A Territorial Adaptive Composite Index for Urban Energy Poverty: Local Vulnerability Drivers

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Abstract. Energy poverty is increasingly recognised as a multidimensional challenge affecting urban resilience, public health and social equity across European cities. Despite the availability of consolidated national indicators, existing monitoring frameworks often lack the spatial resolution required to support local decision-making and place-based policy design. This paper proposes an aggregated and territorially sensitive urban energy poverty index that integrates six analytical drivers socio-economic, building-related, energy, climatic, urbanistic and institutional within a flexible composite indicator structure. The methodological contribution lies in the integration of high-resolution local data with official European indicators and in the adoption of an entropy-based weighting system, which derives data-driven weights from the variability of indicators across neighbourhoods. The methodology is applied to the Mediterranean city of Catania (Italy), revealing pronounced intra-urban disparities in energy vulnerability, with composite index values ranging from 0,04 in affluent central areas to 0,74 in peripheral public housing districts. The results demonstrate that the proposed approach captures spatial patterns and dominant drivers of energy poverty that remain invisible in aggregated statistics, providing a robust analytical basis for targeted urban energy and social policies.

Keywords: Energy poverty · Urban vulnerability · Composite index · Territorial drivers · Mediterranean cities · Entropy weighting

1 Introduction

Energy poverty has become a central concern in European energy and social policy, particularly in the context of the energy transition, climate change and rising energy prices [1–3]. Originally framed around insufficient access to adequate heating, energy poverty is now increasingly understood as a broader condition of vulnerability encompassing cooling needs, housing quality, socio-economic deprivation and exposure to

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environmental stressors [4–6]. At the European level, monitoring frameworks based on EU-SILC data, such as consensual and expenditure-based indicators, including the Low-Income High Costs (LIHC) indicator, are widely adopted [7–9]. More recently, the Energy Poverty Advisory Hub (EPAH) has promoted a harmonised set of primary and secondary indicators to support policy development across Member States [10, 11]. While these instruments are effective at national and regional scales, they provide limited support for urban scale decision-making due to their coarse spatial resolution and limited sensitivity to local conditions [12–14]. These limitations are particularly evident in Southern European and Mediterranean cities, where climatic conditions, urban heat island effects and increasing cooling demand significantly affect household energy needs [15–17]. Existing indicators, largely calibrated on winter heating deprivation, tend to underestimate vulnerability in such contexts, neglecting summer thermal stress and microclimatic exposure [18–20]. Recent studies have highlighted that cooling-related energy poverty affects a substantial proportion of Mediterranean households, with significant health implications during increasingly frequent heatwaves [21, 22]. Against this background, this study advances the state of the art by proposing a territorially sensitive composite index specifically designed for urban energy poverty analysis. The methodological contributions are threefold: (i) the integration of high-resolution local data enabling neighbourhood-scale analysis; (ii) the adoption of an entropy-based weighting system that derives data-driven weights from the variability of indicators across neighbourhoods, moving beyond the equal-weight assumption commonly used in composite; and (iii) the explicit incorporation of summer thermal stress, addressing a persistent Mediterranean gap in existing monitoring frameworks. Taken together, these elements transform the index from a descriptive metric into an operational tool for intra-urban energy poverty diagnosis and policy targeting. The framework is applied to the city of Catania as a representative Mediterranean case study, providing empirical evidence of its ability to reveal intra-urban disparities and support place-based policy design. Catania represents an ideal test case due to its combination of significant socio-economic fragility (the lowest median household income among Italian metropolitan cities at € 12,200/year), ageing building stock with poor energy performance (52.1% in classes F-G), extreme summer climatic stress with temperatures reaching 46 °C and over 110 days per year with perceived temperatures above 35 °C. The paper is structured as follows: "Materials", which presents the neighbourhoods of Catania under analysis; "Methods", which presents the methodological approach developed; Results, which highlights the composite index values for the districts of Catania, Librino, Angeli Custodi/San Cristoforo and Corso Italia, for which the vulnerability profiles by driver and spatial distribution are presented and a driver decomposition analysis is proposed; "Discussion", in which some reflections are offered and certain results are compared with reference to intra-urban disparities and the limits of aggregate statistics. The Mediterranean Gap and Policy Implications are also highlighted. "Conclusion": A brief summary of the paper's content is provided.

2 Materials

Catania is characterised by marked contrasts in demographic structure, socio-economic conditions, building stock characteristics and urban morphology [23, 24].

Librino is one of the largest public housing districts in Southern Italy, developed from the late 1960s as part of a major urban expansion plan. Its urban form is defined by large-scale residential blocks, extensive road infrastructures and limited green areas. The neighbourhood is widely documented as an area of socio-economic fragility, with high unemployment rates, low educational attainment and a predominantly ageing building stock constructed before the introduction of national energy performance regulations [23]. Angeli Custodi/San Cristoforo, located in the historic centre, is characterised by compact morphology, narrow street networks and a high concentration of pre-1945 buildings. According to ISTAT sub-municipal indicators [23], the area records elevated levels of socio-economic vulnerability, demographic ageing and housing deprivation. Historic-centre districts in Catania have been widely analysed for their structural decay and limited maintenance. Zia Lisa, situated near the airport and major transport infrastructures, presents a heterogeneous urban fabric combining low-rise residential units, informal expansions and more recent constructions. The area is documented as having intermediate socio-economic conditions and limited availability of public services and green spaces [24]. Corso Italia, in contrast, is one of the most affluent coastal areas of Catania. It is characterised by high-quality residential buildings, wide boulevards, commercial activities and access to services. According to ISTAT income and education data, the area ranks among the highest in the municipality in terms of socio-economic indicators [23]. These four areas collectively represent the main socio-spatial configurations documented in Catania's urban literature, historic-centre districts, large-scale public housing estates, mixed peripheral zones and consolidated neighbourhoods, providing a diverse empirical context for the study. Figure 1 illustrates the municipalities of Catania and the districts that compose them.

Istat has produced a list of areas in Catania experiencing high levels of socio-economic hardship. The index is called IDISE (Index of Socio-economic Disadvantage of Individuals and Households at sub-municipal level) and is based on data verified as of 2021. Angeli Custodi has the highest Idise score in the city. The percentage of individuals living in households with no income is particularly high (52.7%), whilst those in low-income households account for 75.8%. The same applies to the low level of education (76.5%), and the number of young people aged 15 to 29 who are neither in employment nor in education and are not engaged in any training activity stands at 66.9%. The next highest percentages were also found in Librino, where the low level of education stands out, and in Zia Lisa regarding socio-economic deprivation.

Figure 2 identifies the Areas of Socio-Economic Deprivation in Urban Areas (ADU).

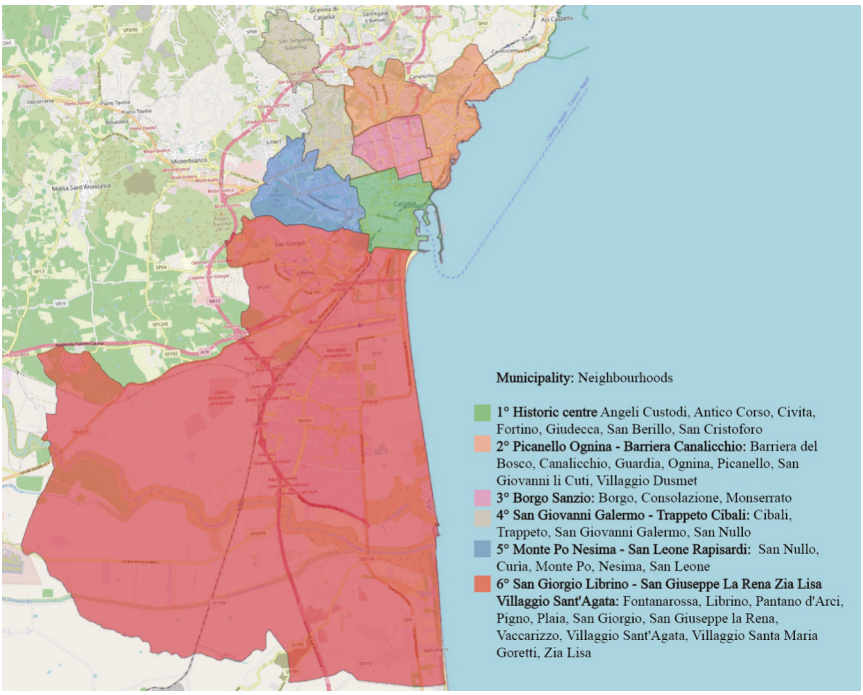


Fig. 1. Municipalities of Catania

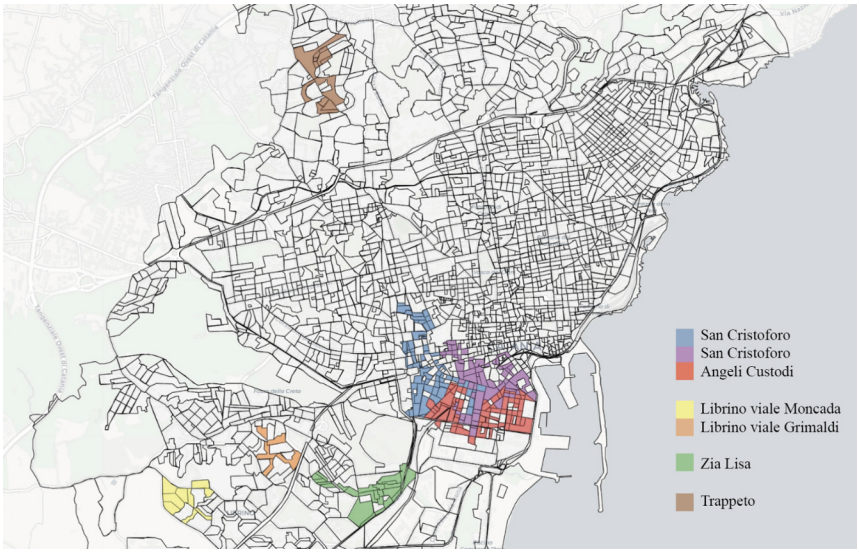


Fig. 2. Areas of Socio-Economic Deprivation in Urban Areas (ADU).

3 Methodology

The proposed methodological framework follows a structured, multi-phase approach designed to integrate heterogeneous data sources, derive data-driven weights, and ensure internal coherence and transparency in the construction of the composite index. The framework, illustrated in Fig. 3, comprises six sequential phases: (1) data collection from European and local sources; (2) definition of six territorial drivers; (3) normalisation of indicators; (4) driver weights through an entropy-based data-driven procedure; (5) composite index computation; (6) Spatial distribution of local vulnerability to energy poverty in the case studies and local driver decomposition analysis.

To assess the robustness of the index, a sensitivity analysis was performed by testing alternative weighting scenarios. In Scenario B, the weight of the IDISE index score increased by 10%, while the remaining weights were kept unchanged. In Scenario C the weight of the CDD index score was increased by 10%. In Scenario D the weight of the green space score was increased by 10%. The results confirmed the stability of the index and the consistency of neighbourhood rankings across scenarios.

Finally, the classification of vulnerability levels was based on quartile thresholds derived from the empirical distribution of Iuep values, defining four classes of increasing vulnerability: Low, Medium, High, Critical. This data-driven classification ensures a non-arbitrary interpretation of local energy poverty patterns and supports the identification of priority areas for policy intervention (Fig. 4).

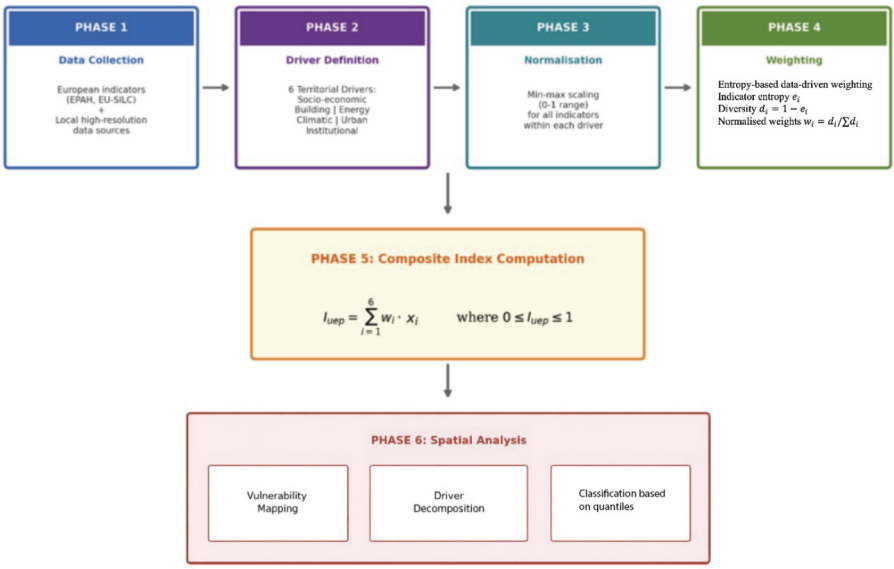


Fig. 3. Schematic representation of the six-phase methodological framework integrating European indicators with high-resolution local data through an entropy-based data-driven weighting procedure.

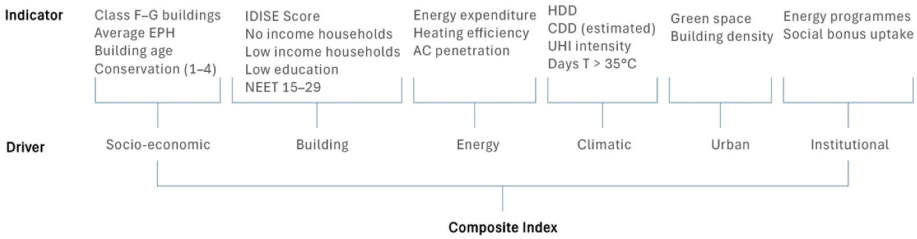


Fig. 4. Hierarchical structure for the aggregation of indicators

3.1 Data Collection from European and Local Sources

The construction of the composite index relies on a structured data collection process that integrates harmonised European indicators with high-resolution local datasets. This multi-scalar approach ensures both conceptual alignment with EU-level frameworks on energy poverty and an accurate representation of the socio-spatial specificities of Catania's neighbourhoods. At the European level, the study draws on the Energy Poverty Advisory Hub (EPAH) and EU-SILC-based indicators, which provide the foundation for identifying primary and secondary dimensions of energy poverty. These sources offer a framework for interpreting income deprivation, energy expenditure and household vulnerability across Member States, and serve as the reference for structuring the six analytical drivers adopted in this study. While European indicators are not available at intra-urban scale, they provide the methodological baseline against which local data are contextualised. Local data constitutes the core of the dataset and allow for a fine-grained characterisation of the selected districts. ISTAT sub-municipal indicators, including the IDISE index (Index of Socio-economic Disadvantage of Individuals and Households), provide detailed information on income deprivation, educational attainment, unemployment, and the incidence of NEETs aged 15–29. These indicators capture the socio-economic dimension of vulnerability and reveal pronounced disparities between historic-centre districts, peripheral public-housing areas and consolidated neighbourhoods. Building-related information was derived from municipal and regional datasets, including the Regional Energy Cadastre (SIAPE), which provides data on the distribution of energy performance classes (F–G), average energy performance (EPH), building age and conservation status. These variables reflect the structural fragility of the building stock and its limited compliance with contemporary energy-efficiency standards, particularly in pre-1945 historic fabrics and in large public-housing estates constructed before national energy regulations. Climatic exposure was assessed through locally validated indicators, including heating degree days (HDD), estimated cooling degree days (CDD), urban heat island (UHI) intensity and the number of days with temperatures exceeding 35 °C. These variables reflect the climatic pressures that shape energy needs in Mediterranean cities and highlight the relevance of cooling-related vulnerability, which is often underestimated in conventional European monitoring frameworks. Urban and environmental conditions were characterised through municipal datasets describing green-space availability, building density and service accessibility. These indicators capture the morphological and environmental constraints that influence both thermal comfort and exposure to climatic stress. Finally, institutional indicators, including the uptake of national

social energy bonuses and the presence of local energy programmes, were collected from municipal and regional administrative sources. These variables provide insight into the capacity of households to access support mechanisms and into the effectiveness of local policy responses. By integrating European conceptual frameworks with detailed local data, the study constructs a territorially sensitive dataset capable of capturing the multi-dimensional nature of urban energy vulnerability. This integrated approach ensures both methodological coherence with EU-level definitions and the spatial resolution required for intra-urban analysis.

3.2 Territorial Drivers

Six analytical drivers are identified, each capturing a specific dimension of urban energy vulnerability: (1) Socio-economic driver: encompassing income levels, unemployment rates, educational attainment and demographic vulnerability indicators derived from ISTAT sub-municipal data (IDISE index); (2) Building-related driver: capturing building age, conservation status, energy performance class (APE), construction materials and building typology from the Regional Energy Cadastre (SIAPE); (3) Energy driver: including estimated energy consumption, heating/cooling system type and efficiency, thermal demand, and energy expenditure share; (4) Climatic driver: measuring exposure to thermal stress through temperature extremes, urban heat island intensity, heating degree days (HDD) and cooling degree days (CDD); (5) Urban driver: accounting for building density, urban green availability, and service accessibility; (6) Institutional driver: assessing local policy effectiveness and presence of energy programmes including Renewable Energy Communities.

3.3 Entropy-Based Weighting System

A key methodological innovation is the adoption of a territorial weighting system calibrated to the specific context under analysis. Unlike conventional composite indicators that assume equal weights for all dimensions, the proposed approach recognises that the relative importance of vulnerability drivers varies across territorial contexts [15, 16]. To ensure transparency, replicability and the absence of subjective assumptions in the construction of the composite index, indicator weights were derived through an entropy-based data-driven procedure. Entropy weighting is widely used in composite indicator literature as it assigns higher weights to indicators that exhibit greater variability across territorial units, reflecting their higher informational content.

Let x_{ij} denote the normalised value (0–1) of indicator i in neighbourhood j. For each indicator, the proportion p_{ij} is computed as:

$$p_{ij} = \frac{x_{ij}}{\sum_{j=1}^{m} x_{ij}}$$

where m is the number of neighbourhoods. The entropy value of indicator i is then calculated as:

$$e_i = -k \sum_{j=1}^{m} p_{ij} \ln(p_{ij})$$

with $k = \frac{1}{\ln(m)}$ ensuring $0 \leq e_i \leq 1$. Higher entropy values indicate that the indicator is relatively uniform across neighbourhoods and therefore carries limited discriminatory power.

The degree of diversification (or information utility) of each indicator is defined as:

$$d_i = 1 - e_i$$

Indicators with higher variability across neighbourhoods exhibit higher d_i values and thus contribute more to the composite index. Final weights are obtained through normalisation:

$$w_i = \frac{d_i}{\sum_{i=1}^{n} d_i}$$

where n is the total number of indicators. This ensures that all weights are positive and sum to one.

The entropy-based procedure allows the weighting structure to emerge directly from the data, avoiding normative or arbitrary assumptions and ensuring that indicators with greater spatial differentiation exert a proportionally larger influence on the final index.

3.4 Composite Index Computation

The indicators within each driver have been normalised using min-max and max-min normalisation, on a scale from 0 to 1. Instead of assigning equal weights to the six drivers, the study adopts an entropy-based weighting procedure to derive objective, data-driven weights. The entropy method quantifies the amount of information carried by each indicator across the four neighbourhoods: indicators showing higher variability contribute more to the composite index, while more uniform indicators receive lower weights. For each indicator, entropy e_i, diversity $d_i = 1 - e_i$, and normalised weights w_i were computed. Driver-level weights W_k were then obtained by aggregating the weights of the indicators belonging to each driver. The composite urban energy poverty index (I_{uep}) is calculated as a weighted sum of normalised indicators:

$$I_{uep} = \sum_{i=1}^{n} w_i x_i \text{ where } 0 \leq \text{ Iuep } \leq 1 \quad (1)$$

w_i is the entropy-derived weight of each indicator i; x_i = normalised value of indicator i for the given neighbourhood; n = total number of indicators included in the composite index.

The index ranges from 0 (no vulnerability) to 1 (maximum vulnerability).

In addition, four thresholds have been identified for the energy poverty vulnerability index: Critical, High, Medium and Low.

3.5 Vulnerability Thresholds

A schematic spatial representation of local vulnerability to energy poverty was produced using the four vulnerability classes derived from the empirical distribution of the composite index values. The classification is based on quartile thresholds (Q1, Q2, Q3), ensuring a fully data-driven and non-arbitrary definition of vulnerability levels.

4 Results

This section presents the results of the composite urban energy poverty index as applied to the selected study areas. Index values, driver-level scores and spatial distributions are reported to illustrate the internal variability and multidimensional characteristics of the urban context under analysis.

4.1 Territorial Drivers in Four Neighbourhoods of Catania

The variables that characterise the six specific dimensions of energy vulnerability have been identified in the four districts. Table 1 shows the values of all the considered variables. Table 2 shows the normalised values of IDISE score.

Table 1. The territorial drivers' indicators in four neighbourhoods of Catania (our elaboration)

Category	Indicator	Unit	Angeli Custodi	Librino	Zia Lisa	Corso Italia
Socio-economic	IDISE Score	index	114.2	112.2	107.5	85
Socio-economic	No income households	%	52.7	45	35	8
Socio-economic	Low income households	%	75.8	70	60	20
Socio-economic	Low education	%	76.5	79.1	65	40
Socio-economic	NEET 15-29	%	66.9	55	45	15
Building	Class F-G buildings	%	70	75	60	45
Building	Average EPH	kWh/m^2/y	200	220	180	120
Building	Building age	years	60	50	45	65
Building	Conservation (1–4)	score	3.5	4	2.5	1.5
Energy	Energy expenditure	% income	12	14	10	5
Energy	Heating efficiency	%	65	60	70	85
Energy	AC penetration	%	25	20	35	75
Climatic	HDD	degree-days	833	833	833	833
Climatic	CDD (estimated)	degree-days	900	950	920	850
Climatic	UHI intensity	°C	2.5	3.5	2.5	1.5
Climatic	Days T > 35 °C	days/year	95	110	100	85
Urban	Green space	m^2/capita	2	5	8	15

(*continued*)

Table 1. (*continued*)

Category	Indicator	Unit	Angeli Custodi	Librino	Zia Lisa	Corso Italia
Urban	Building density	m^3/m^2	4.5	3.8	2.5	3.2
Institutional	Energy programmes	count	1	2	1	3
Institutional	Social bonus uptake	%	35	40	30	5

Table 2. The normalised indicators for the territorial drivers in four neighbourhoods of Catania (our elaboration)

Category	Indicator	Unit	Angeli Custodi	Librino	Zia Lisa	Corso Italia
Socio-economic	IDISE Score	index	1	0.93	0.77	0
Socio-economic	No income households	%	1	0.83	0.6	0
Socio-economic	Low income households	%	1	0.9	0.72	0
Socio-economic	Low education	%	0.93	1	0.64	0
Socio-economic	NEET 15-29	%	1	0.77	0.58	0
Building	Class F-G buildings	%	0.83	1	0.5	0
Building	Average EPH	$kWh/m^2/y$	0.8	1	0.6	0
Building	Building age	years	0.75	0.25	0	1
Building	Conservation (1–4)	score	0.8	1	0.4	0
Energy	Energy expenditure	% income	0.78	1	0.56	0
Energy	Heating efficiency	%	0.8	1	0.6	0
Energy	AC penetration	%	0.91	1	0.73	0
Climatic	HDD	degree-days	0.5	0.5	0.5	0.5
Climatic	CDD (estimated)	degree-days	0.5	1	0.7	0
Climatic	UHI intensity	°C	0.5	1	0.5	0
Climatic	Days T > 35 °C	days/year	0.4	1	0.6	0

(*continued*)

Table 2. (*continued*)

Category	Indicator	Unit	Angeli Custodi	Librino	Zia Lisa	Corso Italia
Urban	Green space	m^2/capita	1	0.77	0.54	0
Urban	Building density	m^3/m^2	1	0.65	0	0.35
Institutional	Energy programmes	count	1	0.5	1	0
Institutional	Social bonus uptake	%	0.86	1	0.71	0

4.2 Composite Index Values

The estimation of the composite energy poverty vulnerability index is based on the weighting system that was identified and described in the "Methods" section.

The application of the framework to four representative urban areas in Catania reveals substantial intra-urban disparities. Table 3 presents the composite index values. Librino exhibits the highest vulnerability ($I_{uep} = 0{,}74$), classified as critical, followed by Angeli Custodi/San Cristoforo ($I_{uep} = 0{,}69$). In contrast, Corso Italia shows low vulnerability ($I_{uep} = 0{,}04$). The difference between the most and least vulnerable neighbourhoods is 0.70 on a 0–1 scale, indicating extremely pronounced intra-urban disparities.

Table 3. Composite Index Values (our elaboration)

	Angeli Custodi	Librino	Zia Lisa	Corso Italia
Iuep	0,69	0,74	0,48	0,04

4.3 Vulnerability Thresholds

The quartile thresholds derived from the distribution of Iuep values are: Q1 = 0,37, Q2 = 0,59, Q3 = 0,71. These thresholds define four vulnerability classes: Low (0,04–0,37), Medium (0,37–0,59), High (0,59–0,71), Critical (0,71 –0,74).

A schematic spatial representation of local vulnerability to energy poverty was produced using the four vulnerability classes derived from the empirical distribution of the composite index values. Figure 5 presents the composite index values ordered by decreasing vulnerability, classification is based on quartile thresholds, ensuring a fully data-driven and non-arbitrary definition of vulnerability levels. The classification into four vulnerability thresholds is as follows: Librino in the critical vulnerability category, Angeli Custodi in the high category, Zia Lisa in the medium category and Corso Italia in the low category.

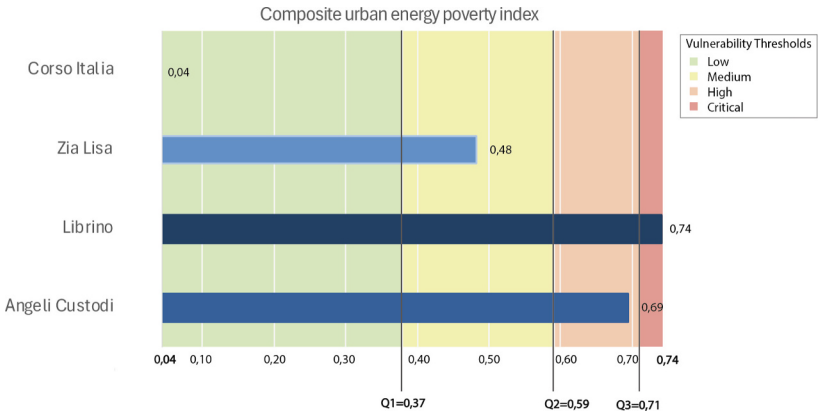


Fig. 5. Composite urban energy poverty index values with vulnerability classification thresholds. (our elaboration).

4.4 Spatial Distribution

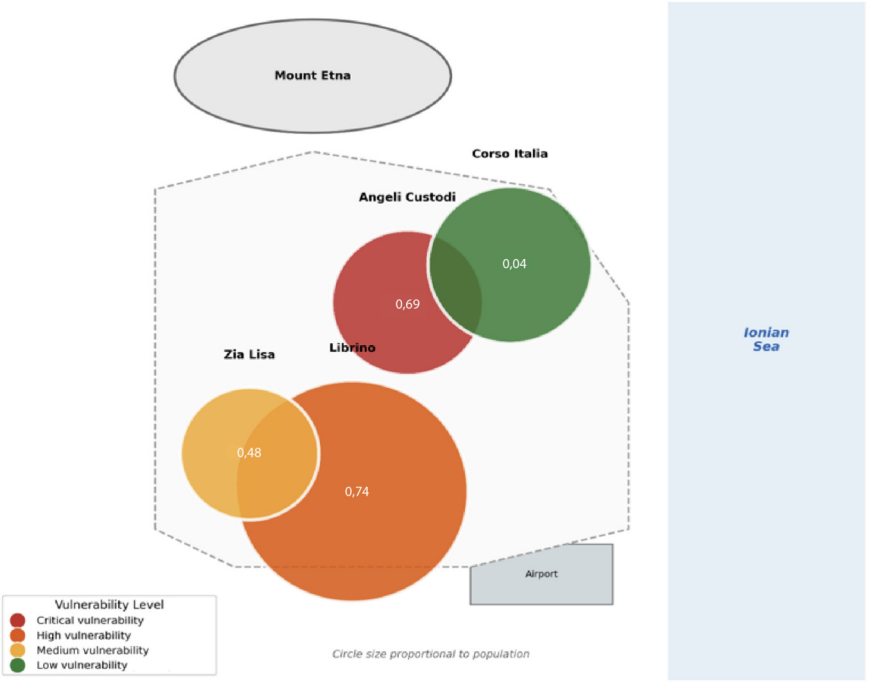


Fig. 6. Schematic spatial representation of energy poverty vulnerability in Catania. Circle size proportional to population; colour indicates vulnerability level.

Figure 6 presents the spatial distribution of vulnerability. A clear geographical pattern emerges critical vulnerability concentrates in the south-western periphery (Librino) and

degraded historic centre (Angeli Custodi), while low vulnerability characterises eastern coastal areas (Corso Italia). This polarisation reflects historical development patterns, with social housing isolated from central services. Circle size represents population, while colour encodes the vulnerability class.

4.5 Driver Decomposition Analysis

Figure 7 shows the value for each driver of local vulnerability and presents the decomposition of composite indices into weighted driver contributions. In Angeli Custodi, there is the highest value of the socio-economic driver.

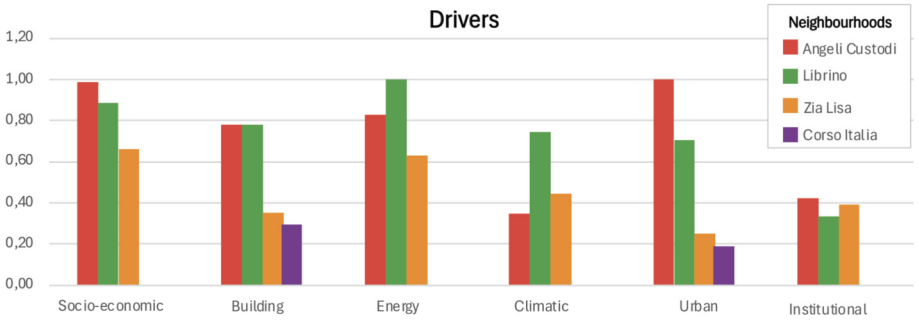


Fig. 7. Decomposition of composite index by weighted driver contribution.

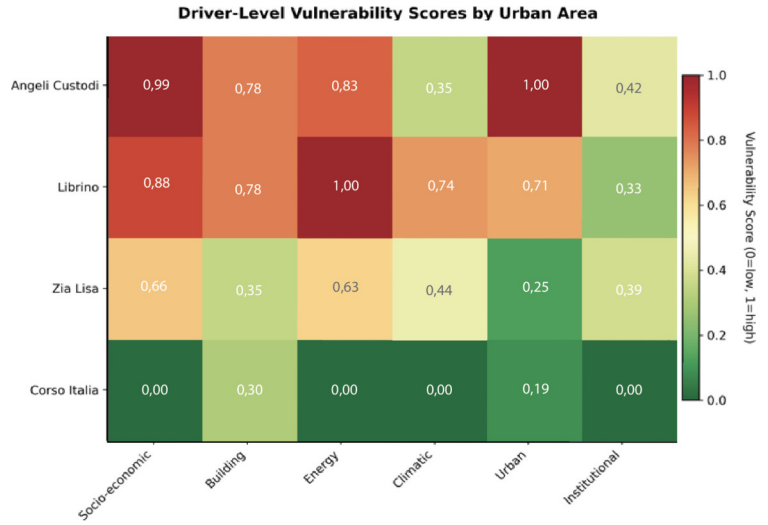


Fig. 8. Heatmap of driver-level vulnerability scores. Values range from 0 (green) to 1 (red).

In Librino and Angeli Custodi, there is the highest value of the building driver. Librino presents also the highest value of the energy driver. Corso Italia has the highest value in the building driver. The heatmap in Fig. 8 visualises raw driver scores, enabling rapid identification of critical hotspots.

4.6 Sensitivity Analysis

To assess the robustness of the index, a sensitivity analysis was performed by testing alternative weighting scenarios. Table 5 shows the baseline scenario that uses entropy-based weights. In Scenario A, the weight of the IDISE index score increased by 10%, while the remaining weights were kept unchanged (Table 6). In Scenario B the weight of the CDD index score was increased by 10% (Table 7). In Scenario C the weight of the green space score was increased by 10% (table 9). The results confirmed the stability of the index and the consistency of neighbourhood rankings across scenarios (Table 7).

Table 5. Baseline scenario (our elaboration)

	Socio-economic	Building	Energy	Climatic	Urban	Institutional
Angeli Custodi	0,99	0,78	0,83	0,35	1,00	0,42
Librino	0,88	0,78	1,00	0,74	0,71	0,33
Zia Lisa	0,66	0,35	0,63	0,44	0,25	0,39
Corso Italia	0,00	0,30	0,00	0,00	0,19	0,00

Table 6. Scenario A, weight of the IDISE index score increased by 10% (our elaboration)

	Socio-economic	**Building**	**Energy**	**Climatic**	**Urban**	**Institutional**
Angeli Custodi	0,99	0,78	0,83	0,35	1,00	0,42
Librino	0,88	0,78	1,00	0,74	0,71	0,33
Zia Lisa	0,66	0,35	0,63	0,44	0,25	0,39
Corso Italia	0,00	0,30	0,00	0,00	0,19	0,00

Table 7. Scenario B, weight of the CDD index score increased by 10% (our elaboration)

	Socio-economic	**Building**	**Energy**	**Climatic**	**Urban**	**Institutional**
Angeli Custodi	1,01	0,78	0,83	0,35	1,00	0,42
Librino	0,90	0,78	1,00	0,74	0,71	0,33
Zia Lisa	0,68	0,35	0,63	0,44	0,25	0,39
Corso Italia	0,00	0,30	0,00	0,00	0,19	0,00

Scenario A

Table 8. Scenario C, weight of the Green Space index score increased by 10% (our elaboration)

	Socio-economic	Building	Energy	Climatic	Urban	Institutional
Angeli Custodi	0,99	0,78	0,83	0,36	1,00	0,42
Librino	0,88	0,78	1,00	0,77	0,71	0,33
Zia Lisa	0,66	0,35	0,63	0,46	0,25	0,39
Corso Italia	0,00	0,30	0,00	0,00	0,19	0,00
				Scenario B		

5 Discussion

5.1 Intra-urban Disparities and the Limits of Aggregate Statistics

The results provide compelling evidence that energy poverty in Mediterranean cities is characterised by profound intra-urban disparities invisible in aggregate statistics. The composite index differential between Librino (0,74) and Corso Italia (0,04) exceeds 100%, revealing spatial inequality within a single municipality that rivals disparities typically observed between European countries. This corroborates research highlighting spatial heterogeneity of energy poverty [14, 26] while providing quantitative evidence of urban-scale disparity magnitude. The ISTAT IDISE data confirm the socio-economic dimension: Angeli Custodi records 114.2 versus 85.0 for Corso Italia a 34% differential. Our composite framework demonstrates that incorporating building, energy, climatic, urban and institutional dimensions amplify these disparities, as vulnerable populations concentrate in areas with multiple overlapping risk factors. This aligns with environmental justice literature emphasising cumulative and intersectional urban vulnerabilities [27, 28].

5.2 Building Stock as Primary Driver

The decomposition analysis reveals that the 'building driver' factor is highest in disadvantaged areas, indicating that it contributes to vulnerability in these areas (Librino 0,78; Angeli Custodi 0,78). These carries significant policy implications, as building-related vulnerability is amenable to intervention through retrofitting. SIAPE data indicate 52.1% of Catania's stock in classes F-G, with average consumption exceeding 166 kWh/m^2/year. In Librino, buildings consist predominantly of 1970s social housing (IACP/ATER) with estimated consumption exceeding 220 kWh/m^2/year, constructed before energy efficiency requirements, featuring uninsulated concrete walls, single-glazed windows and centralised heating with no cooling provision. The PNRR-funded 'Librino Città Moderna' project (€10 million) represents a positive development, though existing stock requiring renovation vastly exceeds current investment. These findings corroborate research demonstrating that fiscal incentives (Superbonus 110%) disproportionately benefited higher-income households capable of advancing costs, while energy-poor households in social housing were largely excluded [29, 30]. This regressive outcome underscores the need for targeted programmes directly addressing vulnerable housing without requiring upfront resident investment.

5.3 Summer Thermal Stress: The Mediterranean Gap

The climatic driver reveals a distinctive pattern in Mediterranean cities. Although summer heat stress is severe across the entire municipality, characterised by recurrent heatwaves exceeding 45 °C, more than 110 days per year with perceived temperatures above 35 °C, and CDD values between 850 and 950, the indicator displays substantial intra-urban variability. Climatic scores range from 0,74 in Librino to 0,00 in Corso Italia, reflecting marked differences in urban heat island intensity, built-form density, surface materials and ventilation conditions. Urban heat island effects compound these conditions, with + 3–4 °C differentials in Librino. These conditions have documented health impacts: recent research estimates significant excess heat-related mortality in comparable contexts [31]. These results indicate that thermal exposure is not spatially uniform: disadvantaged neighbourhoods experience significantly higher microclimatic stress than affluent coastal areas. Despite this variability, the climatic driver contributes less to the composite index than socio-economic or building-related factors. This is not due to low climatic relevance, but to the relative magnitude of inequalities: socio-economic deprivation and building obsolescence exhibit even stronger spatial contrasts, thus receiving higher entropy-based weights. The climatic driver therefore captures a widespread environmental stressor that amplifies vulnerability where adaptive capacity is limited but does not dominate the multidimensional profile. The results highlight that Mediterranean energy vulnerability emerges from the interaction between severe climatic exposure and unequal adaptive capacity, rather than from climatic conditions alone. By incorporating a cooling-related climatic indicator, the framework addresses a well-documented gap in European monitoring systems, which remains centred on winter heating. This inclusion provides a more complete representation of thermal vulnerability in cooling-stressed contexts and strengthens the capacity of the index to reflect the specific challenges faced by Mediterranean cities [15, 22]. The territorial weighting system further departs from equal-weight assumptions, recognising that driver importance varies across contexts [32].

5.4 Policy Implications

The institutional driver is highest in Angeli Custodi, indicating that the area is already targeted by public interventions; however, the persistence of high vulnerability across all other drivers suggests that current strategies may not be sufficient to address structural conditions. Interventions must combine retrofitting with social support: energy poverty advisory services, enhanced social bonuses and integration with urban regeneration under ‘Decreto Caivano’ The sharp contrast in the energy driver between Librino and Corso Italia reflects differences in building efficiency, access to modern heating and cooling systems, and the relative weight of energy expenditure on household income. High absolute energy spending in affluent areas does not translate into vulnerability when it represents a small share of disposable income. These patterns are consistent with the higher building and urban vulnerability observed in the most deprived neighbourhoods, highlighting the need for targeted renovation and urban adaptation policies. Several limitations should be acknowledged: (i) IDISE data refer to 2021; (ii) climatic indicators are modelled estimates; (iii) single case study limits generalizability. Future research

should address these through finer spatial scales, temporal dynamics and linkage with consumption data.

5.5 Sensitivity Analyses

The sensitivity analysis confirms the robustness of the composite index under moderate perturbations of key drivers. Across all scenarios, the relative ranking of neighbourhoods remains unchanged, with Librino consistently showing the highest vulnerability, followed by Angeli Custodi, Zia Lisa and Corso Italia. This stability indicates that the multidimensional structure of the index is not driven by single-driver fluctuations but by persistent structural differences across neighbourhoods. Scenario A, which increases the socio-economic indicator (IDISE) by 10%, produces only marginal variations (+0.02 in Angeli Custodi and Librino; +0.02 in Zia Lisa), confirming that socio-economic deprivation is already a dominant component of vulnerability. The limited numerical change reflects the fact that these neighbourhoods already score very high in the baseline scenario (0.66–0.99), leaving little room for further escalation.Scenario B, which increases the climatic indicator (CDD) by 10%, generates slightly larger variations, particularly in Librino (from 0.74 to 0.77) and Zia Lisa (0.44 to 0.46). This confirms that climatic exposure is an amplifying factor: it increases the magnitude of vulnerability in already disadvantaged areas but does not alter their relative position. Corso Italia remains unaffected, reflecting its higher adaptive capacity. Scenario C, which increases green space by 10%, produces small reductions in the urban driver (e.g., Angeli Custodi from 1.00 to 0.86; Librino from 0.71 to 0.60), but again without modifying the overall ranking. This suggests that improvements in environmental quality can mitigate vulnerability. Overall, the sensitivity analysis demonstrates that the index is structurally stable. The scenarios intensify or alleviate vulnerability but do not determine the spatial hierarchy.

6 Conclusions

This study has proposed and applied a multidimensional composite index for urban energy vulnerability assessment. The Catania case demonstrates that integrating six drivers at high spatial resolution reveals substantial intra-urban disparities that remain hidden in conventional indicators. The methodological contributions are threefold: (i) the integration of high-resolution local data enabling neighbourhood-scale analysis; (ii) the use of entropy-based weighting to reflect context-specific variability; and (iii) the explicit incorporation of summer thermal stress, addressing a persistent Mediterranean gap in existing monitoring frameworks. These innovations provide a flexible and transferable approach for assessing energy vulnerability in diverse urban contexts. By identifying the dominant drivers in each neighbourhood, the framework supports the design of targeted interventions that address the structural and environmental mechanisms shaping vulnerability. As European cities face the dual challenge of decarbonisation and climate adaptation, spatially explicit and climate-sensitive tools such as the one proposed are essential to ensure that the energy transition reduces, rather than reinforces, existing urban inequalities.

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