}{(1+r)^{t-1}} - \sum_{t=1}^{T} \frac{PB_{a,t}}{(1+r)^{t-1}} = 0 \tag{7}$$

The availability of the public good green spaces, G, influences the conditional electricity demand of an optimizing household in a given municipality a and in a given year t (for clarity we here omit the individual, regional, and time subscripts).

The private household. Each household i (we now omit the subscripts for notational clarity) derives utility, u, from the consumption of a generic good, x — which we treat as the numeraire, with $p_x = 1$ —, and electricity, q_E:

$$u = u(q_E, x) \tag{8}$$

where $u_{q_E} > 0$ and $u_x > 0$.

Electricity consumption is a function of the locally experienced meteorological conditions, c, which in turn are influenced by the availability of green spaces, G:

$$q_E = q_E(c(G), G)$$

where $q_{E_c} = \frac{\partial q_E}{\partial c}$ can be either positive or negative depending on the level of c relative to a set-point of thermal comfort, $\bar{c}$. We assume that G has also a direct impact on q_E, e.g. through its influence on lifestyle and behavioral choices, for instance the tendency to spend more time outdoors if a household lives in a more green-dense neighborhood. The effect on green spaces on electricity occurs through two mechanisms:

$$q_{E_G} = \frac{\partial q_E}{\partial G} = \underbrace{\frac{\partial q_E}{\partial G}}_{\text{Direct effect}} + \underbrace{\frac{\partial q_E}{\partial c} \cdot \frac{\partial c}{\partial G}}_{\text{Indirect effect}}$$

We apply a comparative static analysis to the constrained optimization problem of the household and use the implicit function theorem to derive the impact of the exogenous variable G on the household optimal demand of electricity, $q_E^*(p_E, y; G, c, B, Z)$. We differentiate the three FOCs for q_E, x, and λ (see Appendix) with respect to G, and apply Cramer's rule to obtain the effect of G on the optimal demand $\frac{\partial q_E^*}{\partial G}$. Since from the second-order sufficient conditions for constrained maximization, the sign of the Jacobian matrix is positive, since we assume that green spaces reduce temperature, $\frac{\partial c}{\partial G} < 0$ and we have that $p_x^2 u_{q_E q_E} < 0$ and $u_{x q_E} \geq 0$, then the sign of $\frac{\partial q_E^*}{\partial G}$ is determined by the sign of $\frac{\partial q_E^*}{\partial c}$:

If $\frac{\partial q_E^*}{\partial c} < 0$, then $\frac{\partial q_E}{\partial G} > 0$

If $\frac{\partial q_E^*}{\partial c} > 0$, then $\frac{\partial q_E^*}{\partial G} < 0$

Figure 1 represents the comparative static effect of G on electricity demand for different levels of c. The green line depicts electricity demand following an increase in green spaces, and the area between the black and green curves represents the energy savings from SGS's temperature regulation effect. Our empirical analysis aims at empirically estimating the sign and the magnitude of $\frac{\partial q_E^*}{\partial G}$. Our auxiliary regression shows empirically that $\frac{\partial c}{\partial G}$ is negative (see Results section).

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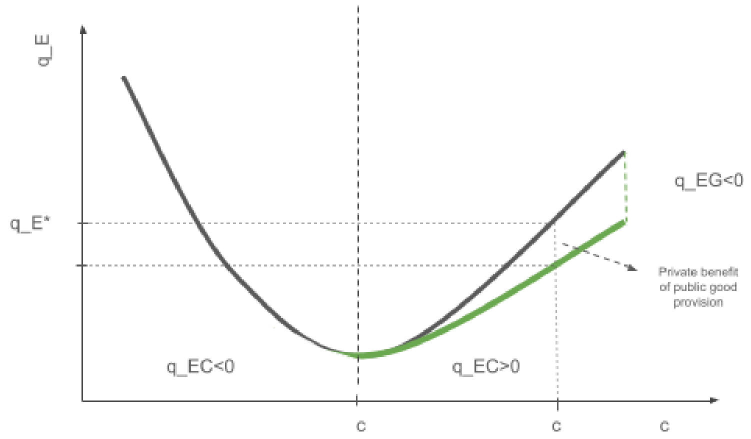

Figure 1. Schematic framework of the assumed SGS effect on electricity consumption. The area between the black and the green lines represents the household energy saving induced by SGS's temperature regulation effect.

3 Data

To empirically evaluate our theoretical framework, we assemble two datasets. First, we combine data on monthly metered household electricity use, with municipality-level climate and SGS indicators. This dataset is used in our main analysis relating green spaces and temperature to electricity demand. This is the core dataset, covering n = 129,524 households located in 2,181 municipalities distributed across Italy over the period between 2020 and 2022. Second, as an ancillary dataset, we combine high spatial resolution (100 meters) data on temperature and SGS for a subsample of 10 large Italian cities selected on the basis of data availability from the UrbClim urban microclimate model runs from the PROVIDE project (Lamboll, Rogelj and Schleussner, 2022). We use this dataset to perform an auxiliary set of regressions to estimate the underlying direct relation between SGS and local temperature. We exploit the greater spatial granularity and the variation that exists even within a given city to examine the local association between temperature and SGS.

Metered household electricity consumption data. We assemble household electricity consumption data available at Point Of Delivery (POD) for the 2020-2022 period. Our sample comprises residential electricity contracts, implying that a POD identifies a household. The data are provided by a private utility operating throughout Italy. The dataset consists of a monthly panel of POD-level data on electricity consumption and expenditure (average bills, unit prices of electricity, and marginal expenditure per unit of energy) with geographic information available at the municipality spatial resolution. It covers 129,524 PODs distributed across 2,181 municipalities of Italy, as mapped in Figure 2 and Figure A-1, and has a monthly temporal resolution (Figure A-2). The right panel of Figure 2 shows that the majority of households allocate more than 25% of their annual electricity expenditure to the summer period June-August.

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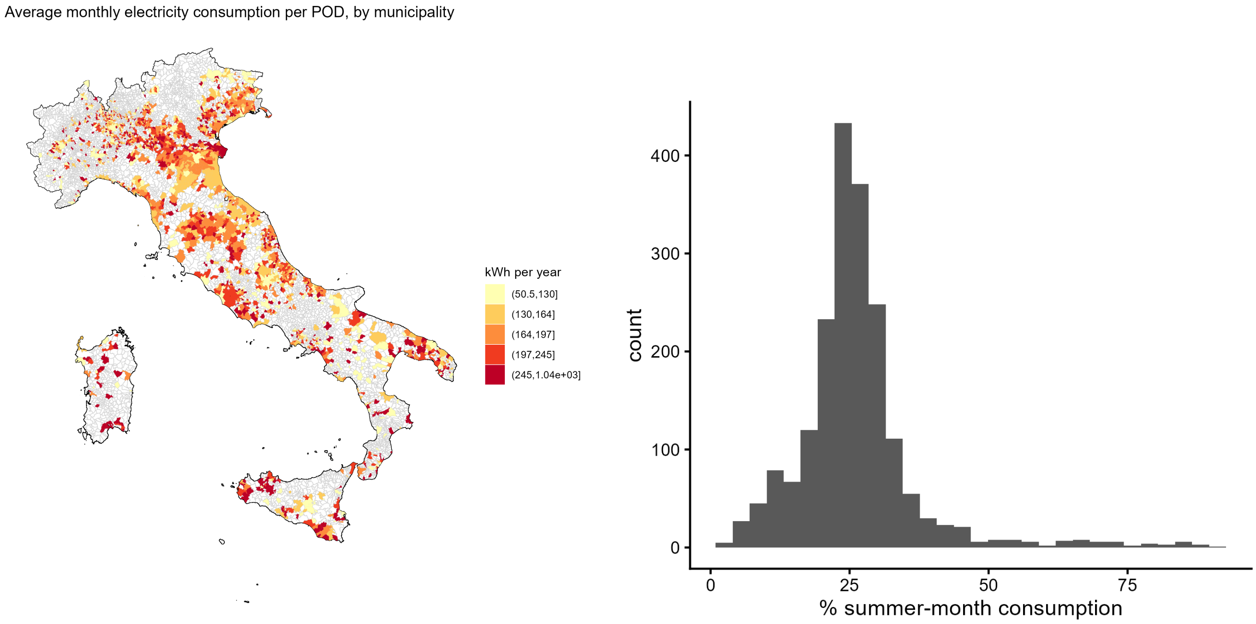

Figure 2. Average monthly electricity consumption per POD across the municipalities covered by the household metered electricity dataset over whole year (left) and share of summer months (June-August) electricity consumption over the total yearly electricity consumption (right).

Municipality-level characteristics. Since the metered electricity consumption data do not include household characteristics, we augment this dataset with some socio-economic attributes at the municipality level to conduct heterogeneity analysis and propensity score weighting (see Section 6). We calculate a time-invariant measure of total resident population in the municipality, *pop*, based on the GHS-POP gridded population 2019 revision from the EC-JRC (Florczyk et al., 2019); based on total population and the land area of the municipality, we obtain the average population density, *popdens*. Henceforth, we categorize municipalities into urban (population density 500), semi-urban (density between 250 and 500), and sparse (density <250). We retrieve the average annual income at the municipality level, *avgincome*, based on the ISTAT yearly, municipality level average taxable income (ISTAT, 2024) for the 2020-2022 period. We also construct a set of indicators of the shares of the building stock in each municipality that were built in a set of year groups based on the GHS-AGE R2025A data product from the European Commission JRC (2025). Finally, we augment each observation with the latitude and elevation of the municipality's centroid coordinates pair, obtained from Amazon Web Services (AWS) Terrain Tiles AWS (2025) .

Meteorological data. The main meteorological variables used to perform the main analysis on metered electricity consumption include the monthly average of daily maximum temperatures, $Tmax$, and - in an additional specification - the Cooling Degree Hours (CDH) per month, CDH. While $Tmax$ captures acute exposure to heat, CDH is calculated as the count of hours in a given month when the hourly average temperature is above a threshold level of 25° C and it captures the chronic or cumulative exposure to heat. These variables are computed from hourly temperature data from ERA-5 Land climate reanalysis data (Copernicus Climate Change Service, 2019) available at the native spatial resolution of about 9km for the period covered by our metered electricity consumption data (2020-2022). The two heat metrics are extracted within the administrative boundaries of each municipality, weighted over space by population density to attribute more weight to temperatures in the proximity of densely populated areas. Figure 3 illustrates a map of the spatial variability of the calculated climate metrics across municipalities for their yearly maximum value across months, while Figure A-3 presents similar maps for the twelve months of the year. As a remark, in the fall and winter months in Italy, temperature drops significantly, which explains a median value of 0 for monthly CDH, as seen from Table 1 below.

In parallel, for conducting the auxiliary regressions to demonstrate the effect of SGS on local heat metrics, we leverage high-granularity climate data derived from the PROVIDE Climate Risk Dashboard (Lejeune et al., 2024), which delivers 100-meter spatial resolution heat metrics (sum of monthly Cooling Degree Hours and monthly average of daily maximum temperatures) for a pool of cities calculated based on the urban-scale climate model UrbClim (De Ridder, Lauwaet and Maiheu, 2015). The simulations of UrbClim explicitly account for the cooling role of vegetation through the use of high-resolution land cover data, shading algorithms, and energy balance modeling. For the case of Italy, data for the following ten cities, which are also part of the GVI and metered electricity consumption datasets and are rather homogeneously distributed across the territory of Italy, are currently available: Turin, Genoa, Milan, Bologna, Padua, Rome, Palermo, Trieste, Naples, and Bari.

The use of spatially granular climate data in the auxiliary analysis is motivated by the lack of within-city variation in the municipality-level weather variables derived from ERA5-Land which are used in the main regression analysis. These coarser variables are insufficient for investigating the assumed SGS–temperature mechanism. Spatially granular climate data from PROVIDE are available only for 2008–2017, and we treat this interval as a historical climatological baseline. For each grid cell within the ten cities, we compute the mean monthly values over this ten-year span to obtain representative seasonal conditions, a standard practice in climate science (Hersbach et al., 2020). Although this period precedes the weather–consumption window examined in the main analysis (2020–2022), the mismatch does not undermine the identification of the underlying physical mechanism—temperature reduction through vegetation cover. While this mechanism can be influenced by long-term factors such as urban development or building characteristics, these features change slowly. In the relatively stable urban settings of Italy, substantial shifts over a single decade are unlikely.

As an additional comparative exercise, we evaluate the consistency between the yearly sum of CDH derived from ERA-5 Land (using the average across years for the period 2020-2022) and the spatially granular UrbClim PROVIDE dataset, providing yearly sum of CDH based on simulation year 2020 (i.e. the representative climate, and not the specific weather year). For the ten cities where the granular PROVIDE data is available, Figure A-8 shows that - while generally consistent - coarser municipality-level data from ERA5 Land tends to systematically underestimate the yearly heat metrics, compared to granular climate model output data at the within-city level. This is likely owing to the coarse spatial resolution of the ERA5 reanalysis data, which does not explicitly resolve for the urban heat island (UHI) effect (Adinolfi et al., 2023).

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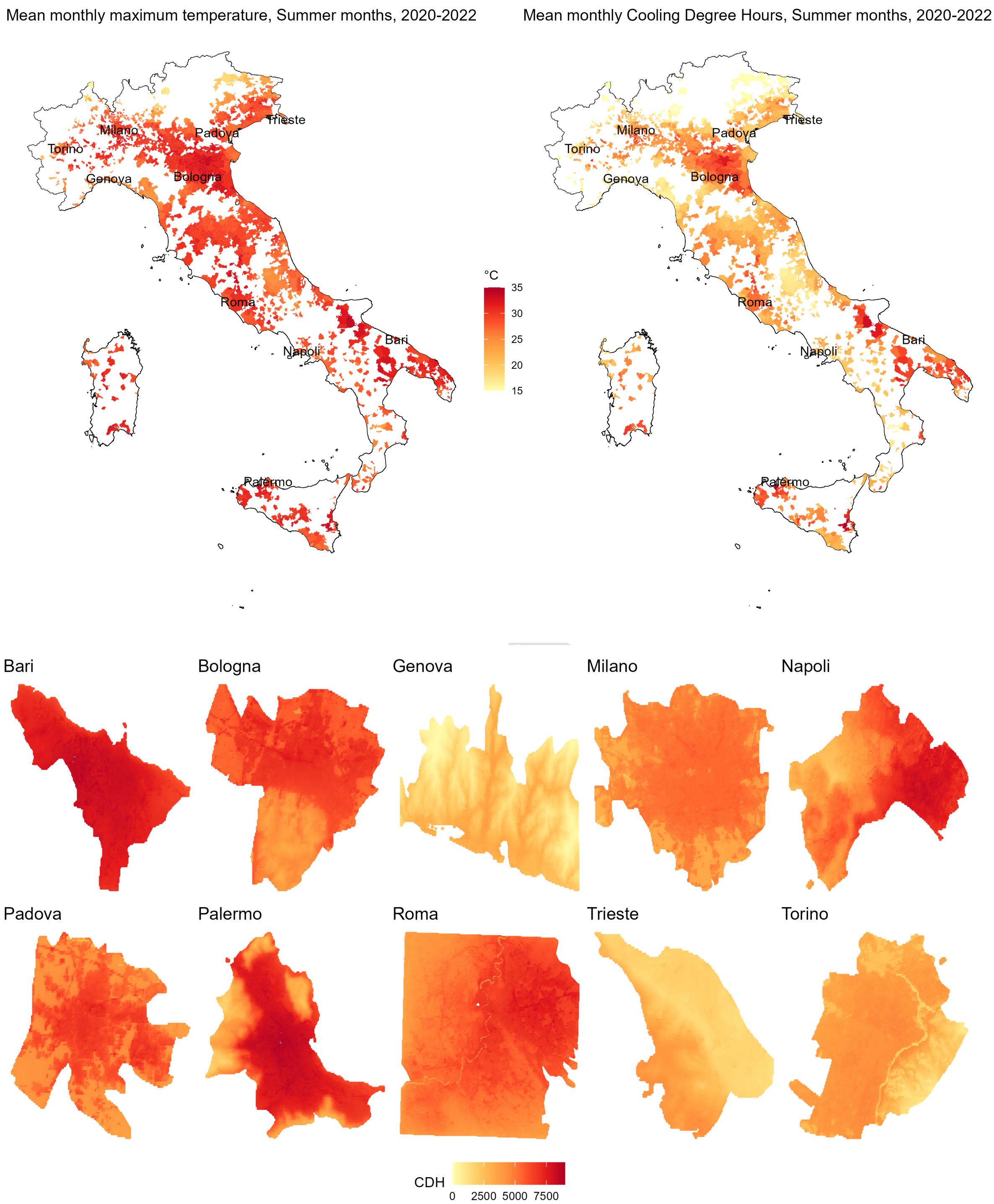

Figure 3. Maps of municipality-level heat metrics - average monthly level across the Summer months (June-August). Top-left: Monthly mean maximum temperature (Data source: ERA-5 Land); Top-right map: Monthly mean Cooling Degree Hours (Data source: ERA-5 Land); Bottom panel: Spatial distribution of Cooling Degree Hours (CDH) heat metric in ten large Italian municipalities (Data source: PROVIDE Climate Risk Dashboard). Note: the location of the ten large Italian municipalities where high-resolution urban microclimate data is available is reported in the upper panel maps.

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Street green space data. We adopt the methodology developed in Falchetta and Hammad (2025) [1] to estimate the GVI in a set of randomly picked sampling coordinates along streets in each year and within each municipality. Based on such samples, we derive the average GVI for each municipality covered in our electricity consumption dataset. To contextualize the interpretation of GVI values, Figure A-9 illustrates representative street-based imagery examples and their associated GVI value. Figure 4A illustrates a map of the average GVI value in each Italian municipality for which electricity data are available (with a yearly analysis of the distribution and time trend, and a regional heterogeneity assessment presented in Figure A-7). Figure 4B illustrates within-city heterogeneity for the ten cities used in the second database to examine the relationship with the more granular meteorological data. Finally, the Supplementary Appendix file contains a table providing a range of municipality-level statistics (including the estimated average GVI value) for all municipalities covered by our analysis.

Sampling-point specific urban covariates. For conducting the auxiliary regressions evaluating the direct effect of green spaces on local temperatures within each of the ten municipalities where granular climate data is available, we also extract a set of sampling point-specific (i.e. in the same randomly sampled point locations were GVI estimates are obtained within each city) covariates. These variables describe additional local urban features and their inclusion in the empirical model aims at controlling for confounding factors and isolating the individual contribution of SGS. Such factors include: local average buildings height and population density from the EC-JRC GHS-BUILT-H 2023 and GHS-POP 2023 data products (Florczyk et al., 2019), having a spatial resolution of 100 meters; the local presence of water bodies, with data obtained from the Copernicus Land Monitoring Service (Copernicus, 2018) with a spatial resolution of 100 meters; and local elevation obtained from the AWS Terrain Tiles (AWS, 2025), with a 30-meter spatial resolution.

[1] Falchetta and Hammad (2025) train a machine learning algorithm to estimate the GVI (a street-based indicator of vegetation density, ranging within a theoretical range of 0 to 100%; see Seiferling et al. (2017) for details) at any coordinate point in urban areas of the world based on high-resolution multispectral satellite data and additional granular data.

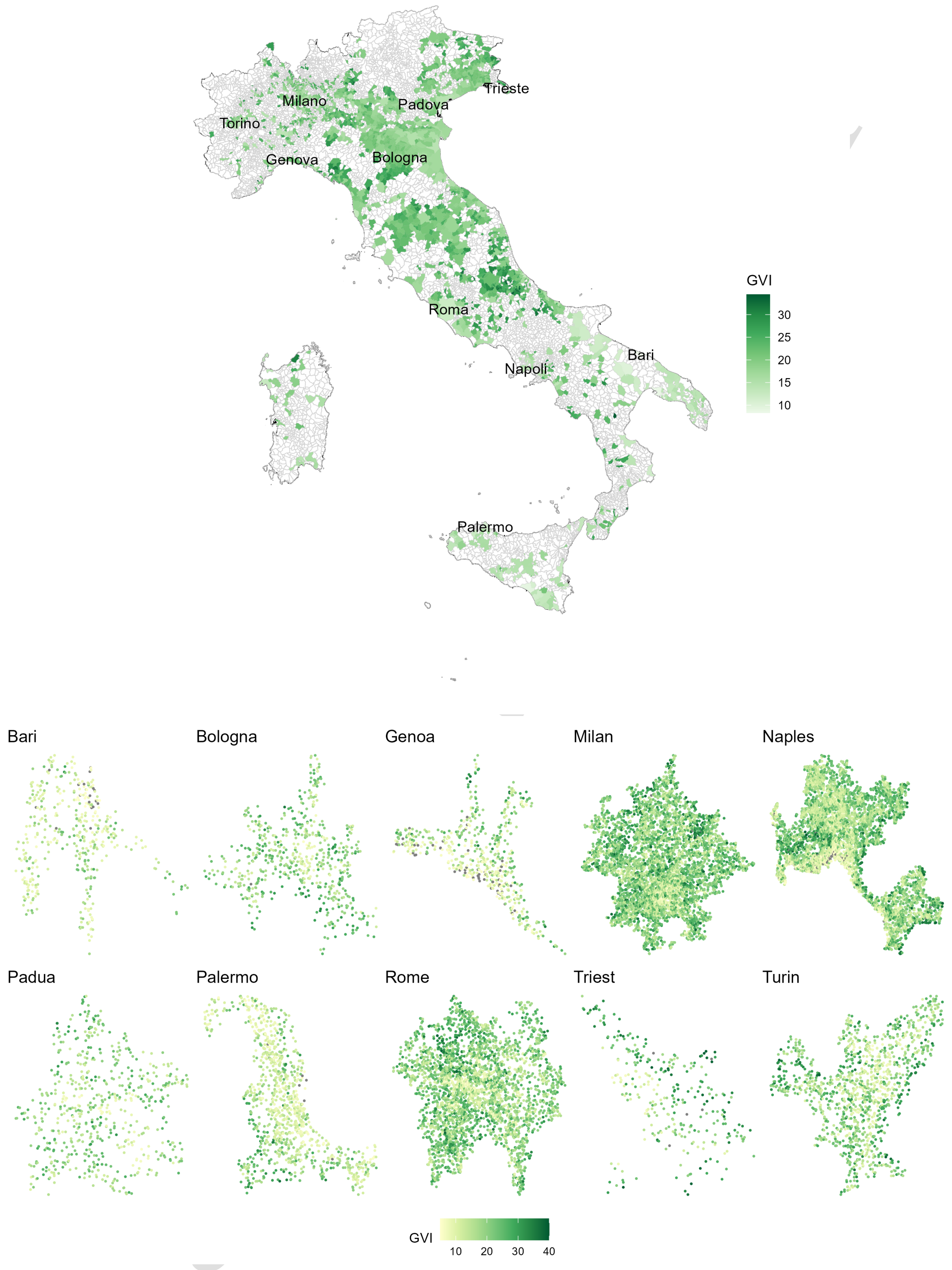

Figure 4. Maps of the spatial distribution of the GVI (average value over 2020-2022 period). Top panel: Map of municipality-level mean GVI in areas covered by the metered electricity consumption dataset; Bottom panel: within-city GVI heterogeneity in ten large Italian municipalities used in the auxiliary regression. Data source: Falchetta and Hammad (2025). Note: the location of the ten large Italian municipalities visualized in the lower panel is reported in the upper panel map.

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3.1 Descriptive statistics

Average monthly maximum temperature across the whole year ranges within an interquartile range of 12.8–27°C, whereas the summer average monthly maximum temperature during June, July, and August ranges between 27 and 31.4°C, with an average value of 29.1°C (see Table 1 and Figure A-4 for a heatmap of the frequency of observations by T_{max} and GVI exposure levels). The average value of GVI across the Italian municipalities considered varies between 8 and 37, with a standard deviation of 3. Figure A-6 presents a histogram of the distribution of GVI in 2022, showing the presence of tails on both sides of the distribution. Significant spatial variation in the GVI level across municipalities and regions is observed, as seen from Figure 4 and summarized with boxplots in Figure A-7, with higher average density in Central Italy and in areas near the Alps. Regarding the temporal variation in GVI, Figure A-5 shows municipality level maps of the absolute and percentage change for the 2020-2022 period covered by our analysis, highlighting a moderate and spatially widespread decrease in GVI over the study period. Average annual electricity consumption ranges within an interquartile range of 101-223 kWh/household/month, whereas summer electricity during June, July, and August, ranges between 97-219 kWh/household/month. At the municipality level, hotspots of municipalities with electricity peaks appear in several regions of both the North and South of Italy, with a pattern that, especially in summer, reflects more the local altitude than the latitude. Note that for regression analysis, we drop observations (POD x month x year) with consumption of less than 50 kWh/POD/month to remove PODs-month combinations in periods of the year when such homes are not regularly inhabited[2]. Finally, electricity expenditure metrics at the POD-level are summarized for each region in Table A-16.

In addition to the dataset used in the main electricity consumption analysis, Table A-1 reports summary statistics for the auxiliary analysis based on within-city sampling points data to assess the impact of SGS on urban temperature, controlling for relevant covariates.

[2]We deem this a reasonable threshold which can be reached by always-on appliances such as refrigerators and appliances in standby mode, considering that according to national statistics the average household consumes around 145 kWh/household/month in Italy (ARERA, 2025). Note that we assess the implications of excluding POD-month observations with consumption below 50 kWh/household/month, on the grounds that such a threshold likely reflects the usage profile of an unoccupied or rarely used dwelling (e.g., a vacation home), given that the combined consumption of a refrigerator/freezer and standby appliances alone can reach this level. Such filtering procedure decreases the sample size by 12.7%, from n = 3,563,158 to n = 3,109,091. Table A-9 compares the results that are obtained when re-estimating the main quadratic specification for (i) the full sample (without filtering) and (ii) the filtered sample (the same used in the main specifications presented in the Results section). These demonstrate that the sign and the statistical significance remain consistent in the full sample and on the filtered sample, while coefficient magnitudes differ despite the only moderate reduction in observations count.

Table 1. Summary statistics of the household metered electricity consumption data and covariates.

	Min	Q1	Median	Mean	Q3	Max	SD
Year	2020	2020	2021	2021.1	2022	2022	0.8
Month	1	4	7	6.6	10	12	3.5
Electricity use (kWh/POD/month)	50	100.6	150	180.6	222.5	14189.6	130
Monthly T_{max}	-10	12.8	18.6	19.6	27	35.2	8.1
Monthly T_{mean}	-12.9	8.6	14	15.1	21.9	29.9	7.5
Monthly T_{min}	-16.4	4.7	9.6	10.9	17.1	26.4	6.9
Monthly Cooling Degree Hours (CDH)	0	0	0	418.3	519.7	3761.4	722.3
Green View Index (GVI)	8	16.9	17.9	18.9	20.6	36.9	3
Tot. population	77.7	12823	33912.4	124968.8	358482.8	2607104.2	149590.1
Pop. density (pop/km^2)	2.3	226.4	344.5	984.8	2611.9	8107.2	1074
Avg. income (€)	10511.3	21914.9	23496.8	23655.6	27238.6	48385.6	3006.1
% no buildings	0.0	0.3	0.6	0.5	0.7	1.0	0.2
% buildings < 1980	0.0	0.2	0.2	0.3	0.5	0.9	0.1
% buildings 1980-1990	0.0	0.0	0.0	0.0	0.1	0.1	0.0
% buildings 1990-2000	0.0	0.0	0.0	0.1	0.1	0.2	0.0
% buildings 2000-2010	0.0	0.0	0.1	0.0	0.1	0.2	0.0
% buildings 2010-2020	0.0	0.0	0.0	0.0	0.0	0.1	0.0
Elevation	-37.0	15.0	61.0	87.8	79.0	2736.0	144.1

Note: Electricity use and climate metrics are measured at a monthly level; GVI is measured at a yearly level; Tot. population, pop. density, avg. income and building age features are time-invariant in the three-year panel.

4 Empirical framework

4.1 Main analysis: street green space and household electricity demand

We rely on the household metered electricity consumption dataset with municipality-level treatment variables to implement the following interactions-based, quadratic temperature specification, which allows us to capture the POD-level and municipality-level fixed effects, as well as additional time-invariant and time-trend components:

$$\begin{aligned} log(q_{E,i,m,t}) = \beta_1 H_{a(i),m,t} + \beta_2 H^2_{a(i),m,t} + \beta_3 SGS_{a(i),t} + \beta_4 H_{a(i),m,t} \cdot SGS_{a(i),t} + \beta_5 H^2_{a(i),m,t} \cdot SGS_{a(i),t} + \\ \zeta_i + \theta_a + \mu_m \times \lambda_a + \rho_t + \varepsilon_{i,a,m,t} \end{aligned} \tag{9}$$

where, for each household i, municipality a, month m, and year t, q_E is the metered electricity consumption, H is the spatial average value at the municipality level of - depending on the specification - the monthly average of daily maximum temperature or the monthly cooling degree hours calculated with a threshold comfort temperature of 25°C; SGS is the average street green space in municipality a at year t as measured by the GVI index. The identification strategy exploits POD (ζ), municipality (θ), year (μ), month (λ) and region by year dummies (ρ, allowing to capture unobserved time-variant variation that is specific to each region in each given year, such as regional policies or localized weather events) fixed-effects to absorb household, seasonal, yearly, as well as location-invariant unobserved factors such as building type and quality, geographical and environmental factors and conditions, appliance stock, behavior, electricity price, as well as COVID and gas price crisis exogenous shocks, and hence isolate our quantity of interest, namely the role of municipality-level SGS on the POD-level temperature-electricity demand relation. The error term, ε, is clustered at the municipality and POD level, and captures the residual unobserved variation in the outcome.

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4.2 Mechanism analysis: street green space and local temperature regulation

Our main specification outlines the role of SGS in moderating the temperature-electricity consumption relation. A key mechanism underlying this phenomenon is likely the cooling effect of SGS, particularly during hot periods, when it can serve as an alternative to other electricity-consuming cooling methods. However, our main specification does not enable us to clarify the underlying mechanism of such interplay, i.e. the direct temperature regulating effect of SGS. To explore this result, we exploit within-municipality spatial variation in SGS coverage and local temperature levels, which we can retrieve for a subset of municipalities (see Data section for details). We estimate the following spatially granular regression model:

$$T_{c,a,t} = \delta_1 T_{a,t} + \delta_2 SGS_c \times T_{a,t} + \zeta_c + \mu_t + \varepsilon_{c,a,t} \tag{10}$$

where, for each sampling cell c, municipality a and month t, T is the average monthly maximum temperature for the climatological period 2008-2017, SGS is the local density of street green space (average value across years), ζ are cell-level fixed effects and μ are monthly fixed effects. The error term, ε, is clustered at the cell and month level, and it captures the residual unobserved variation in the outcome. The coefficient δ_2 captures the cooling effect of SGS coverage.

The regression setup is hence a month-cell panel with 12 observations for each cell and where, for each cell c, meteorological variables capture the local historical average value at each month of the year. Using the average monthly max temperatures reduces the dimensionality of the panel, being virtually equivalent to estimating a two-way fixed-effects regression (TWFE) with data demeaned by month-of-year. The choice is therefore one of implementation rather than identification. The regression specification thus captures the within-city spatial (cross-sectional) and average seasonal variation. The covariates included in the auxiliary regressions (specifically, the GVI and the population density variables, while the elevation and water bodies variables are assumed to be time-invariant) refer to years 2017-2023 and 2020, respectively. Both variables are sufficiently time-stable to confidently rule out that they might have significantly and systematically deviated from the temporally near climatological period (2008-2017).

In the auxiliary specification, SGS coverage is a time-variant variable (GVI data has yearly, but no monthly variation), and hence its main effect is absorbed by cell-level fixed effects. As temperatures recorded at the city level can be considered exogenous in this setting, under the assumption that temperature discrepancies within the city are not a driver to the presence of green spaces in specific cells, the coefficient captures how a common temperature shock is perceived in different areas of a city depending on the presence of SGS, net of unobserved time-invariant spatial heterogeneity and seasonality.

As a robustness test, we augment this specification by including a quadratic term of SGS or, in alternative, a quantile-based categorical bins specification based on the distribution of the continuous SGS variable, to test for the non-linearities in the effect of GVI on temperature. Finally, we also test the robustness of our results to the explicit inclusion of a vector of time-invariant cell-level covariates (including population density, water bodies presence, and elevation), instead of controlling for cell-level fixed effects. The elevation and water bodies variables are assumed to be time-invariant over the period covered by the time-variant variables.

5 Results

5.1 The role of street green space for residential electricity consumption

We estimate Equation 9 to appraise the role of SGS in residential electricity demand through its mediating effect on temperature, as hypothesized in Figure 1. Table 2 illustrates the results of different regression specifications, with the preferred one being the quadratic in temperature specification with POD, municipality, year, month and

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region-by-year fixed effects and municipality and POD-level clustered standard errors, reported in column (5). The key coefficients of interest are the interactions between heat metrics (maximum temperature in our main specification, and cooling degree hours and temperature quantile bins as alternative variables, Table A-7) and GVI levels (i.e. the multiplication of the two treatments of interests). Table A-3 reports specifications which only include temperature to compare the results without the inclusion of the GVI mediator variable.

Table 2. POD-level fixed-effects regression results on household metered electricity consumption

	(1)	(2)	(3)	(4)	(5)
Variables					
T_{max}	0.0091***	0.0096***	0.0126***	0.0125***	-0.0753***
	(0.0020)	(0.0020)	(0.0032)	(0.0032)	(0.0142)
GVI	0.0304***	0.0151***	0.0144***	0.0131***	-0.0146***
	(0.0029)	(0.0016)	(0.0015)	(0.0017)	(0.0051)
$T_{max} \times GVI$	-0.0007***	-0.0008***	-0.0007***	-0.0007***	0.0022***
	(0.0001)	(0.0001)	(9.42×10^{-5})	(9.41×10^{-5})	(0.0006)
T_{max} square					0.0020***
					(0.0003)
T_{max} square $\times$ GVI					$-6.61 \times 10^{-5***}$
					(1.58×10^{-5})
Mean outcome (kWh/POD/month)			180.6		
Total avg. marginal effect of GVI	0.0162	0.0003	0.0004	0.0004	-0.0012
Fixed-effects					
Municipality	Yes	Yes	Yes	Yes	Yes
POD	Yes	Yes	Yes	Yes	Yes
Year		Yes	Yes	Yes	Yes
Month			Yes	Yes	Yes
Region-year dummies				Yes	Yes
Fit statistics					
Observations	3,106,695	3,106,695	3,106,695	3,106,695	3,106,695
R^2	0.75649	0.75686	0.77694	0.77697	0.77813
Within R^2	0.02727	0.01948	0.00368	0.00363	0.00878

Notes: *Dependent variable: logarithm of monthly metered electricity consumption (kWh)*
Clustered (Municipality & POD) standard-errors in parentheses
*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

All regression specifications suggest the existence of a regulating function of SGS on the temperature-electricity demand relation. SGS partly reduces heat-related electricity consumption: the results of the quadratic treatments regression specification (5) show that temperature and electricity demand have a U-shaped quadratic relation, with SGS affecting such quadratic relation - and a stronger effect on the hot temperature side of it (right-hand side of the curve). Interestingly, the GVI main coefficient is negative and statistically significant, highlighting that households living in more SGS-dense municipalities tend to display lower electricity consumption levels due to unobserved factors (such as behavior or housing energy efficiency). In the linear specifications (as we move from column (1) to (4) gradually adding POD, municipality, time, and time-trend fixed-effects to absorb variation from unobservable confounders), the average monthly maximum temperature has a negative effect on electricity demand when the entire year is considered, reflecting the Italian climate, which tends to lead to overall higher electricity consumption in wintertime for heating and lighting.

Figure 5 illustrates this effect by showing, in the top row, the average model predictions of residential electricity demand at different levels of heat exposure, differentiated by GVI level. The lines clearly demonstrate both the U-shaped electricity demand response to temperature, with strong increases during cold temperature periods of the year, a minimum value at moderate temperatures, and a further spike once temperature grow further. Moreover, the differentiated predictions across GVI levels show the cooling role of SGS and its relevance for mitigating the increase of electricity consumption during periods of the year when hot temperatures are experienced. This is particularly visible in the lower panel of the figure. For instance, we estimate that a representative household when the monthly average maximum temperature stands at 30° C would consume 170 kWh/month if the average municipality GVI level is 20 (a value at the 35th percentile of the municipalities GVI levels distribution), while such consumption would be reduced to 163 kWh/month (-4.2%) if GVI stood at 25 (a value at the 80th percentile of the municipalities GVI levels distribution). On the other hand, we find evidence of a much more moderate positive association between electricity consumption and GVI during cold periods of the year, consistently with (Alberini et al., 2019).

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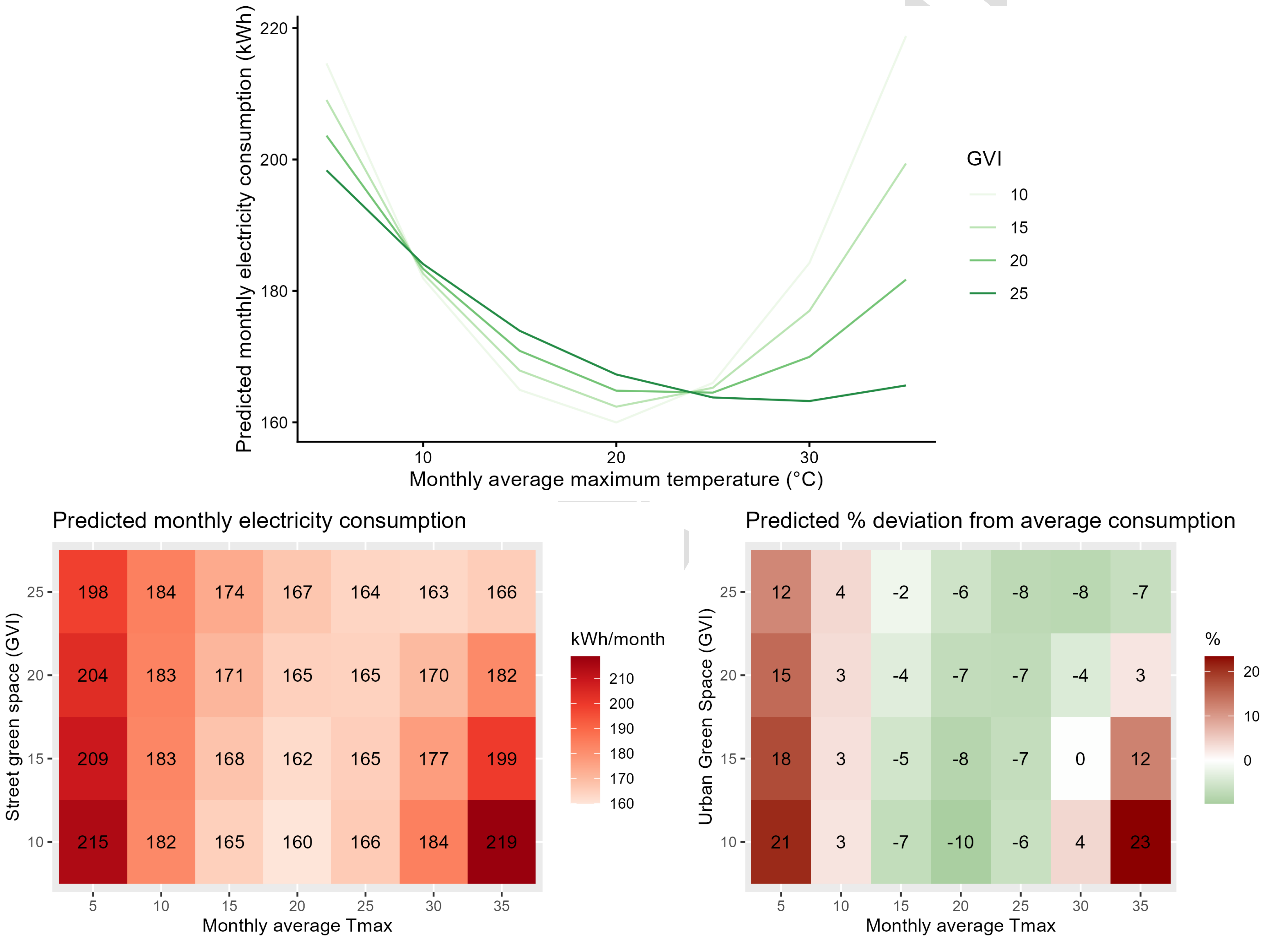

Figure 5. Predicted value and change in monthly electricity demand at different levels of GVI and for different maximum temperatures.

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5.2 Exploring mechanisms: street green space and local temperature levels

In our main specification, we find that SGS has a mediating role in the relationship between electricity consumption and temperatures. As previously discussed, one of the key underlying mechanisms is that SGS can decrease urban temperature and, in turn, affect the usage of temperature mitigating household appliances. We evaluate the impact of SGS on urban heat by estimating Equation 10. Table 3 presents the regression results based on granular SGS and microclimate data for within-city locations in the ten large municipalities in Italy covered by the PROVIDE dataset (as discussed in the Data section). Results show that areas of cities with higher GVI level warm less in relation to the average warming experienced throughout the city. This finding is consistent across the linear (column 1), quadratic (column 2) and quantile piecewise (column 3) specifications, where the β_2 interaction coefficient of local SGS and local T_{max} is found to be negatively associated with the average maximum temperature of the city, net of month and grid cell fixed-effects. Specifically, the linear specification (1) shows that, for every 1-unit of local GVI index, we estimate around a 1% reduction in the local maximum air temperature value with respect to the city-scale average maximum air temperature. Considering the average values of 20.2 of T_{max} and of 20 of GVI across the ten cities assessed in this supplementary analysis, we estimate a total average reduction of 0.2° C in the average maximum temperature (T_{max}) due to SGS cooling role within each municipality. The magnitude of this result is within the range of the literature when referring to the cooling efficiency of urban green space on air temperature (Li et al., 2025) and it reflects the average effect across all months of the year. We also find evidence of non-linearity in the effect of GVI: the estimated coefficients demonstrate that GVI is mildly non-linear, in particular in the right-hand-side of the distribution, where higher GVI values determine a more than linear reduction in the heat metrics, consistently with what noted in the literature (Ouyang et al., 2020). To conclude, column (4) displays the result of an alternative specification where cell-level fixed effects are omitted so as to directly include in the specification the local GVI and additional time-invariant cell-level variables. Consistently with the results of the other columns, the specification of column (4) provides evidence of a local negative association between GVI and T_{max}, net of cell-level covariates. Consistent with our empirical design, the results are unchanged when preserving inter-yearly variation while including month-of-year level fixed effects (Table A-17).

The results of this supplementary analysis further reinforce the theoretical foundation for evaluating the implications of SGS for residential electricity use in relation to the temperature-energy demand relation. As a remark, the mediating role of SGS for decreasing heat-related electricity use in building is likely larger in magnitude the direct air temperature reduction found in the 100-meter resolution microclimate model output data only. These data display only moderate spatial variation within each city, contrarily to surface temperature, which is found to vary by much larger ranges within cities (Cao et al., 2021). SGS levels are also strongly related to factors such as reduced solar radiation through shading (Hsieh et al., 2018; Pandit and Laband, 2010), which has a strong impact on indoor heat stress but is not directly observable in our meteorological data.

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Table 3. Regression results for the granular analysis to assess the role of street green space (net of additional urban feature covariates) for local heat levels, relative to the city-wide level. The regression is based on the ten large municipalities covered by the PROVIDE dataset.

Dependent Variable:	Local monthly maximum temperature ($Tmax_{c,a,t}$)			
Model:	(1)	(2)	(3)	(4)
Variables				
$Tmax_{a,t}$	1.012***	1.040***	1.016***	
	(0.0046)	(0.0068)	(0.0048)	
$GVI \times Tmax_{a,t}$	-0.0005***	-0.0034***		
	(7.12×10^{-5})	(0.0004)		
GVI square $\times Tmax_{a,t}$		7.9×10^{-5}***		
		(9.21×10^{-6})		
Q1 $GVI \times Tmax_{a,t}$			-0.0138***	
			(0.0019)	
Q2 $GVI \times Tmax_{a,t}$			-0.0126***	
			(0.0018)	
Q3 $GVI \times Tmax_{a,t}$			-0.0117***	
			(0.0017)	
Q4 $GVI \times Tmax_{a,t}$			-0.0126***	
			(0.0017)	
GVI				-0.0061***
				(0.0018)
Pop. dens				0.0011***
				(0.0001)
Elevation				0.0006
				(0.0004)
Water bodies				0.0017
				(0.0024)
Fixed-effects				
Grid cell	Yes	Yes	Yes	
Month	Yes	Yes	Yes	Yes
Municipality				Yes
Fit statistics				
Observations	147,396	147,396	147,384	147,396
R^2	0.99692	0.99694	0.99693	0.96996
Within R^2	0.85584	0.85671	0.85646	0.00527

Clustered (id & variable) standard-errors in parentheses
*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

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6 Heterogeneity, robustness, and potential limitations

Heterogeneity analysis. To explore the heterogeneous role of SGS in mediating the temperature-energy demand relation, we evaluate the range of different effects across PODs, municipalities, regions, and conditional to different municipality-level features such as income level and population density. Figure 6 illustrates the range of model-predicted electricity consumption across PODs in the sample conditional on different levels of monthly average maximum temperature and GVI. The plot shows that the range of variation in predicted values becomes significantly larger as temperature grows. GVI reduces energy use, but has the opposite effect at low temperatures, where energy use among PODs living in more SGS-dense municipalities slightly increases.

An analysis of variance model (ANOVA) further highlights that the difference in means across bins of GVI (i.e., the role played by GVI in mediating the temperature–electricity demand relation) is statistically significant across all temperature intervals (Table A-10). The magnitude of the F-statistics notably increases with temperature — from around 246 in the [5,10]°C bin to over 130,000 in the [30,35]°C bin — suggesting that the moderating effect of GVI becomes increasingly pronounced as temperatures rise. This pattern supports the interpretation that SGS plays a stronger role in reducing electricity demand during hotter conditions, consistent with the idea that vegetation mitigates heat-related energy use through local cooling effects.

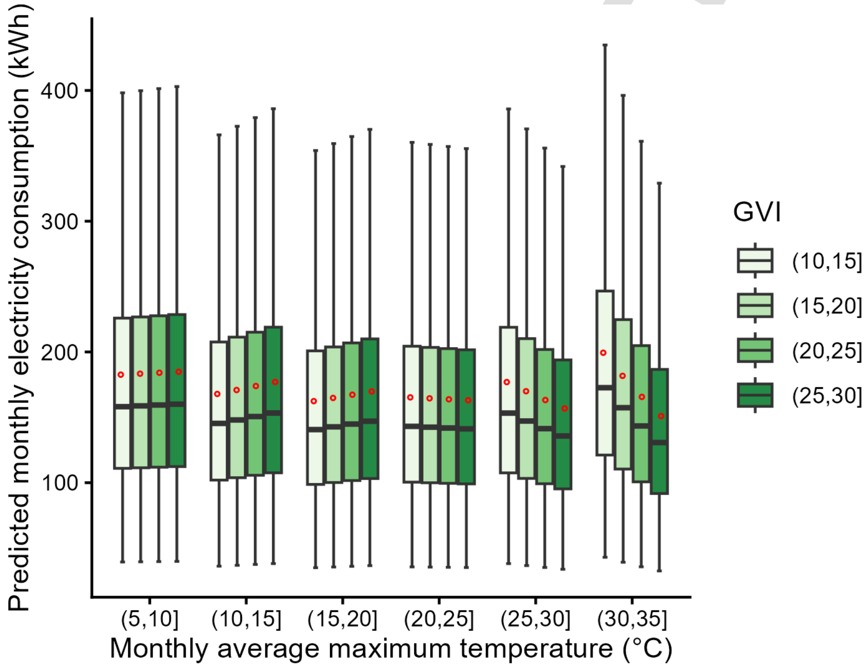

Figure 6. Box-plots of the range of impact of GVI on the effect of maximum temperature on electricity consumption. Red dots identify the mean value across each whisker.

We conduct two additional sets of regressions to evaluate if municipalities that are characterized by higher and lower than median summer heat (municipality-level median 2020-2022 June-August = 27.73°C) and GVI levels (municipality-level median 2020-2022 June-August = 21.327) respond differently to hot temperatures and show differences in the mediating role of SGS identified in our main specification. Specifically, we first estimate if households living in each of these subsets of municipalities respond differently to $Tmax$ over cold and hot months, respectively; then, we test for the mediating role of GVI in the relation between $Tmax$ and electricity consumption.

Tables A-13 and A-14 display the results of these specifications. We find that hotter municipalities have a nearly 60% higher response to temperature during hot months than less hot municipalities (2.7% vs. 1.7% growth per °C),

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likely reflecting the wider availability of cooling appliances in buildings; on the other hand, colder municipalities are more responsive to high temperatures in decreasing consumption during cold months of the year. Looking at the mediating role of GVI, we find that GVI mediates 60% more the maximum temperature-driven in electricity consumption in hotter than in colder municipalities.

Moving to the municipality SGS level heterogeneity analysis, we find that households in less SGS-dense municipalities react twice as much (1.9% vs. 0.6% per GVI point) to hot temperatures during hot months of the year compared to those living in more SGS-dense municipalities, while they react half to hot temperatures during cold months of the year. With regards to the mediating role of GVI, we find that GVI mediates 80% more the maximum temperature-driven in electricity consumption in less SGS-dense than in more SGS dense municipalities. This finding can be interpreted as evidence of the decreasing returns of investing in SGS (i.e., increasing GVI is more efficient in municipalities where it is less available).

In addition, we also conduct regression analysis for stratified sub-samples by the degree of urbanization of the municipality and its wealth level (Table A-6), showing that households in rural and semi-urban (vs. urban) and in lower income municipalities are both more sensitive to temperature and benefit more from GVI for their electricity consumption level. We also aggregate the data to carry out an analysis where each unit of observation represents the average of the POD consumption at each municipality and time period (Table A-2 for descriptive statistics and Table A-8 for regression results).

Finally, we conduct a set of supplementary regressions where re-estimate the double interaction quadratic model among our two treatment variables of interest (T_{max} and GVI) for each of the twelve months of the year, and we derive model-based predictions to evaluate heterogeneity in the moderating effect of GVI across months of the year. Figure A-10 reports the results of such analysis. The slope patterns suggest that GVI tends to mitigate the negative association between higher temperatures and the outcome during the warmer months (e.g., June–July), when greener areas are associated with lower predicted values as temperatures rise. Conversely, during some of the cooler months, the moderating role of GVI appears weaker or even slightly reversed, indicating that vegetation exerts a seasonally dependent buffering effect that is strongest in mid-summer and less pronounced in winter.

Summer tourism heterogeneity. We evaluate the heterogeneity across municipalities that are classified by ISTAT (the Italian national statistical office) as summer-tourism destination (maritime, mountainous, and lake tourism). Hot periods of the year may bear a confounding signal owing to the fact that a significant proportion of residents in non-touristic municipalities may temporarily relocate to holiday homes towards touristic municipalities. Hence, we aim at evaluating whether there is a significant difference in the temperature-electricity demand relation across summer-tourism destinations municipalities and non summer-tourism municipalities. Table A-11 illustrates the results of the comparative regressions analysis. While coefficients' signs and statistical significance are unchanged between the two sub-samples, we find that summer touristic municipalities show stronger energy consumption responses to hot temperatures, as well as a more salient moderating role of SGS. We attribute this to the fact that individuals on holiday may behave differently from residents: for example, they may more intensively use cooling systems in holiday homes or in rented properties due to behavioral biases or moral hazard on electricity prices.

Treatment variables and specifications. We evaluate the sensitivity of the results to the choice of the treatment variable for measuring heat exposure, as well as to the model specifications, fixed-effects inclusion, and clustering of standard errors. Table A-4 and Table A-8 demonstrate that the main results presented above - in terms of their sign, magnitude, and significance - are robust to such checks. We quantify the relation using Cooling Degree Days (CDD), Cooling Degree Hours (CDH), and temperature quantile bins as the treatment heat metric (Table A-7). We also add a binary variable for COVID in year 2020 and we appraise the relevance of different spatial resolution of entity-specific yearly time trend (municipality and/or province). Finally, we evaluate the uncertainty in the statistical significance of the effect in our main quadratic temperature specification when clustering standard errors at different levels of aggregation, as shown in Figure A-12, demonstrating robustness in the significance of the estimate of the main coefficients of interest.

Across-municipality sorting and endogeneity concerns. Based on the established physical understanding of the process through which SGS regulate urban temperatures, as well as the exogeneity of the latter with respect to city-scale decision variables different than land use, we can be confident about the lack of omitted variables in shaping the estimates of the ancillary regression linking within-city variation in SGS and temperature. On the other hand, concerns relating to the possibility that more SGS-dense municipalities might be non-random with respect to the distribution of households energy behaviors need to be addressed. For instance, SGS may be non-randomly distributed with respect to households showing a lower propensity to increase electricity during warm days. Another sorting mechanism may lay in the possibility that more SGS-dense municipalities might be systematically cooler, and thus electricity consumption may simply follow this pattern.

We are aware that there might be factors simultaneously affecting electricity consumption at the POD level and the measured level of SGS at the municipality level. For example, individuals living in a more green space-dense neighborhood have been found to spend more time outside (Feng, Toms and Astell-Burt, 2021); in parallel, households living in more SGS-dense areas might also display stronger preferences for energy efficiency and green behaviors (Alcock et al., 2020) or the use of housing and/or appliances retrofitting incentives, including through peer and network effects (Huang, 2024). These unmeasurable factors and dynamics might potentially bias our main regression estimate of the role of SGS for moderating the electricity use response to temperature. Specifically, all these concerns might imply smaller-than-estimated direct effects of SGS on household electricity consumption.

To seek to address these concerns, we calculate propensity score weights to evaluate the hypothesis of sorting of households across municipalities based on the GVI level, conditional on other characteristics of the municipality which are potentially correlated with GVI levels. These include the average income level of households living in the municipality; log of total population and population density in the municipality (potential proxies of energy behavior); the distribution of maximum temperature across months of the years (local climate); the summer tourism destination classification of the municipality; the latitude and elevation of the municipality; and a vector of variables providing the share of buildings in the municipality by 10-year age of construction classes. Note that these variables might also indirectly capture unobserved factors of which they are jointly strong predictors, and crucially in the context of this study, the probability of AC prevalence (De Cian et al., 2025).

We first calculate observation weights based on the following equation:

$$\begin{aligned} SGS_{a,t} = {} & INCOME_{a,t} + Tmax_{a,m,t} + POPDENS_a + log(POP_a) + SUMMERDESTINATION_a + \\ & LATITUDE_a + ELEVATION_a + BUILDAGECLASES_a + \varepsilon_{a,m,t} \end{aligned} \tag{11}$$

where weights are estimated using entropy balancing (Tübbicke, 2021; Vegetabile et al., 2021). We then evaluate weighted and unweighted covariates-treatment correlations, as shown in Figure 7. Then, in a second step, we re-estimate the main specification (Eq. 9) in both its unweighted (original) and its (propensity weights) weighted formulations. Table A-12 shows that the propensity score weighted regression results are consistent with those of our main specification in terms of sign, significance and shape and magnitude of the estimated curves (Figure A-11) - with weighted regression coefficients decreasing slightly in magnitude. This finding rules out that the observed covariates are meaningfully biasing the coefficient estimates due to non-random across-municipality sorting of households.

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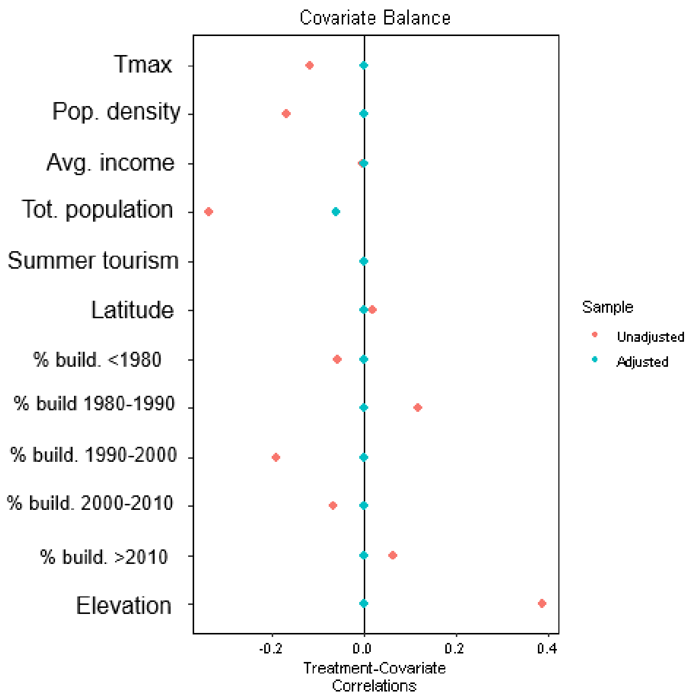

Figure 7. Covariate balancing robustness: love plot of pre and post-weighting co-variates correlation.

Residual sorting concerns and limitations. Despite the extensive supporting evidence illustrated so far on the energy-saving effect of SGS, there exist residual limitations to our findings that cannot be tackled in the context of the data and empirical settings of this paper. Existing unobservable household-specific and time-sensitive characteristics might still be correlated with both variation in GVI and electricity consumption levels, inducing spatial sorting and self-selection in our sample of consumers that would not be captured by either our controls or fixed-effects structure. These may include, for instance, preferences and energy efficiency of households: individuals who adopt a more sustainable consumption profile, as well as those living in more energy-efficient homes, and may prefer to live in high SGS areas within each municipality. Moreover, unobservable house refurbishment programs affecting space heating and cooling energy use in specific types of households, as well as other targeted policy measures (e.g. air-conditioning purchase subsidies), may occur, though the short duration of the panel makes major changes in building insulation or household environmental preferences unlikely to occur at scale.

While residual limitations exist, the relationship described in this paper is robust to considering a set of measures at the municipality level (such as income and composition of buildings) that are a reasonably good proxy for these unobservable characteristics. Future research may explore the possibility to combine granular data on urban microclimate and SGS with higher spatio-temporal resolution of electricity demand across cities, as well as a more comprehensive set of household characteristics.

7 Climate change and policy impact simulations

Based on the estimated models, we carry out a set of policy and climate change impact simulations to appraise the potential influence, *ceteris paribus*, on household electricity use of i) SGS densification policies, ii) climate change, and iii) their interaction. Specifically, we evaluate policies increasing SGS and the impacts of climate change on temperature around 2050. For climate, we focus on the RCP 8.5 climate change scenario[3] from the CMIP6 models ensemble, which produces downscaled climate projections for the climatological period 2045-2055. The data are

[3] See https://www.ipcc.ch/report/ar6/wg1/chapter/chapter-4/ for details.

obtained from the NASA NEX-GDDP-CMIP6 database (Thrasher et al., 2022). We consider monthly maximum temperature (T_{max}) and compare two cases: future temperatures under RCP 8.5 projections for around 2050 (H_{cc}) and historical forcing temperatures (H_{hist}), both based on the CMIP6 climate model outputs. In parallel, SGS increase policy scenarios (SGS_s) are defined, where s indicates a minimum target value for mean GVI at the municipality level assigned to all municipalities in our sample. We compare current GVI levels scenario ($\bar{s}$) with five alternative levels, i.e. $s \in [\bar{s}, 15, 20, 21, 24, 27]$. In each scenario, all municipalities a where $GVI_a < s$ are set to exactly match the target value s. These target GVI values correspond approximately to the 5th, 35th, 50th, 75th and 90th percentiles of the distribution of municipality-level GVI in the sample covered by our analysis. This translates into 6%, 37%, 47%, 74% and 90% of the count of unique municipalities in our sample being targeted by the five GVI target-driven policies, respectively.

We obtain a total of 12 combinations, 11 projected scenarios and one benchmark (current climate and current GVI level combination). For all the simulated policy combinations, we compute predictions from our empirically-estimated preferred quadratic model specification presented above to calculate the simulated change in household electricity consumption and spending from the status quo (Δq). Formally, we compute:

$$\Delta q_{E,i,a} = (\widehat{q_{E,i,a}}|SGS_a = SGS_s, H_a = H_{cc}) - (\widehat{q_{E,i,a}}|SGS_a = SGS_{\bar{s}}, H_a = H_{hist}) \tag{12}$$

The results of the simulation analysis are provided in Table 4. Under the current climate, SGS enhancing policies would reduce residential electricity consumption in the municipalities covered by our analysis. For instance, the summer months municipality-level average reduction in response to SGS increase policies ranges from 0.07 to 3.3% (compared to current consumption levels), depending on the GVI target value simulated. On the other hand, while simulating the impact of climate change on temperature and hence on electricity demand by 2050 under RCP scenario 8.5, we find that in the absence of SGS policy, on average the summer consumption would increase by 4.3%. However, if a SGS increase policy is implemented, such climate-induced increase in energy use would be reduced substantially, up to a net reduction of -1.8% under an ambitious SGS policy (s=27). As a remark, the climate change-driven increase in electricity demand estimated is likely to be a lower bound due to the projected increase in air conditioning penetration (De Cian et al., 2025) and other temperature-sensitive appliances, which are not explicitly captured in our model (but implicitly captured by POD and municipality-level fixed effects in the short-term panel) and might drive a more extensive hot temperature-related surge in household electricity use as penetration grows. For reference, Figure 8 visually illustrates the spatial heterogeneity in the estimated average percentage impact of climate change (RCP 8.5, year 2050) on residential electricity demand in each municipality covered by the analysis under a policy aimed at increasing SGS to a minimum level of municipality-level mean GVI of 21 - a value at around the median of the current distribution across municipalities. Such policy would reduce by more than two thirds the climate change-driven projected increase in summer residential electricity consumption under RCP 8.5 climate conditions around 2050 (compared to a scenario without SGS policy).

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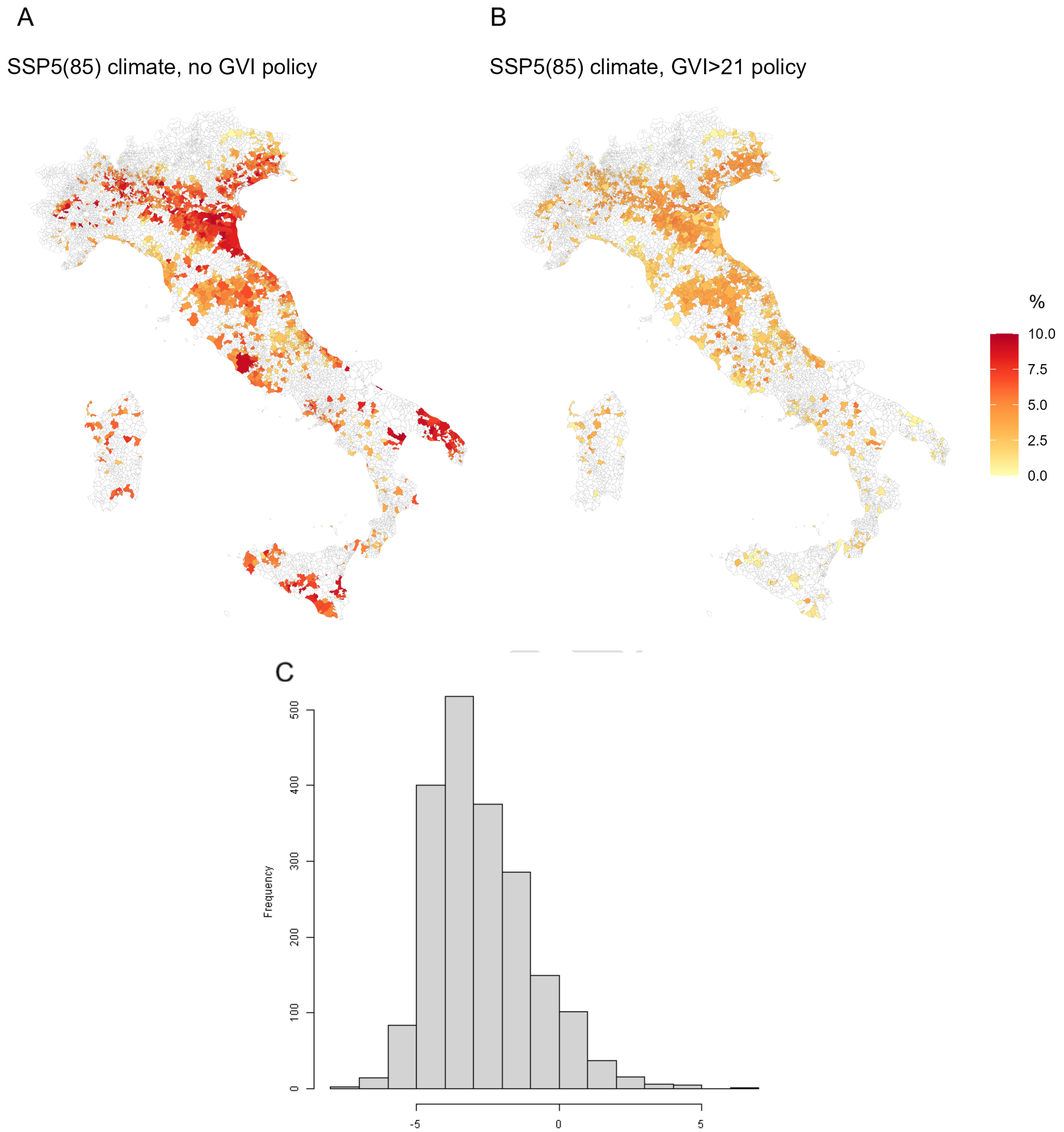

Figure 8. Climate change-induced, municipality-level average change (%) in summer monthly electricity consumption under a RCP 8.5 climate in year 2050 with (A) current GVI levels; (B) a GVI ≥ 21 policy; (C) histogram of municipality-level average change between (A) and (B).

As seen from Table 4, we use the model to extrapolate over all Italian municipalities and 26 million households in the country[4] to estimate the corresponding reduction (or negative reduction, i.e. net increase) in the quantity of

[4]We feel confident in assuming that the POD-level metered metered consumption dataset used in our analysis provides a good representation of the universe of Italian PODs across the whole country for two main reasons: (i) first, as displayed in Figure 2, our consumption dataset represents municipalities across the whole Italian territory, providing evidence of good geographical coverage. (ii) Second, we show that the

energy consumed (TWh/summer) and its weight on the total yearly residential electricity consumption ($\text{TWh} \cdot \text{yr.}^{-1}$). Finally, we also estimate emission reductions under the current average carbon intensity of the electricity sector in Italy of 372 $gCO_2e \cdot kWh^{-1}$.

Table 4. Policy and climate change simulations results summary: reduction in electricity use (TWh) and related CO_2 emissions (metric tons) with minimum GVI target values ($\geq$) compared to current climate and SGS levels in the universe of Italian households.

	avg. % change	Δ TWh summer	% yearly resid. electr. cons.	Δ CO_2 (Mt)	Ely. tot (TWh/summer)
GVI ≥ 15, historical T_{max}	−0.08	−0.10	−0.15	−0.04	18.50
GVI ≥ 20, historical T_{max}	−0.85	−0.44	−0.68	−0.16	18.16
GVI ≥ 21, historical T_{max}	−1.17	−0.53	−0.83	−0.20	18.06
GVI ≥ 24, historical T_{max}	−2.36	−0.83	−1.29	−0.31	17.77
GVI ≥ 27, historical T_{max}	−3.77	−1.13	−1.76	−0.42	17.46
GVI current*, SSP5(85) T_{max}	4.91	1.26	1.95	0.47	19.87
GVI ≥ 15, SSP5(85) T_{max}	4.76	1.08	1.68	0.40	19.68
GVI ≥ 20, SSP5(85) T_{max}	3.37	0.46	0.72	0.17	19.06
GVI ≥ 21, SSP5(85) T_{max}	2.79	0.29	0.45	0.11	18.89
GVI ≥ 24, SSP5(85) T_{max}	0.56	−0.25	−0.39	−0.09	18.34
GVI ≥ 27, SSP5(85) T_{max}	−2.08	−0.81	−1.26	−0.30	17.78

Note: *Current (with current GVI and historical T_{max}) estimated residential electricity consumption per summer (June-August) in the universe of Italian municipalities is 18.61 TWh.

Implications for household electricity expenditure

Simulated changes in household electricity consumption as a result of climate change impacts and SGS increase policies may directly translate into changes in private energy expenditure, hence having significant welfare repercussions. To estimate the magnitude of such potential changes, we derive the monthly and municipality-specific marginal price of electricity and cost per unit of energy consumed based on the energy billing information attached to the metered consumption data. Under the assumption of historical prices - justified by the challenge to project average retail electricity prices in year 2050 due to the plethora of factors involved - and marginal cost of energy, we conduct a back-of-the-envelope calculation that considers the representative household in our sample and projects the results of the expenditure change analysis on both (i) the households living in municipalities that are part of the sample of the metered consumption data of our empirical analysis, and (ii) on the universe of 26 million Italian households and 7,896 municipalities.

Figure 9 summarizes the results of the analysis showing, for each scenario, the simulated change (with respect to current consumption levels under the historical climate and GVI values) in the average household summer monthly expenditure for energy bills in year 2050. The numbers are computed by multiplying the projected variations in summer electricity consumption levels by the median price per kWh and overall expenditure per kWh paid by consumers in each municipality. The results show that such change spans between about an average saving of 3.2€/household/summer (in a scenario of historical climate and *s*=21 GVI target) up to an expenditure increase of 13.5€/household/summer in a scenario of RCP 8.5 climate change and no SGS increase policy, which accounts for around 11.6% increase of the average of a household's summer expenditure for electricity. A similar figure based on the unit price of electricity (rather on the marginal cost of energy per unit consumed) is provided in Figure A-13.

distribution of consumption levels in our POD-level dataset is consistent with the country-level statistics reported by ARERA (the energy sector public regulatory agency of Italy, https://www.arera.it/dati-e-statistiche). Taking 2022 as an example, the most recent year in our dataset, we find that the median consumption level is at 143.5 kWh/POD/month, almost perfectly consistent with the value of 145 kWh/POD/month reported by ARERA for residential customers.

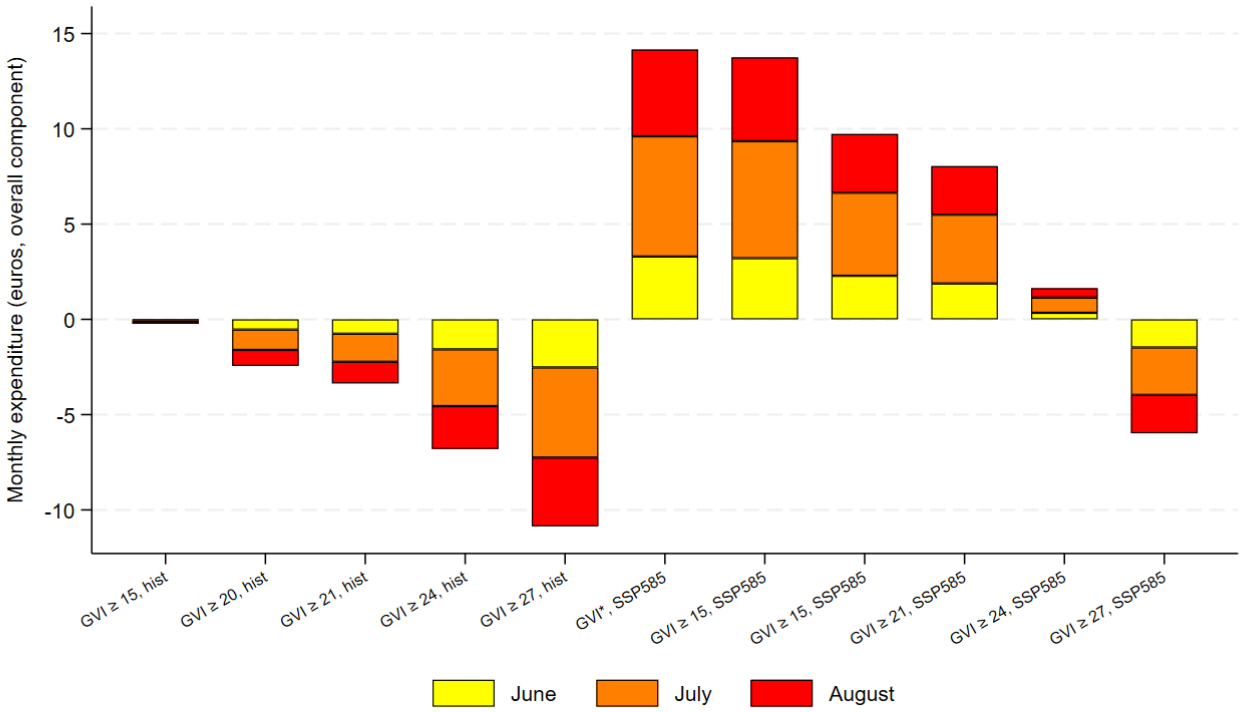

Figure 9. Estimated change in the household summer monthly expenditure for energy bills in the GVI policies and RCP 8.5 climate change impact simulations in year 2050. Average Δ€ per household per month under the assumption of historical marginal energy costs.

To summarize the expenditure analysis and gauge their magnitude across the entire population, Table 5 illustrates the potential saving for (i) an average national household; (ii) the population of households living in the municipalities represented in our metered consumption dataset, in aggregate; and (iii) for the entire population of Italian households and municipalities, in aggregate. With regards to the latter, the results show that a scenario of RCP 8.5 climate change and moderate SGS increase (*s*=21) would only increase household electricity expenditure by €202 million, while a scenario of RCP 8.5 climate change and no SGS increase policy would cause private increase in expenditure up to €355 million per summer, translating into a gross private saving of €153 million per summer if the SGS policy is implemented.

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Table 5. Simulated changes in household electricity expenditure: average summer monthly bill, median price per kWh and median expenditure (sp). For each GVI policy and climate change scenario, the variation in summer consumption (c), energy components summer spending, and overall summer spending is calculated for an average Italian household (i), the aggregate of households in our sample of municipalities (ii), and the aggregate of households in the country (iii). The table also reports the total number of households in our sample of municipalities and in the country. These are used to calculate the variation in total spending (ΔS) for the two populations, expressed in thousands of euros.

	Household electricity expenditure			Population household numbers	
	avg. bill (euros/month)	P/kWh (med)	sp/kWh (med)	HHs (N, sample)	HHs (N, country)
	116.57	0.103	0.389	7095696	26400326

	Simulated variations in electricity spending						
	i. Average Italian household			ii. Represented municipalities (aggregate)		iii. National (aggregate)	
Scenario	Δc (kWh)	Δsp (energy) (euros)	Δsp (total) (euros)	ΔSP (energy) (1000 euros)	ΔSP (total) (1000 euros)	ΔSP (energy) (1000 euros)	ΔSP (total) (1000 euros)
GVI ≥ 15, hist	-0.587	-0.058	-0.221	-409.5	-1566.2	-1523.6	-5827.4
GVI ≥ 20, hist	-6.107	-0.618	-2.324	-4384.4	-16493.7	-16312.5	-61366.6
GVI ≥ 21, hist	-8.421	-0.854	-3.194	-6059.9	-22666.1	-22546.7	-84331.7
GVI ≥ 24, hist	-17.012	-1.748	-6.470	-12402.8	-45911.1	-46146.0	-170817.2
GVI ≥ 27, hist	-27.115	-2.802	-10.332	-19883.6	-73310.6	-73979.0	-272760.3
GVI*, SSP585	35.133	3.653	13.465	25920.1	95542.3	96438.7	355475.9
GVI ≥ 15, SSP585	34.092	3.550	13.070	25188.7	92739.6	93717.2	345047.9
GVI ≥ 20, SSP585	24.075	2.531	9.248	17959.4	65620.2	66820.1	244147.3
GVI ≥ 21, SSP585	19.820	2.096	7.646	14874.1	54250.4	55340.9	201844.8
GVI ≥ 24, SSP585	3.906	0.436	1.557	3096.2	11046.8	11519.7	41101.0
GVI ≥ 27, SSP585	-14.971	-1.536	-5.685	-10901.0	-40342.4	-40558.2	-150098.4

Implications of policy costs for public budgets

SGS expansion and maintenance imply public costs to continuously provide a range of ecosystem services, including the indirect benefit of household electricity expenditure reduction through hot temperatures reduction, which is the focus of this paper. To assess the magnitude of such costs to achieve the policy goals simulated above, we produce a supplementary analysis of the public finances implications of SGS expansion and maintenance. We retrieve a panel dataset of every Italian local municipality's yearly budget, by cost entry, for the 2017-2023 period. The data is provided by OpenBDAP - the official portal of the Italian State General Accounting Department. Specifically, we select the cost entry classified as *"Maintenance of public green spaces and enhancement of the natural environment"*) and we evaluate the responsiveness of municipality-level GVI levels to the yearly local capital investment and expenditure in such budget entry. The data are summarized in Table A-15 and Figure A-14, showing that the average values of municipality-level investment and expenditure are about €103,729 and €225,947 per year, respectively, but significant upper and lower tail exist in the distribution - driven by the high values in large municipalities and by the small average size of Italian municipalities.

Table 6, shows the result of a municipality and yearly fixed effect regressions, implying an average requirement of €68.5 million and €13 million per year in the green space expenditure and investment of a municipality, respectively, for every additional local GVI point, net of average differences across municipalities and of country-wide shocks across years. It should be noticed that the estimated fiscal response to GVI is a lower-bound estimate, as tree canopies are a function of time after plantation, and it was shown that it takes between 30-60 years for a tree to provide its maximum level of benefits (Li et al., 2023).

Table 6. Regression results on responsiveness of public municipality investment and expenditure in the "maintenance of public green spaces and the enhancement of the natural environment" budget entry to variation municipality-level yearly GVI levels.

Dependent Variable:	*GVI*
Variables	
Million €/year × Expenditure	0.0146***
	(0.0040)
Million €/year × Investment	0.0771***
	(0.0227)
Fixed-effects	
Municipality	Yes
Year	Yes
Fit statistics	
Observations	76,998
R^2	0.94475
Within R^2	0.00027

Clustered (Municipality) standard-errors in parentheses
*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

Considering a time horizon of 25 years until 2050, we compute the total investment and expenditure requirement (IER) for reaching the GVI targets simulated in each scenario as the ratio between the required increase in the GVI to reach the target s in each municipality a and the estimated marginal cost (the coefficients of Table 6) of increasing the GVI by one unit MC^{GVI}:

$$IER_a = \frac{\Delta GVI_a^s}{MC^{GVI}} \tag{13}$$

We then compute the net present value (NPV) by discounting the investment and expenditure cashflows with a discount rate of 3% (following the European Commission CBA guidelines for social projects):

$$NPV_{IER_a} = \sum_{t=1}^{25} \frac{IER_{a,t}}{(1+0.03)^{t-1}} \tag{14}$$

Finally, we compute the Equivalent Annual Annuity (EAA) (i.e., the cost per year over the entire lifespan) from the NPV as:

$$EAA_{a,t} = NPV_{IER_a} \times \frac{0.03}{1-(1+0.03)^{-25}} \tag{15}$$

Across the municipalities covered by our analysis, we compute a NPV_{IER_a} of €24.8 billion over the 25-year planning horizon, which translates into an $EAA_{a,t}$ of €1.4 billion per year to achieve the GVI policy objective of s=21. Scaling the calculation to all Italian municipalities brings the *NPV* figure to a value of €36.9 billion and the *EAA* figure to €2.1 billion per year. This figure corresponds to around €35 per capita. When looking at the distribution of the *EAA* metric across municipality (illustrated in Figure 10), we find that achieving the s=21 policy implies a median *EAA* of about €1 million / municipality / year.

The *NPV* and *EAA* calculations are also applied to the estimated gross national-level private saving in energy bills of about € 0.15 billion per summer if the GVI policy objective of s=21 is achieved, so as to obtain comparable cost and benefit metrics. This shows that private electricity expenditure savings yield an *NPV* of €2.7 billion and an

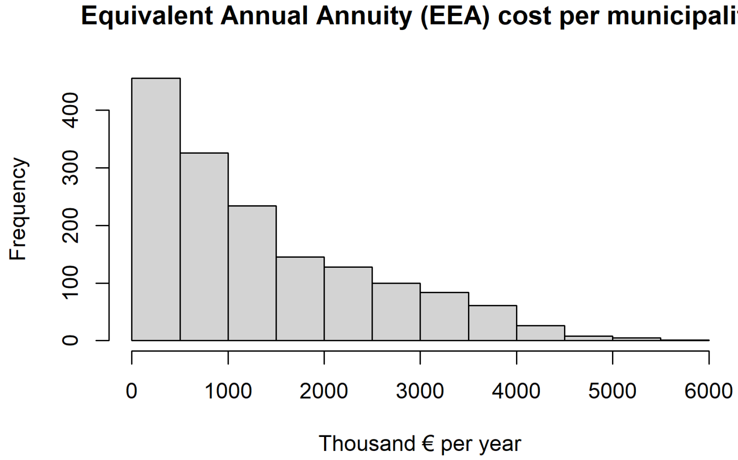

Figure 10. Distribution of the estimated Equivalent Annual Annuity (investment + expenditure) across municipalities to achieve the s=21 GVI policy goal with a 25-year planning horizon and a 3% discount rate. The values sum to a total of about €2.1 billion per year across all Italian municipalities.

EAA of €0.15 billion per year, hence accounting for about 7.3% of the estimated policy costs. This finding should be read under the lens of SGS being a provisioning source of a wide range of ecosystem services, which translate into public and private benefits, with energy use reduction being only a component of such benefits. Moreover, our analysis demonstrates that increasing urban SGS is costly, and it should be targeted in those areas where it is most effective, rather than a one-size-fits-all solution.

8 Discussion and conclusions

Our paper is the first quantitative assessment of the benefits of SGS in terms of reduced summer electricity consumption with a large spatio-temporal coverage. Our work contributes to the understanding of the interaction between public and private climate change adaptation (Tompkins and Eakin, 2012) and the related cost and benefit streams. Our findings confirm the importance of SGS as a key regulating factor in the temperature-energy demand relation. SGS density - as measured by the GVI - has a strongly significant non-linear effect on the impact of temperature on household electricity demand, with the strongest impact being a consumption reduction effect under high heat exposure. Such responses are heterogeneous, as they depend on morphological and socio-economic characteristics such as the extent of greening, the degree of urbanization, temperature, and income characteristics, as well as on a range of unobserved household and city-specific characteristics, such as behavioral responses. The choice of the heat exposure metric also plays a role, as the type of indicator (i.e. cumulative vs. acute heat) as well as the variables selected to measure it play a role in determining the magnitude of the mediating effect of SGS.

Despite some residual limitations to the strategy highlighted above, our study generates new knowledge in relation to the intersection between climate change adaptation and mitigation, and the role of nature-based solutions to reduce the feedback impacts of adaptation while providing ecosystem service co-benefits. This is potentially achieved both through the energy demand and expenditure reductions in supporting climate change mitigation efforts, and in the quest for sustainable solutions for adaptation to climate impacts such as heat exposure. For instance, based on our empirical findings, we estimate that a policy aimed at increasing SGS to a minimum level of municipality-level mean GVI of 21 - a value at around the median of the current distribution across the municipalities covered by our analysis - would strongly contribute to offsetting more than two thirds of the climate-induced increase in residential electricity consumption. Such policy would lead to a reduction of around three quarters of the climate-induced expected increase in household summer electricity consumption under RCP 8.5 climate conditions around 2050, compared to a scenario of current GVI levels. This corresponds to a gross national-level private saving in energy bills of €0.15 billion per summer in year 2050. SGS increase and climate change impact scenarios on residential electricity consumption could be assessed in energy and integrated assessment models to evaluate the role of SGS for the mitigation-adaptation synergies and trade-offs in relation to the energy needs for adaptation to heat exposure (which are found to be very significant (Colelli et al., 2022; Mastrucci et al., 2022; Van Ruijven, De Cian and Sue Wing, 2019) and in the analysis of interactions among public and private adaptation actions, including equity and social-ecological justice considerations in urban adaptation (Rocha et al., 2024).

Our proposed back-of-the-envelope calculation shows how private savings for electricity account for around 7.3% of the estimated yearly discounted maintenance costs. This, in turn, highlights a substantial, and potentially overlooked, economic benefit of urban green spaces. Policymakers should incorporate energy savings - alongside the wider range of ecosystem services, public health benefits, including mortality reduction and well-being (Van den Berg et al., 2015*b*), and intrinsic economic values (Urban, 2018) - when performing comprehensive cost-benefit analysis and evaluating the welfare implications associated with the expansion of green spaces.

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Author contributions

G.F. and E.D.C. designed the study and created the theoretical framework; G.F. assembled the data and carried out the formal analysis; J.L. processed the metered electricity consumption data and conducted the expenditure change calculations; G.F. produced the figures and tables; all authors wrote and edited the manuscript.

Competing interests

The authors declare no competing interests.

Data and materials availability

The replication code, instruction for accessing the input data, and the output data generated in this study are available in a Github repository under: https://github.com/giacfalk/sgs_electricity_replication.

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Street green space and electricity demand: evidence from metered consumption data

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ABSTRACT

Growing climate change impacts call for increased efforts to adapt and to reduce its adverse consequences on society. Adaptation responses can themselves be a source of climate risk, generating negative environmental externalities while entailing budgetary costs for both governments and private citizens. A key example is the private use of air-conditioning for indoor air temperature regulation in the face of rising urban heat. In this paper, we empirically evaluate the impact of street green spaces (SGS) on residential electricity demand through their urban temperature regulation effect. We exploit a monthly panel of household metered electricity demand data from 129,524 households located in 2,181 municipalities distributed across Italy, in the period between 2020 and 2022. We find evidence of a significant non-linear mediating role of SGS on the impact of temperature on household electricity demand. The most salient effect is a reduction in electricity consumption when hot temperatures occur - lowering monthly average electricity consumption by up to 11-25% (for monthly maximum temperatures of 30 and 35° C, respectively). The observed moderating effects of SGS are heterogeneous across municipalities, as they depend on contextual factors such as the degree of urbanization, baseline heat and SGS levels, and average income level. To dissipate across-municipality sorting concerns, we conduct propensity score weighting on a range of potentially confounding observables, and find our results remain consistent. We estimate that a policy increasing the average Green View Index (GVI) level across all municipalities to a value comparable to the median of the current distribution would reduce the growth in residential electricity consumption driven by climate change by more than two thirds (under Representative Concentration Pathway 8.5 climate conditions around 2050). This corresponds to a gross national-level private saving in energy bills of €150 million yearly in 2050. This is a noticeable benefit that represents about 7.3% of our estimated costs to implement such policy, and informs on a potentially substantial social and economic benefit of urban green spaces. Our results provide new quantitative evidence of the role of street green spaces for both energy demand reduction, and therefore climate change mitigation, and in terms of outdoor temperature reduction, supporting climate change adaptation.

Keywords

Street green space; energy demand; public-private adaptation; urban heat islands; nature-based solutions; climate change impacts

JEL classifications:

D12, O13, Q41, Q5

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Statements and Declarations

Author contributions

G.F. and E.D.C. designed the study and created the theoretical framework; G.F. assembled the data and carried out the formal analysis; J.L. processed the metered electricity consumption data and conducted the expenditure change calculations; G.F. produced the figures and tables; all authors wrote and edited the manuscript.

Competing interests

The authors declare no competing interests.

Data and materials availability

The replication code, instruction for accessing the input data, and the output data generated in this study are available in a Github repository under: https://github.com/giacfalk/sgs_electricity_replication.

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- Analysis of metered electricity consumption data from ~130,000 households in Italy.
- Street trees moderate electricity–temperature response non-linearly.
- Cooling effect of street trees reduces electricity demand at high temperatures.
- Benefits vary by urbanization, income, climate, and baseline greenery levels.
- Increasing SGS could cut 2050 climate-driven electricity growth by over two-thirds.

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