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Spatial analysis of energy communities and energy vulnerabilities in Spain

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ABSTRACT

Energy communities are increasingly recognized for promoting citizen-led transitions toward a just energy system. This paper provides an empirical study examining the distribution of collective action initiatives (CAIs) within Spain's energy transition, focusing on their alignment with local energy generation configurations and energy vulnerability, reflected in socio-economic conditions at the municipal level. This study uses spatial and statistical analyses to assess CAI distribution with a minimal set of socio-economic indicators characterizing basic dimensions of energy vulnerability and its standardized index, as well as energy assets across Spanish municipalities. Results show modest correlations between CAIs and indicators such as income levels and measures of income distribution. However, no significant link is found with income inequality, as measured by the Gini index, when considering high and low-population municipalities separately. Spatial clustering analysis with Local Moran's I reveals a low yet significant association between mean household income and low-capacity PV installations in neighboring areas, suggesting localized economic factors may influence renewable adoption patterns. The study also investigates CAIs' limited impact on addressing gender disparities within the energy sector, finding weak correlations with gender-balanced participation. These findings underscore the strengths and limitations of CAIs in supporting community resilience while highlighting their current insufficiency in addressing broader socio-economic inequalities. Furthermore, this paper discusses the results within a framework for preliminary CAI mapping within energy vulnerability contexts, offering insights for analytically-guided municipalities selection for in-depth, mixed-method exploration of community-led energy initiatives.

1. Introduction

European nations are witnessing a significant increase in self-consumption energy systems, particularly photovoltaic (PV) installations, propelled by supportive policies, declining renewable energy costs, and rising electricity prices (Dasí-Crespo et al., 2023; Banerjee, 2022; Ahmadiahangar et al., 2022; D'Adamo, 2018). The "Clean Energy for All Europeans" package (European Commission, 2017) promotes energy communities (ECs) in municipalities tools to tackle energy poverty ("REPowerEU Plan," 2022), seen as fostering citizen participation and ensuring equitable distribution of renewable energy costs and benefits, particularly for disadvantaged groups enabling just energy transition (Standal et al., 2023; van Bommel and Höffken, 2021; Hewitt et al., 2019).

Energy poverty and vulnerability, primarily caused by structural inequalities in income and access to energy, pose a substantial challenge to just energy transition (Bouzarovski and Simcock, 2017). In short, energy poverty is seen as an imbalance between household incomes and energy expenses, driven by energy prices and housing energy efficiency (European Commission, 2020). The concept of "vulnerability" is multifaceted, appearing across various research contexts such as food security, natural hazards, disaster risk management, public health, and climate change (Füssel and Klein, 2006). Within disaster research, vulnerability is defined as "the characteristics and circumstances of a community, system, or asset that make it susceptible to the damaging effects of a hazard" (UNDRR, 2007).

In the context of energy, vulnerability reflects the risk of inadequate access to essential energy services, which is exacerbated by income disparities and high energy costs (Bouzarovski et al., 2014). Systematic reviews emphasize the just energy transition framework, which advocates fairness in distributing benefits, costs, and decision-making power within energy systems (Standal et al., 2023; van Bommel and Höffken, 2021). The concept of *energy poverty,* also referred to as *fuel poverty* or *domestic energy deprivation* (Bouzarovski and Simcock, 2017), is often framed within the energy justice three-tenet domain framework: distributive, procedural, and recognitional justice (Sovacool and

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Dworkin, 2015), as a particular form of *injustice* and *inequality* (Heffron, 2022; Sovacool, 2014; Walker et al., 2010).

Within the specific context of energy poverty and vulnerability, global reviews have covered the challenges of effective mapping and the application of appropriate indicators (Al Kez et al., 2024; Volodzkiene and Streimikiene, 2023; Siksnelyte-Butkiene et al., 2021; Gatto and Busato, 2020; Gouveia et al., 2019; Romero et al., 2018). The studies highlight the importance of multidimensional, context-sensitive indicators and mapping with simplicity and policy relevance (Gatto and Busato, 2020; Gouveia et al., 2019; Romero et al., 2018), spanning the perspective across Europe (Johansson et al., 2022; Barrella et al., 2022; Gómez-Navarro et al., 2021; Sareen et al., 2020; Bosch and Schmidt, 2020; Lacey-Barnacle, 2020), and the Global South (Tikadar and Swami, 2025; Al Kez et al., 2024; Majumder et al., 2023; Nederhand et al., 2023; Pérez-Fargallo et al., 2023; Avila et al., 2022).

1.1. *State-of-the-art: framing energy community emergence factors and spatial mapping of vulnerabilities*

Empirical spatial studies across Europe link the emergence of citizen renewable energy initiatives to improved regional quality of life (Berka and Creamer, 2018; Lode et al., 2022a). National and regional studies in Central Europe highlight institutional relatedness as a key factor supporting the establishment of energy communities (Punt et al., 2022), alongside bridging and bonding social capital, with the latter playing a stronger role in advancing renewable energy at the sub-regional level (Geskus et al., 2024). These dynamics are framed within broader research on policy, regulatory, and financial drivers of community energy growth (López et al., 2024; Krug et al., 2023).

Energy community members are driven by diverse motivations, often emphasizing direct participation, inclusivity, and social values, unlike traditional top-down energy market actors (Dudka et al., 2023; Wittmayer et al., 2021). However, studies acknowledge that shareholders do not always act altruistically (Radtke and Ohlhorst, 2021; Bauwens, 2016). Members of larger, well-established energy communities may prioritize financial benefits, while those in smaller, newer communities may often focus on social issues over economic returns (Dudka et al., 2023; Bauwens et al., 2022). Research highlights economic benefits, particularly from PV installations (Cutore et al., 2023; Gajdzik et al., 2024; Wierling et al., 2021). Additionally, qualitative studies explore factors influencing the emergence, deployment, and growth of energy communities (Lode et al., 2022b; Standal et al., 2023) while also revealing controversies such as reported limitations in diversity and inclusivity within membership structures and socio-economic backgrounds (Radtke and Bohn, 2023).

Another research perspective also considers geographical inequalities in resource distribution, mapping and comparing local contexts and examining their impact on and interaction with policy and governance, as reflected in theoretical studies (Garvey et al., 2022; Bouzarovski and Simcock, 2017; Sovacool and Dworkin, 2015). Spatial analysis of these inequalities (often framed as injustices) focuses on factors such as the evenness, concentration, and centralization of energy generation systems (Perez-Sindin et al., 2022) or energy poverty, using composite indices for space heating and cooling (Gouveia et al., 2019). Approaches to addressing social vulnerability (Cutter et al., 2003) also seek to identify social, economic, and political drivers of environmental risks. Recent reviews (Painter et al., 2024) highlight the growing application of social vulnerability indices, which increasingly rely on quantitative and spatial methods with secondary or tertiary data to inform adaptation strategies addressing uneven vulnerabilities. The global to local scale of analysis determines the choice of spatial units and data, shaping the understanding of energy access, quality, and contextualized energy use issues (Hanke and Guyet, 2023; Sareen et al., 2020).

An expanding field of research explores the just energy transition and the emergence of energy communities. However, a recent review (Lode et al., 2022c) highlights that energy communities develop at different speeds and scales, often remaining fragmented, while factors such as the geographical dimensions of the transition remain underexplored. In this context, the present study contributes by employing a combination of methodological approaches to examine the geographic distribution of CAIs, local energy vulnerability conditions, and existing energy infrastructure. The central research question is: “In what socio-economic contexts linked to energy vulnerability are CAIs distributed at the sub-regional level, and does this vary by type and scale of energy infrastructure?”. The study pursues three objectives: (1) allocate and map CAIs from knowledge inventories and local energy infrastructure configurations; (2) conduct evidence-based spatial analysis connecting socio-economic and energy vulnerability-related indicators with CAIs’ local energy configurations in Spain (3) apply parallel statistical normalization and standardization methods to compare and interpret energy vulnerability context across mapped units of Spanish municipalities. This study adopts a theoretical lens informed by research on community energy initiatives mapping (Lode et al., 2022a), the role of renewable energy infrastructure in shaping CAIs (Sovacool et al., 2022), and the link between individual and regional-level inequalities (Martin, 2005). Together, these elements serve as an analytical perspective to examine CAI distribution in (i) areas with marked income disparity, (ii) specific energy vulnerability, and (iii) renewable or fossil energy capacity patterns.

The article is structured as follows: Section 2 outlines the methodology, terminology, data inventory, and methods. Section 3 describes the data and indicators for the case study, covering energy installations, energy vulnerability, and CAI distribution. Section 4 presents results on the distribution of citizen-led initiatives across Spanish municipalities and associative analyzes of energy production, socio-economic indicators, and contextualized energy vulnerability index in municipalities with energy communities. Section 5 discusses the spatial distribution and specific socio-economic context of identified CAIs in potentially high-vulnerability areas, highlighting prospects for in-depth studies on support measures and energy vulnerability factors at the municipal level. Finally, Section 6 provides conclusions.

2. Materials and methods

The methodology framework is based on a combined approach to measuring the uneven distribution of energy infrastructure commonly used within residential studies (Rodriguez-Moral and Vorsatz, 2016), electricity energy generation configurations, and socio-economic indicators for contextualizing energy vulnerability.

This work organizes the methodology into three principal stages (Fig. 1). The first corresponds to the gathering and interpreting of spatial and statistical data on the aggregation level of local administrative units (LAU). In the second stage, the retrieved data are preprocessed, approaching spatial allocation, codification, and mapping, which serves as a baseline for the explorative analysis. The third consists of exploring the relationships between CAIs and the following: (i) energy generation configurations, (ii) socio-economic indicators, (iii) a calculated social vulnerability index, and (iv) spatial correlation analysis using Local Moran’s I (Anselin, 1996).

2.1. *Key terminology*

Citizen and community energy initiatives have evolved to encompass

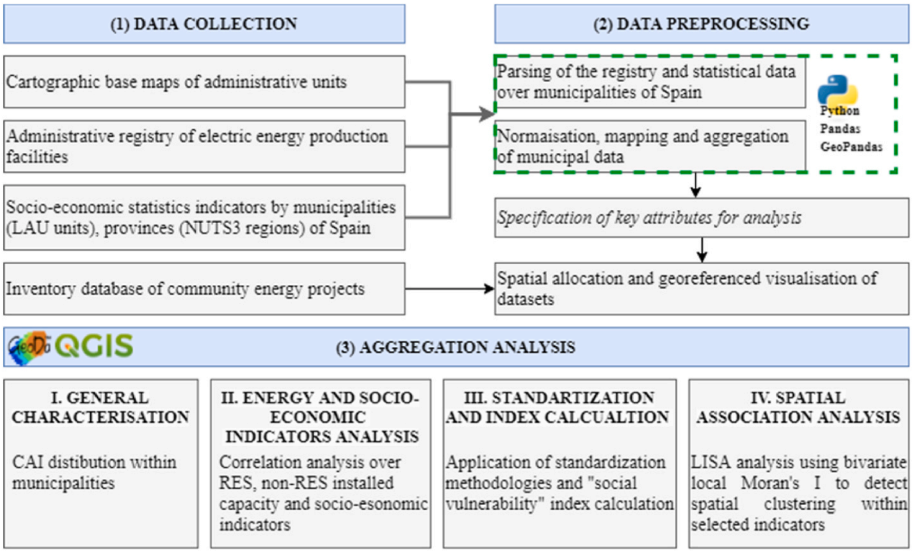

Fig. 1. Methodology framework: Principal steps.

diverse renewable projects beyond installations (Walker and Devine-Wright, 2008). *Collective Action Initiatives* (CAIs) broadly represent citizen-driven efforts supporting energy transitions across social, economic, and environmental dimensions, with energy communities as a key European CAI form (Lupi et al., 2021). The European Commission defines *Energy Communities* (ECs) as collective energy actions centered on democratic participation and local benefits" (Uihlein and Caramizaru, 2020), while others define them as associations of actors focused on participatory energy transformation seeking collective outcomes (Blasch et al., 2021). REScoop emphasizes ECs' cooperative principles and non-commercial focus ("REScoop," 2021).

In this study, "collective action initiative" is utilized, broadly referring to the previous definition of CAI as primarily over-inclusive conceptualizations for citizen-driven activities, projects, and initiatives favoring energy transition. Standing together, "energy community" is a supplementary term following Blasch's definition without necessarily adhering to REScoop's cooperative distinctions.

2.2. Knowledge inventory

Within inventory studies (Wierling et al., 2018), systematically analyzed 2671 energy communities in four European countries, identifying key enablers and the impact of supportive schemes (Hewitt et al., 2019). highlighted five distinct structures of European community energy initiatives, including cooperatives, development trusts, and public-private partnerships. By 2021, ("REScoop" 2021) reported over 1900 energy cooperatives involving 1.25 million citizens, while the European Commission noted 3500 energy communities of various types (Koltunov et al., 2023). Analyzed nearly 4000 communities, emphasizing Germany, the Netherlands, Denmark, and the UK. Schwanitz et al. (2022) indicated varying dynamics and growth trends across countries (Fabbri and Gaspari, 2021; van Bommel and Höffken, 2021). noted equity issues, highlighting incomplete utilization of environmental justice principles and unequal policy benefits in European community energy initiatives. The current research contributes with further data analysis of a Europe-wide inventory of citizen-led energy action collected within 29 countries and holds 10,000 initiatives (Wierling et al., 2023a). The provided database is meant to cover the call of the research community for dataset-driven approaches and include an inventory of initiatives collected over four years by an international team (Wierling et al., 2023b).

2.3. Indicators normalization

Social vulnerability assessment has been a focal point in research, particularly through indices that examine social and environmental fragilities. Many studies have been dedicated to specific hazards like earthquakes, flooding, and landslides (Chen et al., 2013; de Loyola Hummell et al., 2016; Guillard-Gonçalves et al., 2015; Tavares et al., 2018), using spatial mapping and classification techniques. These studies typically utilize a robust set of indicators normalization, weighting, aggregation, and more advanced statistics techniques to map vulnerabilities within spatial units and understand vulnerability drivers over time (Frigerio et al., 2018; Santos et al., 2022). This study applies three simple standardization techniques to simplify statistical data mapping energy vulnerability. This choice addresses the need for methodological transparency and comparability to demonstrate and compare how different normalization approaches influence vulnerability mapping. The comparison of results facilitates the selection of municipalities in Spain that serve as the mapping units, as detailed in Section 3.2.

Municipalities are categorized by selected indicators (Appendix A) through the application of three fast-deploy data-scaling techniques:

(i) Z-score standardization (Eq. (A.1) highlights deviations from the mean, emphasizing extreme values that are useful in the vulnerability context to examine the spatiotemporal patterns (Bronfman et al., 2021; Fekete, 2019; Zhou et al., 2019).
(ii) Min-max normalization (Eq. A.2, A.3) rescales data to a 0–1 range for consistent interpretation, ideal for bounded data and a straightforward method used in many studies (Cutter et al., 2010; Tali et al., 2016; Žurovec et al., 2017; Kablan et al., 2017).
(iii) Maximum value normalization (Eq. A.4, A.5) calculates the ratio of each actual value to the maximum value of the variable (Koks et al., 2015; Chakraborty et al., 2005).

Two types of relationships (directionality) were considered: indicators that increase vulnerability (positive relationship) and those that

Table 1
Statistical indicators used to characterize energy vulnerability at the municipal level.

Indicators for analytical implication to the socio-economic aspect of energy vulnerability	Explanation	Relationship to SVI, positive (+)/negative (−)
1 *Characteristics of the general level of income and how (un)evenly income is distributed among a population*		
Gini index	Income (wealth) inequality measures the cumulative population proportion to income, with 0 as absolute equality and 1 as complete inequality (Druckman and Jackson, 2008)	+
Mean income per person	Simple income and population distribution measures considered within the literature	-
Mean income per household		-
2 *Characteristics of at-risk-of-poverty rate-related context of population*		
Population percentage with income per consumption unit below 60 % of the median [60 M indicator]	European criteria, EUROSTAT at-risk-of-poverty rate (Eurostat, 2021a)	+
3 *Characteristics of living environment*		
Percentage of households in dilapidated or energy-inefficient housing	Energy efficiency of the housing considered by energy poverty (European Commission, 2023)	+
4 *Characteristics of the population through age groups, education, and activity*		
Population (population density)		+
% vulnerable people by age groups 0–12 and 65+	Percentage of population aged under 12 and 65 years ("EPAH Handbooks," 2022)	+
Gender (% female)	Outlined vulnerability within gender and energy context (Bielig et al., 2022; Fraune, 2015)	+
(% male)		Not included
% people with higher education	("EPAH Handbooks," 2022)	-
% of unemployed	Indicator ("EPAH Handbooks," 2022) that includes unemployed and inactive (retired, studying, unable to work) people	+

decrease it (negative relationship). Finally, the Social Vulnerability Index (SVI) was calculated as the average of all indicators per municipality and classified into five *energy vulnerability categories* based on standard deviation, adapted from Cutter et al. (2003): *very low* (<−1.5 std. dev.), *low* (−1.5 to −0.5 std. dev.), *moderate* (−0.5 to 0.5 std. dev.), *high* (0.5–1.5 std. dev.), *very high* (>1.5 std. dev.).

3. Case study

3.1. Contextualization of energy vulnerability with socio-economic indicators

Spain's renewable energy development mirrors global trends, with sector liberalization beginning in 1997, followed by wind energy growth in the 1990s, and solar PV expansion in the mid-2000s (Montoya et al., 2014). Spanish energy cooperatives experienced two growth phases: an early push in the late 1800s in peripheral regions and a post-2010 resurgence with new cooperatives (Krug et al., 2023; Sciullo et al., 2022).

Research on Spain's energy cooperatives highlights sector resistance and regime shifts, with twelve primary cooperatives identified in 2018, and comparisons to Central Europe showing differing models (Capellán-Pérez et al., 2018; Romero-Rubio and de Andrés Díaz, 2015). Spain's leadership in renewable energy is clear from its high RES share in national production (Eléctrica, 2022). Regional factors like education and social cohesion have been linked to the growth of energy communities (Lode et al., 2022a). Low household income remains a key driver of energy poverty, measured by indicators like the "ten percent ratio" (Boardman, 1991) and other combinations (Siksnelyte-Butkiene et al., 2021), including LIHC (Hills, 2012) and MIS (Moore, 2012). Vulnerable areas are mapped using national statistics and energy databases, aiding efforts to address energy poverty (Romero et al., 2018; Sareen et al., 2020).

Spanish energy poverty mapping often relies on expenditure-based indicators (Gómez-Navarro et al., 2021; Martín-Consuegra et al., 2020), while other studies take a multidimensional approach by adding socio-economic and housing condition factors within local context (Capetillo-Ordaz et al., 2024; Modrego-Monforte et al., 2023; Terés-Zubiaga et al., 2023; Martín-Consuegra et al., 2020). Spain's Ministry of Transport maps urban vulnerability in larger cities using historical census data on education, unemployment, and housing quality (Atlas de la Vulnerabilidad Urbana 2001–2011).

The selection of relevant indicators, influenced by data availability and evolving priorities, is crucial but can introduce conceptual biases (Fekete, 2019). This study follows a heuristic approach, leveraging prior studies on indicators' directionality to vulnerability (Gayen et al., 2021; Santos et al., 2022). The EU Energy Poverty Advisory Hub provides a flexible framework with 56 indicators to support local assessments ("EPAH Handbooks," 2022). Table 1 summarizes the indicators used for energy vulnerability in this study.

3.2. Data collection

This section examines the administrative units used in the research, focusing on 8131 municipalities across 52 provinces within Spain's 17 *Autonomous Communities*[1], based on the LAU Classification (Eurostat, 2021b). These regions follow the NUTS-3 classification (European Parliament, 2003) and EUROSTAT's regional typology (Eurostat, 2019), categorizing them as: 'predominantly urban' (80 % of the population resides in urban clusters), 'intermediate' (urban cluster population ranges from 50 % to 80 %), or 'predominantly rural' (where at least half of the population lives in rural grid cells). Municipalities were the primary units of analysis, with geographic data obtained from the GISCO statistical units dataset (Eurostat, 2021c).

The data characterizing the municipal electricity energy generation landscape has been processed from the Spanish public administrative register of electric power production facilities, which contained on the moment of research 67,868 registered records as of December 31, 2023 (MITECO, 2023). The database on the inventory of initiatives described in (Wierling et al., 2023b) collected over four years provided information about the 251 CAIs in Spain as of 2021. The authors of the inventory database state that compared with the literature, about 80 % of the initiatives as of the end of 2021 are included in the database.

The INE (Spanish National Statistics Institute) provides socio-economic municipal-level data used in the research from the Household Income Distribution Atlas (INEbase, 2021). The Atlas of Urban Vulnerability in Spain 2001–2011 provides detailed socio-demographic, socio-economic, residential, and residents' survey-based subjective evaluation of vulnerability indicators (Atlas de la Vulnerabilidad Urbana 2001–2011). Despite its comprehensive information, a limitation is that some regions' last available data is from 2001. Therefore, an indicator

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[1] Spain is divided into a total of 17 autonomous communities, as established by the Spanish constitution of 1978, with a mechanism for the distribution of competences between these and the central government.

Table 2
Datasets for spatial analysis.

Data Description	Source
Spatial data and energy generation sites	
Administrative boundaries, area, and coding of municipalities	Governmental portal of basic topographic data (Geográfica, 2020)
Location of the electric energy generation installations by municipality	Administrative registry of electrical energy production facilities (MITECO, 2023), aggregated on the level of municipalities
Inventory database of collective action initiatives	ENBP All-European Inventory Database on CAIs (Wierling et al., 2023b)
Indicators for energy vulnerability mapping	
• Gini Index • Income: mean per person • Income: mean per household • % of population with income per consumption unit less than 60 % of the median (60 M indicator)	Household Income Distribution Atlas (INEbase, 2021) Instituto de Estadística de Navarra (Government of Navarra, 2021)
• Population (disaggregated by age groups) • % people with higher education • % education level less than lower secondary school (low education) • % of unemployed • Gender (% female, % male)	Population and Housing Census (INEbase, 2021)
% of households in dilapidated or energy-inefficient housing	("Atlas de la edificación residencial," 2011)

Table 3
Categorization of electrical energy production records in Spain.

Main Group	Subgroups and variable names
Photovoltaic	PV: Total capacity PV: Total Units PV: Capacity (>20 kW) PV: Capacity (<20 kW) PV: Units (<20 kW)
Hydro energy	Hydropower: Total Capacity (<10 MW)
Wind onshore	Wind onshore: Total capacity
Cogeneration Waste and Biofuel	Cogen, waste + bio: Total Capacity
Cogeneration fossil fuel	Cogen, fossil fuel: Total Capacity
Other power plants: Total Capacity	Other PP: Total Capacity

referring to residential characteristics was considered to integrate essential information. These indicators are readily accessible and easily integrated into GIS spatial analyses due to their transparent and compliant methodology. The datasets considered for the study are summarized in Table 2 and openly available as resulting joined tables used for analysis (Husiev et al., 2024).

3.3. *Data preprocessing and spatial interpretation*

The dataset preprocessing involved parsing open data using Python's *pandas* and *geopandas* libraries. Municipality names were standardized, and records of energy installations were codified using the INE (6-digit) and NAT (11-digit) codes. A total of 66,184 records with "defined" status were included in the registry of electrical energy production. These were categorized into five groups according to Royal Decree 413/2014 (Ministerio de Industria, 2014), as shown in Table 3. Photovoltaic generation, Spain's most prominent distributed renewable energy, was further analyzed by installation size (≤20 kW and >20 kW), capacity, and installations ≤20 kW. Generation types with few entries, like heat pumps, offshore wind, and solar thermal, were excluded for lack of representation.

The dataset of energy generation installations was processed for alignment with spatial data on administrative units, followed by data curation through pivoting. Spatially coded data was refined using *QGIS and GeoDa* for spatial context and a combination of Python and *Jamovi* for socio-economic context mapping. Data completeness varied across indicators based on official statistics availability. The Spanish CAI sample lacked details on parameters like year of emergence, installed capacity, and ownership. Still, in line with ENBP inventory research (Schwanitz et al., 2023), the study used CAI presence in specific geographic locations, including settlements and municipalities.

4. Results

4.1. *General context of CAI distribution*

This section examines CAI distribution across NUTS-3 regions and urban-rural categories. Spain's demographic trend, known as "empty Spain" (España vaciada), shows high population concentration in Madrid and coastal areas, impacting CAI distribution patterns (Appendix B). As shown in Fig. 2a, 72 % of CAIs are located in six of the

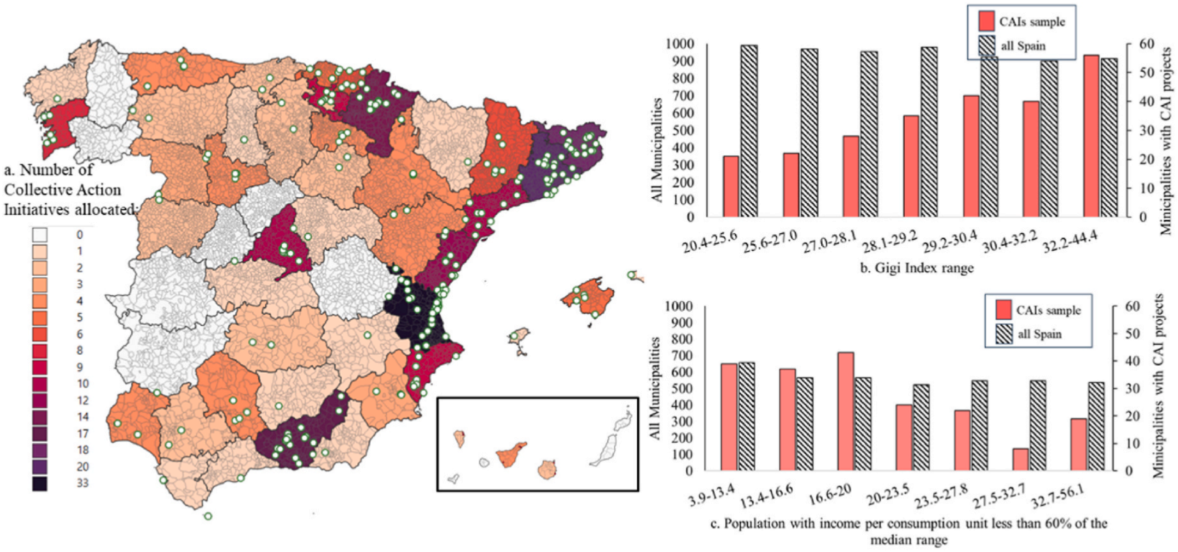
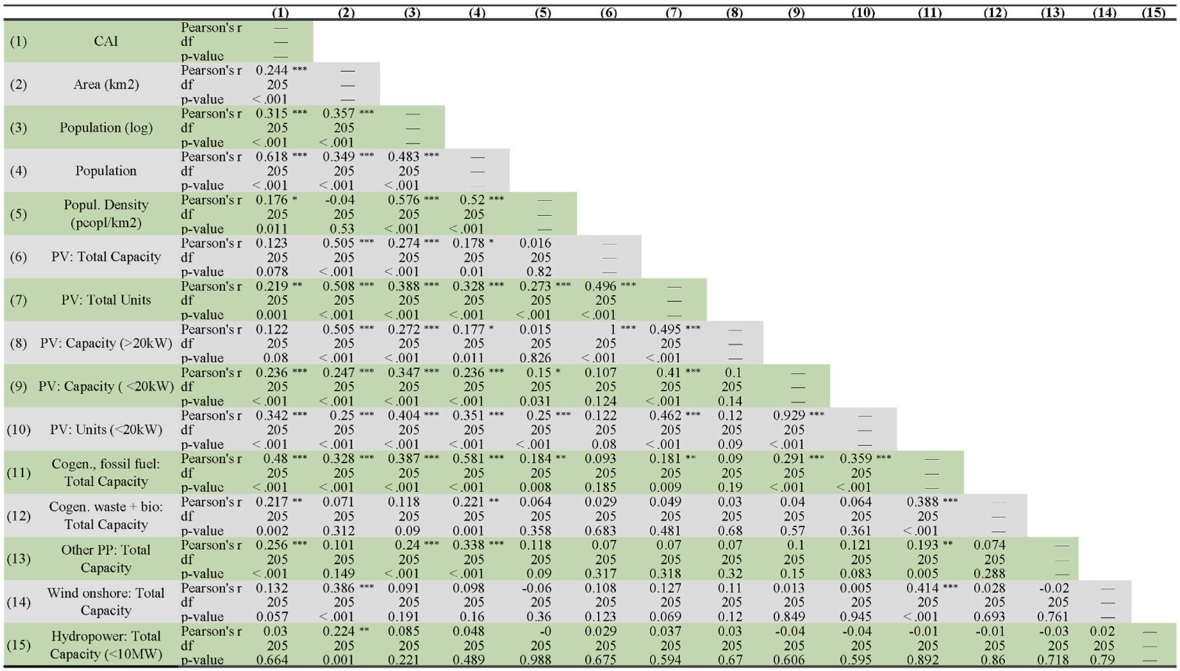


Fig. 2. Distribution of CAIs active in the energy sector in Spain (as of 2021, based on raw data from (Wierling et al., 2023a): (a) Map of allocated CAIs within provinces and municipalities, (b) Gini index, and (c) Population below 60% of the median income for all municipalities (left y-axis) and the sample with CAIs (right y-axis)



			(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
(1)	CAI	Pearson's r	—														
		df	—														
		p-value	—														
(2)	Area (km2)	Pearson's r	0.244 ***	—													
		df	205	—													
		p-value	< .001	—													
(3)	Population (log)	Pearson's r	0.315 ***	0.357 ***	—												
		df	205	205	—												
		p-value	< .001	< .001	—												
(4)	Population	Pearson's r	0.618 ***	0.349 ***	0.483 ***	—											
		df	205	205	205	—											
		p-value	< .001	< .001	< .001	—											
(5)	Popul. Density (peopl/km2)	Pearson's r	0.176 *	-0.04	0.576 ***	0.52 ***	—										
		df	205	205	205	205	—										
		p-value	0.011	0.53	< .001	< .001	—										
(6)	PV: Total Capacity	Pearson's r	0.123	0.505 ***	0.274 ***	0.178 *	0.016	—									
		df	205	205	205	205	205	—									
		p-value	0.078	< .001	< .001	0.01	0.82	—									
(7)	PV: Total Units	Pearson's r	0.219 **	0.508 ***	0.388 ***	0.328 ***	0.273 ***	0.496 ***	—								
		df	205	205	205	205	205	205	—								
		p-value	0.001	< .001	< .001	< .001	< .001	< .001	—								
(8)	PV: Capacity (>20kW)	Pearson's r	0.122	0.505 ***	0.272 ***	0.177 *	0.015	1 ***	0.495 ***	—							
		df	205	205	205	205	205	205	205	—							
		p-value	0.08	< .001	< .001	0.011	0.826	< .001	< .001	—							
(9)	PV: Capacity (<20kW)	Pearson's r	0.236 ***	0.247 ***	0.347 ***	0.236 ***	0.15 *	0.107	0.41 ***	0.1	—						
		df	205	205	205	205	205	205	205	205	—						
		p-value	< .001	< .001	< .001	< .001	0.031	0.124	< .001	0.14	—						
(10)	PV: Units (<20kW)	Pearson's r	0.342 ***	0.25 ***	0.404 ***	0.351 ***	0.25 ***	0.122	0.462 ***	0.12	0.929 ***	—					
		df	205	205	205	205	205	205	205	205	205	—					
		p-value	< .001	< .001	< .001	< .001	< .001	0.08	< .001	0.09	< .001	—					
(11)	Cogen., fossil fuel: Total Capacity	Pearson's r	0.48 ***	0.328 ***	0.387 ***	0.581 ***	0.184 **	0.093	0.181 **	0.09	0.291 ***	0.359 ***	—				
		df	205	205	205	205	205	205	205	205	205	205	—				
		p-value	< .001	< .001	< .001	< .001	0.008	0.185	0.009	0.19	< .001	< .001	—				
(12)	Cogen. waste + bio: Total Capacity	Pearson's r	0.217 **	0.071	0.118	0.221 **	0.064	0.029	0.049	0.03	0.04	0.064	0.388 ***	—			
		df	205	205	205	205	205	205	205	205	205	205	205	—			
		p-value	0.002	0.312	0.09	0.001	0.358	0.683	0.481	0.68	0.57	0.361	< .001	—			
(13)	Other PP: Total Capacity	Pearson's r	0.256 ***	0.101	0.24 ***	0.338 ***	0.118	0.07	0.07	0.07	0.1	0.121	0.193 **	0.074	—		
		df	205	205	205	205	205	205	205	205	205	205	205	205	—		
		p-value	< .001	0.149	< .001	< .001	0.09	0.317	0.318	0.32	0.15	0.083	0.005	0.288	—		
(14)	Wind onshore: Total Capacity	Pearson's r	0.132	0.386 ***	0.091	0.098	-0.06	0.108	0.127	0.11	0.013	0.005	0.414 ***	0.028	-0.02	—	
		df	205	205	205	205	205	205	205	205	205	205	205	205	205	—	
		p-value	0.057	< .001	0.191	0.16	0.36	0.123	0.069	0.12	0.849	0.945	< .001	0.693	0.761	—	
(15)	Hydropower: Total Capacity (<10MW)	Pearson's r	0.03	0.224 **	0.085	0.048	-0	0.029	0.037	0.03	-0.04	-0.04	-0.01	-0.01	-0.03	0.02	—
		df	205	205	205	205	205	205	205	205	205	205	205	205	205	205	—
		p-value	0.664	0.001	0.221	0.489	0.988	0.675	0.594	0.67	0.606	0.595	0.892	0.86	0.718	0.79	—

Note. * $p < .05$, ** $p < .01$, *** $p < .001$; *degrees of freedom (df) = sample size - 2*

Fig. 3. Correlation matrix for the sample of Spanish municipalities with CAIs with registered RES and non-RES installations.

19 autonomous communities: Valencia (54), Catalonia (54), Andalucía (31), Basque Country (20), Navarra (14), and Madrid (10), covering 206 of Spain's 8131 municipalities. Additionally, 15 CAIs are in the Canary Islands (8), Balearic Islands (7), and Ceuta (1). At the NUTS-3 level, provinces with the most CAIs include Valencia (33), Barcelona (20), Girona (18), Granada (17), and Navarra (14), with other significant presences in Madrid (10), Castellon (10), Tarragona (10), Alicante (9), Alava (9), Gipuzkoa (6), and Bizkaia (5).

The population density analysis reveals that most CAIs (51 %) are located in intermediate, close-to-city areas, with 42 % in urban regions, 5 % in rural (close to city) areas, and 2 % in remote rural areas. Notably, 76 % of CAIs are in municipalities with populations under 50,000 and 51 % in regions with fewer than 5000 residents, reflecting Spain's predominantly low-density population distribution (Appendix B).

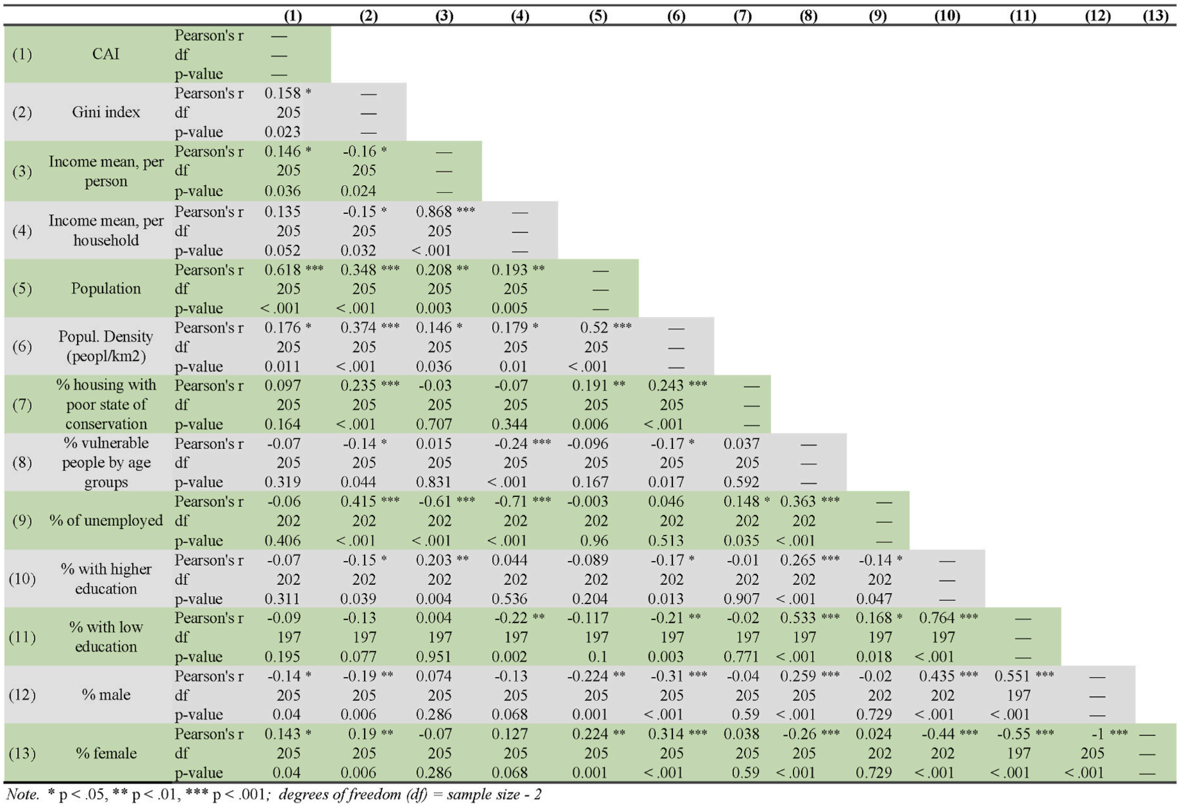
The Gini index analysis indicates that CAIs tend to be registered in municipalities with higher socio-economic inequality (Fig. 2b), with 54 % of CAIs found in areas where the Gini index ranges from 29.2 % to 44.4 %. A Welch's *t*-test confirmed a statistically significant difference in Gini index means between CAI-active municipalities and others ($p < 0.05$). Similarly, CAIs are more common in municipalities with a lower proportion of individuals earning below 60 % of the median income (Fig. 2c). However, the 60 M indicator's limited data coverage (available for 49 % of all municipalities and 77 % of those with CAIs) restricted further analysis and was not included in further steps for energy vulnerability categories mapping. Data availability for economic indicators varied, ranging from 82 % (Gini index, mean income per household) to 99 % (mean income per person); thus, missing values were estimated using linear regression to ensure a complete dataset for analysis. Spatial maps of socio-economic indicators and CAIs are included in Appendix C.

4.2. *Installed generation capacity at municipal scale*

The installed capacity of registered electricity generation sites was analyzed to understand the energy landscape around CAIs (Fig. 3). Population size was log-scaled to explore its relationship with CAIs, and Spearman's rho and Kendall's Tau B coefficients were used as supplementary non-parametric tests to highlight potential discrepancies in some cross-correlation results (Section 4.3). Maps of PV and onshore wind installations are provided in Appendix D.

The findings indicate that CAIs are more closely tied to local population dynamics and the presence of small-scale renewable and cogeneration energy systems rather than large-scale wind or hydropower installations. It is depicted in a significant positive linear relationship with population size (Pearson's $r = 0.618$, $p < 0.001$) and, to a lesser extent, with population density (Pearson's $r = 0.176$, $p = 0.011$) and the area of the municipality. The finding, however, relies on a stronger tendency for CAI to be founded in more populous municipalities (Geskus et al., 2024). Similarly, total PV units (Pearson's $r = 0.219$, $p = 0.001$) are positively correlated, indicating a situation when larger municipalities with more energy infrastructure are more likely to host CAIs.

Small-scale PV installations (<20 kW) show a stronger correlation with CAIs (Pearson's $r = 0.342$, $p < 0.001$) compared to total PV capacity (Pearson's $r = 0.123$, $p < 0.078$), highlighting the importance of distributed renewable energy systems in CAI development. Cogeneration using fossil fuels (Pearson's $r = 0.48$, $p < 0.001$) and waste/biofuel (Pearson's $r = 0.217$, $p = 0.002$) also correlate positively, reflecting CAI associations with existing energy infrastructure. Interestingly, onshore wind capacity (Pearson's $r = 0.132$, $p = 0.057$) has borderline, not significant, and small hydropower (<10 MW) capacity (Pearson's $r = 0.03$, $p = 0.664$) shows no significant correlation, suggesting these technologies are less influential in CAI emergence.



			(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
(1)	CAI	Pearson's r	—												
		df	—												
		p-value	—												
(2)	Gini index	Pearson's r	0.158 *	—											
		df	205	—											
		p-value	0.023	—											
(3)	Income mean, per person	Pearson's r	0.146 *	-0.16 *	—										
		df	205	205	—										
		p-value	0.036	0.024	—										
(4)	Income mean, per household	Pearson's r	0.135	-0.15 *	0.868 ***	—									
		df	205	205	205	—									
		p-value	0.052	0.032	< .001	—									
(5)	Population	Pearson's r	0.618 ***	0.348 ***	0.208 **	0.193 **	—								
		df	205	205	205	205	—								
		p-value	< .001	< .001	0.003	0.005	—								
(6)	Popul. Density (peopl/km2)	Pearson's r	0.176 *	0.374 ***	0.146 *	0.179 *	0.52 ***	—							
		df	205	205	205	205	205	—							
		p-value	0.011	< .001	0.036	0.01	< .001	—							
(7)	% housing with poor state of conservation	Pearson's r	0.097	0.235 ***	-0.03	-0.07	0.191 **	0.243 ***	—						
		df	205	205	205	205	205	205	—						
		p-value	0.164	< .001	0.707	0.344	0.006	< .001	—						
(8)	% vulnerable people by age groups	Pearson's r	-0.07	-0.14 *	0.015	-0.24 ***	-0.096	-0.17 *	0.037	—					
		df	205	205	205	205	205	205	205	—					
		p-value	0.319	0.044	0.831	< .001	0.167	0.017	0.592	—					
(9)	% of unemployed	Pearson's r	-0.06	0.415 ***	-0.61 ***	-0.71 ***	-0.003	0.046	0.148 *	0.363 ***	—				
		df	202	202	202	202	202	202	202	202	—				
		p-value	0.406	< .001	< .001	< .001	0.96	0.513	0.035	< .001	—				
(10)	% with higher education	Pearson's r	-0.07	-0.15 *	0.203 **	0.044	-0.089	-0.17 *	-0.01	0.265 ***	-0.14 *	—			
		df	202	202	202	202	202	202	202	202	202	—			
		p-value	0.311	0.039	0.004	0.536	0.204	0.013	0.907	< .001	0.047	—			
(11)	% with low education	Pearson's r	-0.09	-0.13	0.004	-0.22 **	-0.117	-0.21 **	-0.02	0.533 ***	0.168 *	0.764 ***	—		
		df	197	197	197	197	197	197	197	197	197	197	—		
		p-value	0.195	0.077	0.951	0.002	0.1	0.003	0.771	< .001	0.018	< .001	—		
(12)	% male	Pearson's r	-0.14 *	-0.19 **	0.074	-0.13	-0.224 **	-0.31 ***	-0.04	0.259 ***	-0.02	0.435 ***	0.551 ***	—	
		df	205	205	205	205	205	205	205	205	202	202	197	—	
		p-value	0.04	0.006	0.286	0.068	0.001	< .001	0.59	< .001	0.729	< .001	< .001	—	
(13)	% female	Pearson's r	0.143 *	0.19 **	-0.07	0.127	0.224 **	0.314 ***	0.038	-0.26 ***	0.024	-0.44 ***	-0.55 ***	-1 ***	—
		df	205	205	205	205	205	205	205	205	202	202	197	205	—
		p-value	0.04	0.006	0.286	0.068	0.001	< .001	0.59	< .001	0.729	< .001	< .001	< .001	—

Note. * p < .05, ** p < .01, *** p < .001; *degrees of freedom (df) = sample size - 2*

Fig. 4. Correlation matrix for the sample of Spanish municipalities with CAIs with socio-economic and selected energy vulnerability context indicators.

Table 4

Partial correlation table for municipalities with populations above 5000 and up to 5000 inhabitants in the CAI sample.

		>5000, N = 96	<5000, N = 111		>5000, N = 96	<5000, N = 111
		CAI			CAI	
Gini index	Pearson's r	0.133	0.089	**PV: Units (<20 kW)**	0.35***	0.018
	p-value	0.195	0.355		<0.001	0.852
Income: mean per household	Pearson's r	0.158	0.112	**Wind Capacity**	0.134	0.122
	p-value	0.125	0.241		0.194	0.202
Income: mean per person	Pearson's r	0.179	0.141	**Cogen, fossil fuel: Total Capacity**	0.498***	0.407***
	p-value	0.081	0.14		<0.001	<0.001
Popul. Density (people/km^2)	Pearson's r	0.137	−0.059	**Hydropower: Total Capacity (<10 MW)**	−0.058	0.178
	p-value	0.182	0.539		0.574	0.062
Population (log)	Pearson's r	0.439***	0.097	**Other PP: Total Capacity**	0.262**	–
	p-value	<0.001	0.313		0.01	–
PV: Capacity (<20 kW)	Pearson's r	0.224*	0.019	**Cogen, waste + bio: Total Capacity**	0.221*	–
	p-value	0.028	0.84		0.031	–
PV: Capacity (>20 kW)	Pearson's r	0.078	0.193*	**% vulnerable people by age groups**	0.074	−0.094
	p-value	0.451	0.042		0.473	0.326
%Male	Pearson's r	−0.323**	0.017	**% with higher education**	0.11	−0.048
	p-value	0.001	0.856		0.285	0.619
%Female	Pearson's r	0.323**	−0.017	**% with low education**	−0.077	−0.065
	p-value	0.001	0.856		0.454	0.516
%Unemployed	Pearson's r	−0.048	−0.145	**% energy-inefficient housing**	0.134	0.027
	p-value	0.64	0.135		0.194	0.779

Note. Reported significance * $p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

4.3. *Socio-economic indicators and partial correlation*

The analysis of socio-economic indicators related to energy vulnerability in municipalities with active CAIs is shown in the correlation matrix of Fig. 4. A weak but significant correlation exists between CAI presence and mean income per person (Pearson's r = 0.146, $p < 0.036$). The Gini index shows a borderline significance correlation, referring to earlier results from Section 4.1 suggesting CAIs in areas with higher Gini values. This finding indicates that although CAIs may form in economically unequal areas, there is no linear relationship between CAI presence and income inequality. We also find weak evidence of a positive correlation between registered CAIs and female indicators at the municipality (Pearson's r = 0.143, p = 0.04), as well as Spearman's rho = 0.169, Kendall's tau B = 0.136 (both p = 0.015), suggesting a small but consistent trend, linking to qualitatively explored a gender shift biases (Bielig et al., 2022), though not necessarily a strong linear relationship or one related to population age-sex distribution. In addition, as for the CAI indicator, Spearman's rho and Kendall's tau B showed low

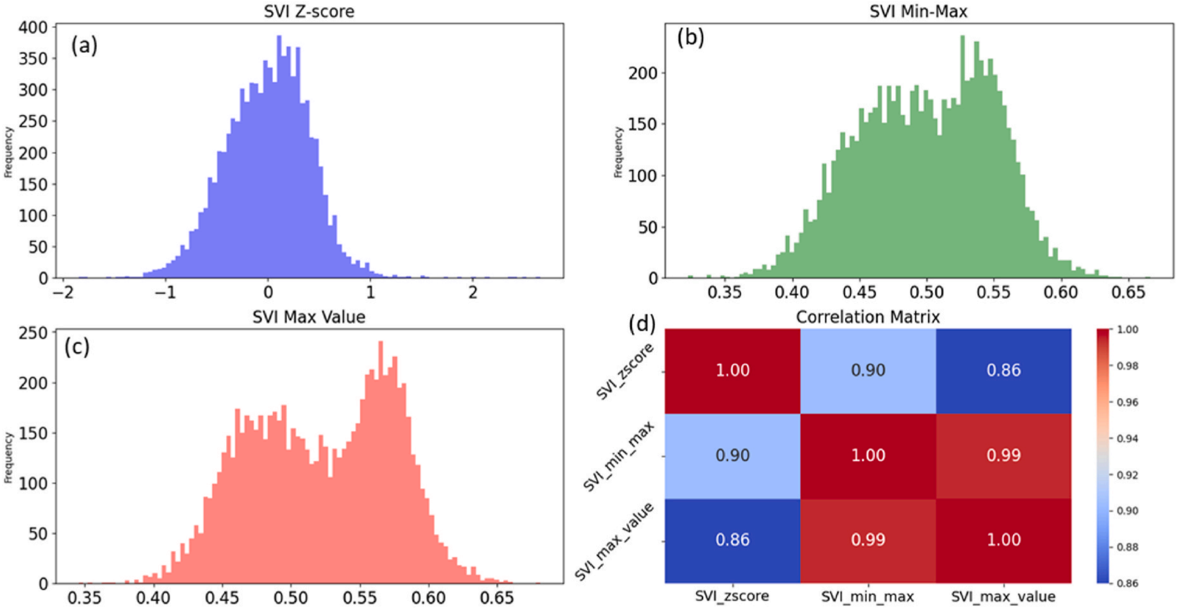


Fig. 5. Distribution of the calculated vulnerability index across Spanish municipalities using statistical simplification techniques: (a) z-score transformation, (b) min-max scaling, (c) max value normalization, and (d) Pearson's cross-correlation coefficient.

but significant correlations for indicators like housing in poor condition (Spearman's rho = 0.168, Kendall's tau B = 0.137, both p = 0.015), while Pearson's r did not show significance.

The partial correlation Table 4 shows that in municipalities with over 5000 people, there is a stronger positive correlation between CAI presence and female percentage (Pearson's r = 0.323, p = 0.001), favoring a link between gender distribution and CAIs instead in larger areas than low populated municipalities. Small-scale PV installations (<20 kW) also show a significant correlation with CAIs in high-population areas (Pearson's r = 0.224, p < 0.001), but this is negligible in low-population areas. The Gini index has no significant correlation with CAI presence in either group, suggesting income inequality is not a key factor. Both high and low-population areas show strong positive correlations between CAIs and fossil-fuel cogeneration capacity (Pearson's r = 0.498, p < 0.001 for high-population; Pearson's r = 0.407, p < 0.001 for low-population), indicating CAIs are linked to established cogeneration sites regardless of population, but more diverse cogeneration technologies for high-populated areas. Additionally, the low-population group of municipalities exhibits moderate correlations between CAIs and higher-capacity PV installations (>20 kW), suggesting a consistent association of CAIs within the context of rural RECs.

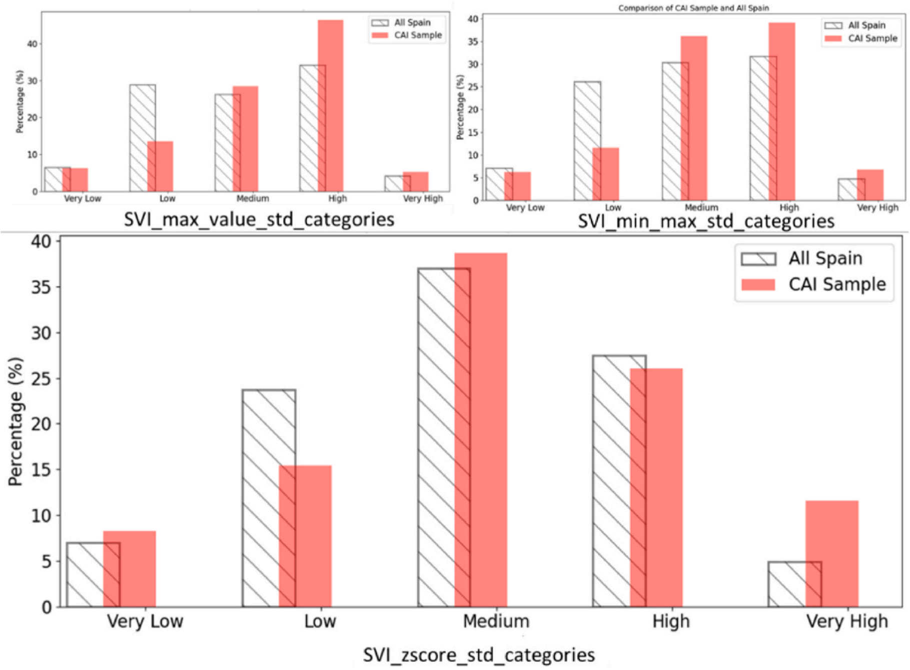


Fig. 6. Distribution of energy vulnerability categories from three standardization statistical simplification techniques for all of Spain and the CAI sample.

Table 5
Identified municipalities with categorized energy vulnerability as 'High' by three standardization statistical simplification techniques within the CAI sample.

Province	Municipality	Province	Municipality
Alacant/ Alicante	Albatera	**Madrid**	Perales de Tajuña
	Callosa de Segura	**Murcia**	Murcia
	Catral	**Asturias**	Oviedo
	Crevillent	**Pontevedra**	Vilagarcía de Arousa
Illes Balears	Deià	**Santa Cruz de Tenerife**	Adeje
	Palma		San Cristóbal de La Laguna
	ses Salines		San Andrés y Sauces
Barcelona	Terrassa	**Cantabria**	Reinosa
Castelló/ Castellón	Atzeneta del Maestrat	**Sevilla**	Isla Mayor
	Cabanes	**Tarragona**	L'Ametlla de Mar
	Castelló de la Plana		Godall
Ciudad Real	Abenójar		Rasquera
Córdoba	Castro del Río		Reus
	Córdoba		Tortosa
	Montilla	**València/ Valencia**	Alpuente
Girona	Girona		Camporrobles
Granada	Deifontes		Catarroja
	Escúzar		Chelva
	Monachil		Faura
	Peligros		Gandia
	Puebla de Don Fadrique		Meliana
	Ventas de Huelma		Ontinyent
Huelva	Arroyomolinos de León		Sagunt/Sagunto
León	Ponferrada	**Valladolid**	Valladolid
	Vega de Valcarce		

4.4. *Energy vulnerability categories across municipalities*

Analyzing the energy vulnerability categories across Spanish municipalities provides a nuanced view of its socio-economic context through various standardization methods (Fig. 5). Approximately 58 % of the municipalities are consistently characterized by similar vulnerability classifications, highlighting a shared vulnerability pattern at the national level and within the subset of municipalities with CAIs. For the overall Spanish sample of 8130 municipalities, 4680 municipalities fell into the same vulnerability category across the three SVI normalization methods, while 3451 differed. Similarly, the CAI sample of 207 municipalities showed 122 with consistent vulnerability and 85 with divergent classifications.

The vulnerability distribution varied based on the standardization method (Fig. 6). Under z-score standardization, most municipalities fell into the *medium* category (38.6 %), while *high* and *very high* vulnerabilities combined accounted for nearly 38 %. With Min-Max normalization, the distribution shifted slightly, with a larger share in the *high* category (39.1 %) and a reduced presence in the *very high* category (6.8 %). Max-value normalization further emphasized high vulnerability, with 46.4 % in the High category (Table 5) and a small percentage in *very high* (5.3 %) (see Appendix C).

In the CAI sample, specific patterns emerged: municipalities frequently clustered in the *medium* and *high* categories across normalization methods, indicating a moderate to high vulnerability baseline for these areas. Thus, 49 CAI municipalities consistently ranked as *high* vulnerability across all methods, while other clusters displayed variations, such as municipalities classified as *medium* in one method and *low* or *high* in others. It underscores the relative stability of vulnerability patterns in specific areas while highlighting administrative units where

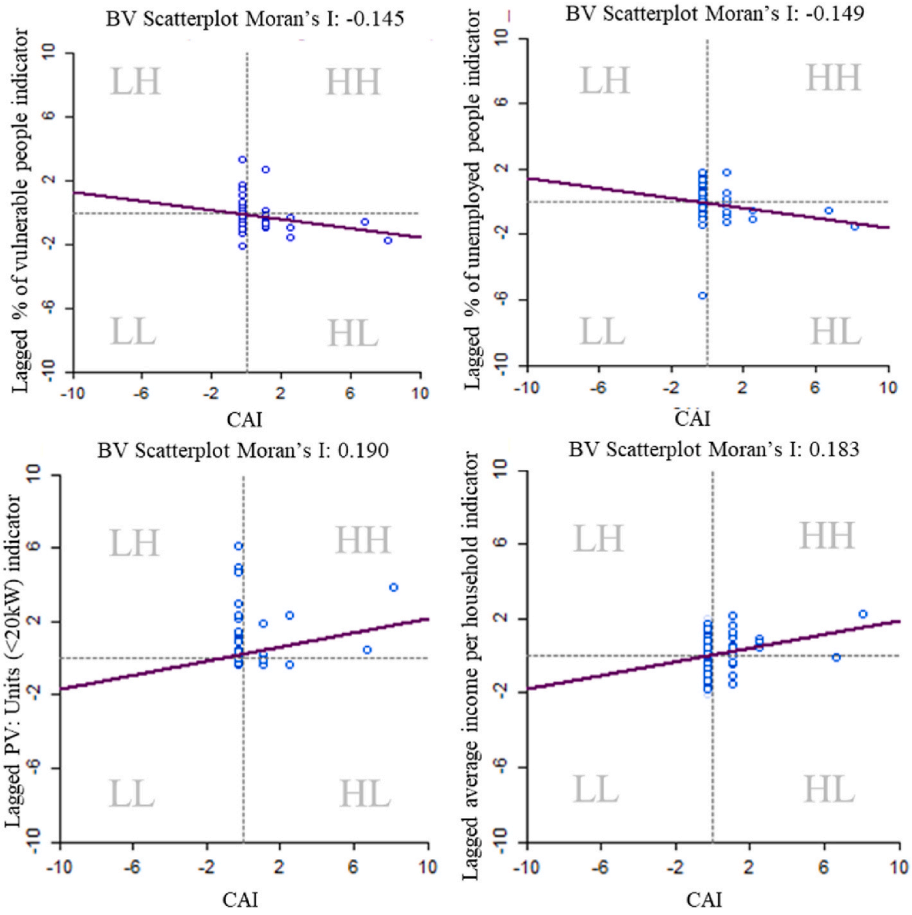


Fig. 7. Local Moran's I bivariate scatterplots for the sample of municipalities with CAIs (x-axis) and specific indicators (y-axis).

Table 6

Summary of highlighted spatial associations with vulnerability levels and notable patterns in CAI sample municipalities.

Province	Municipality	Popul. Num (people)	Indicator	Spatial Association	Vuln. Level (z-score)	Notable Patterns
Alava	Vitoria Gasteiz	248,315	PV Installations (Low Capacity)	HH, HL	Medium	Unique spatial association with other PV-rich areas, neighboring LL/LH pattern in Zigoitia
	Iruña Oka	2478		HH, HL	Low	
	Erriberagoitia	829		HH, HL	Low	
	Zigoitia	1804	Multiple Indicators	LH	Very Low	Consistent LH association
Granada	Puebla de Don Fadrique	2225	Multiple Indicators	LL	High	Located in low-value clusters for key indicators
Andalusia	Orce	1195		LL	Very High	
Andalusia	Rubite	397		LL	Medium	
Granada	Órgiva	5853		LL	Very High	
Granada	Peligros	11,572		LL	High	
Andalusia	Maracena	22,475		LL	Very High	
Asturias	Oviedo	217,164	PV Installations (Low Capacity)	HL	High	High-value PV cluster but low-income areas nearby
Asturias	Llanera	13,827		LH	Medium	Low-value PV cluster but high-income areas nearby

categorization sensitivity to the chosen standardization method can influence vulnerability interpretations.

4.5. Spatial association analysis

Local Moran's I statistics were applied to analyze spatial patterns based on feature locations and values to explore spatial connections between municipalities with CAIs and socio-economic indicators. The analysis focused on energy generation variables and their relationship with social indicators. Simplified vulnerability indexes showed limited interpretive value, with Local Moran's I values below 0.1, and were excluded from pattern interpretation but provided additional context for discussion.

Iterative checks of bivariate (BV) Local Moran's I revealed that the Gini index had minimal explanatory value ($I = -0.016$), while median household income showed weak positive spatial correlation with CAIs ($I = 0.125$). However, p-values around 0.06 suggested spatial randomness. Fig. 7 highlights four indicators depicting trends in outlier density and distribution with weak but significant correlations. Areas with high CAI presence were adjacent to regions with lower percentages of vulnerable populations and unemployment, indicating negative spatial association. Conversely, municipalities with high CAI values often coincided with higher average household income and PV units under 20 kW, indicating positive spatial association.

BV Moran's I for income per household ($I = 0.183$, $p < 0.05$) and PV installations under 20 kW ($I = 0.190$, $p = 0.05$) showed significant positive correlations, while negative associations were observed for vulnerable populations by age ($I = -0.145$) and unemployment ($I = -0.149$). These findings underscore weak but notable spatial trends relative to socio-economic indicators in CAI distribution.

Fig. 7 categorizes values into four spatial association zones: high-high (HH), low-low (LL), low-high (LH), and high-low (HL). HH values represent municipalities with high indicator values surrounded by similarly high-value neighbors, while LL, LH, and HL zones represent other spatial association patterns. Distinct neighboring trends were observed, particularly in the north and south of the country.

Municipalities like Vitoria Gasteiz, Iruña Oka, and Erriberagoitia in the northern region, characterized by PV installations, consistently showed HH/HL clusters across all four indicators. At the same time, their neighbor Zigoitia exhibited LL/LH associations. In the south, LL patterns emerged in municipalities such as Puebla de Don Fadrique, Orce, Rubite, Orviga, Peligros, and Maracena, highlighting areas for further qualitative analysis. Meanwhile, in the southern part of the country, within the Asturias province, municipalities such as Oviedo (HL) and Llanera (LH) stood out for their CAI presence and PV capacity exceeding 20 kWh. BV correlations with household income revealed shifts from HH to LH patterns, marking these areas valuable for investigating spatial differentiation.

5. Discussion

Spain exemplifies stark wealth imbalances between large urban centers, mid-sized cities, and rural areas. Economic activities, resources, and opportunities are heavily concentrated in metropolitan areas like Madrid, Barcelona, and Valencia, which have become economic hubs attracting businesses, investments, and skilled professionals. This urban concentration results in a predominance of CAIs in intermediate and nearly urban regions. Table 6 Summarizes a highlighted spatial association between PV installations and socio-economic indicators in Spanish municipalities.

Section 4.5 highlights northern clusters of low-capacity PV installations with varying vulnerability levels and southern low-value clusters (LL) across multiple indicators. The findings provide a quantitative mapping of the energy vulnerability and generation landscape, offering a data-driven foundation for selecting case studies in qualitative research and deductive approaches. This perspective suggests the need for local exploration of practical challenges (Heuninckx et al., 2023) within a preliminary context-mapped approach, such as a potential group of comparative case studies for in-depth analysis using mixed qualitative and quantitative methods, also extending previous studies on documented cases, such as Som Energia and Goiener (Matschoss et al., 2022). Further research could also adopt a heuristic approach, incorporating a broader set of indicators to empirically examine the driving factors behind CAI emergence and their relation to energy vulnerability in Spain. It could apply further techniques for regression analysis, data weighting, principal component analysis (PCA), and spatiotemporal assessments.

The selection of municipalities with mapped energy vulnerability contexts provides an opportunity for targeted interviews and experimental research. A polarized selection approach could be applied, for example, by comparing CAIs in low and high-vulnerability zones or assessing spatial correlation patterns in installed renewable energy capacities. Such an approach aligns with studies on national-level sub-regional governance solutions (Sokołowski, 2020) and CAI advancement strategies for local case studies (Aparisi-Cerdá et al., 2024; Parreño-Rodriguez et al., 2023). It also reinforces the relevance of purposive area selection, such as those driven by results, targeting municipalities where income inequality is modestly associated with higher unemployment, to explore context-specific investment potential suggested as limited among low-income groups (Magnani and Osti, 2016). Alternatively, a broader indicator set could support research focused on *quantitative surveying addressing the need for ground-truthing processes* (Painter et al., 2024).

In addition, the findings contribute to mapping municipal-level trade-offs—namely, the consequences and compromises involved in designing action plans, energy initiatives, and support measures tailored to local contexts. A recent study by the European Commission's Joint Research Centre (Shortall and Mengolini, 2024) examined energy justice from a bottom-up perspective of energy-poor households within a purposive sample from EU-funded research projects. The study outlined diverse well-being criteria that warrant further assessment. More specifically, further research could evaluate project feasibility and alternative scenarios, particularly in areas with notable spatial associations regarding energy vulnerability categories, supporting tailored CAI development aligned with the EU Solar Energy Strategy ("EU Solar Energy Strategy," 2022). This strategy aims to establish an energy community in every municipality with over 10,000 inhabitants by 2025. Based on collected data and the allocation of CAIs to municipalities, the analysis shows that 33 % of Spain's 759 eligible municipalities ("INE," 2021) host CAIs. This situation also reveals a potential gap for research avenues that concerns EU-level funding for energy community initiatives, which remains inaccessible to many vulnerable groups despite official recognition. While Spain's "Plan + SE" ("More Energy Security") promotes local CAIs through energy cooperatives, it lacks specific legal guidelines for cooperative entities (MITECO, 2022). The plan outlines three key municipal action steps: (1) inventorying public spaces for self-consumption, (2) assessing local self-consumption potential, and (3) setting five-year self-consumption goals. Further resources, such as one-stop-shop guides, open-source planning tools, and EU Recovery and Resilience Fund funding, prioritize support for projects in economically challenged areas ("CE IMPLEMENTA," 2022).

Finally, key limitations should be acknowledged. While justified, the selective choice of indicators may not fully capture the complexity of energy vulnerability, as widely recognized in the literature. Future research could expand socio-economic and infrastructural factors, refine weighting techniques, and incorporate mixed-method approaches. Additionally, inconsistent data on CAIs, along with the lack of centralized accountability and a unified taxonomy, complicates quantitative assessment. However, this also highlights an opportunity to explore emerging public registers of CAIs, such as the recent national registry of energy communities funded through a governmental program in Spain (IDAE, 2025).

6. Conclusions

This study explored the relationships between Collective Action Initiatives (CAIs), energy generation configurations, and socio-economic indicators at the sub-regional level across local administrative units in Spain. As the Gini Index measures, income inequality shows a weak correlation and spatial autocorrelation with CAI presence, indicating it is not a decisive factor. However, areas with higher energy vulnerability and more extensive renewable energy infrastructure display a weak but statistically significant association with CAI activity.

The analysis reveals a trend toward a higher presence of low-capacity PV installations in CAI-active municipalities and the prevalence of fossil-fuel-based cogeneration, particularly in higher populated areas with diversified cogeneration technologies. CAIs are primarily found in municipalities with population densities lower than the national median, reflecting Spain's demographic characteristics. A strong association with higher populations was outlined by certain tendencies, such as gender dynamics in CAI participation with a positive correlation with female representation, greater low-capacity PV installation (<20 kW) in CAI-active municipalities (Pearson's $r = 0.35$, $p < 0.001$). In contrast, this relationship is negligible in low-population areas, where CAI presence shows a slightly stronger correlation with large-scale PV capacity, suggesting a different energy configuration in these municipalities.

The study's approach, which uses EU inventory data on CAI emergence and energy vulnerability mapping as a simplified, deployable metric, establishes a perspective foundation for future research. Mixed-method studies could build on these findings to provide deeper insights through comparative studies or surveys. Future research could build on these findings to further examine local authority awareness, vision, and knowledge exchange among neighboring municipalities or those grouped by indicator patterns and vulnerability levels. It could also explore the practical implications and trade-offs involved in energy transitions and energy community actions—such as balancing social inclusion with cost-effectiveness—particularly in addressing community vulnerability at the community level.

CRediT authorship contribution statement

Oleksandr Husiev: Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Olatz Ukar Arrien:** Writing – review & editing, Supervision. **Marta Enciso-Santocildes:** Writing – review & editing, Supervision.

Declaration of competing interest

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Appendix A. Formulas for data scaling methods: z-score, min-max, and max value normalization

Z-score scaling

$$x' = -\frac{x-\mu}{\sigma} \tag{A.1}$$

where: (μ) is the mean of the feature (x), (σ) is the standard deviation of (x).

Min-Max scaling:

For positive relationship:

$$x' = \frac{x-\min(X)}{\max(X)-\min(X)} \tag{A.2}$$

For positive relationship:

$$x' = 1-\frac{x-\min(X)}{\max(X)-\min(X)} \tag{A.3}$$

Maximum value scaling

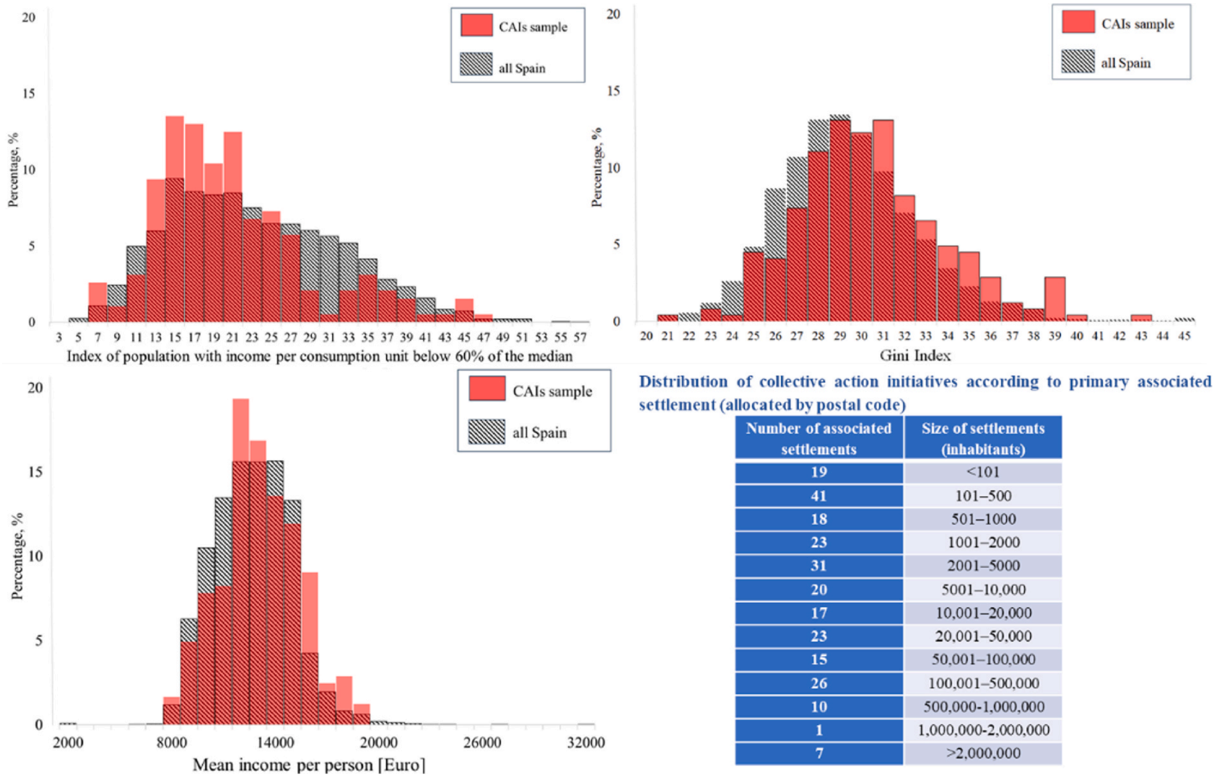
For negative relationship:

$$x' = 1-\frac{x}{\max(X)} \tag{A.4}$$

For positive relationship:

$$x' = \frac{x}{\max(X)} \tag{A.5}$$

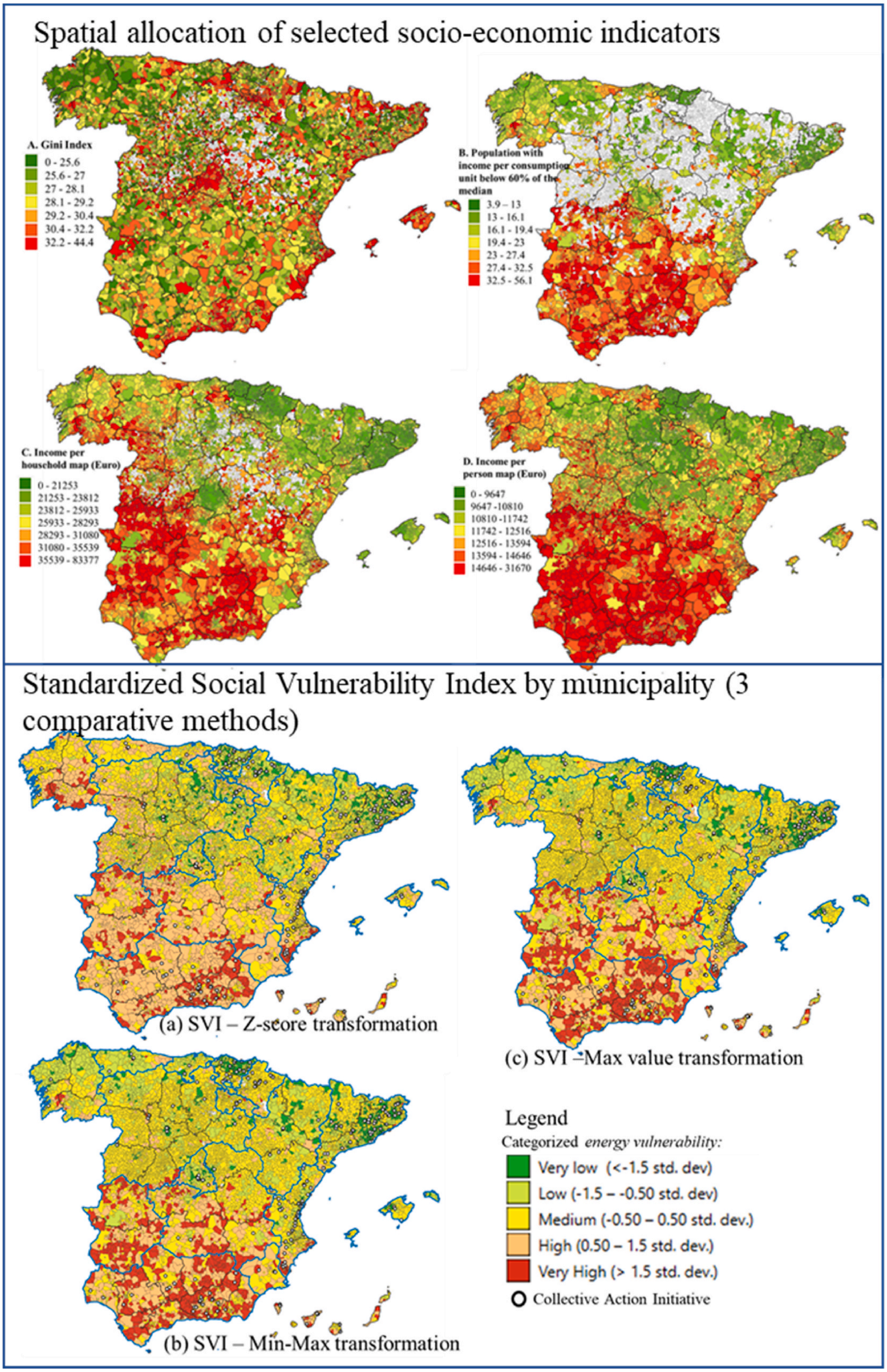
Where, x - Actual value, $\max(X)$- maximum/minimum value



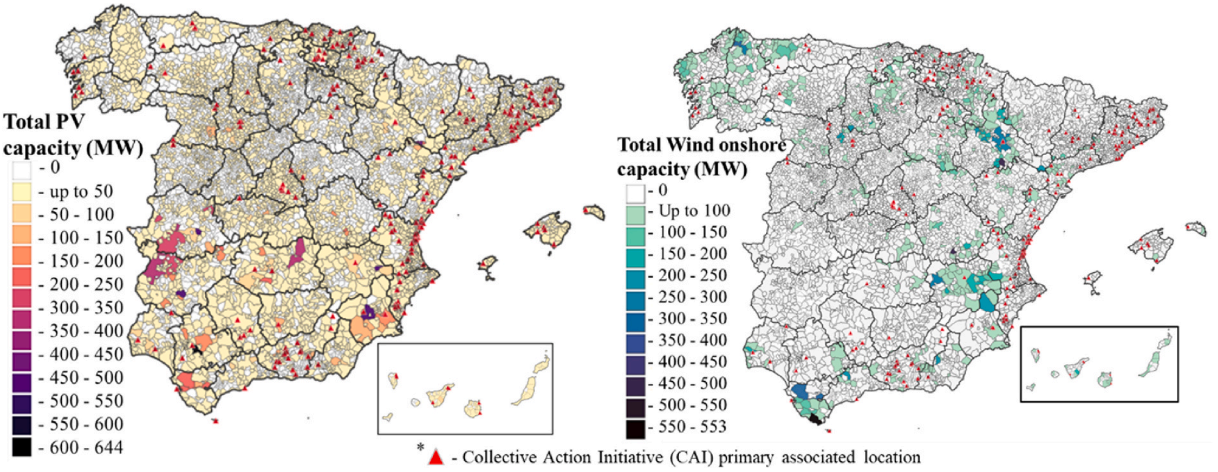
Distribution of collective action initiatives according to primary associated settlement (allocated by postal code)

Number of associated settlements	Size of settlements (inhabitants)
19	<101
41	101–500
18	501–1000
23	1001–2000
31	2001–5000
20	5001–10,000
17	10,001–20,000
23	20,001–50,000
15	50,001–100,000
26	100,001–500,000
10	500,000-1,000,000
1	1,000,000-2,000,000
7	>2,000,000

Appendix B. Comparison of the distribution of selected socio-economic indicators across all local administrative units (LAUs) in Spain with those in which CAIs are identified (2021)



Appendix C. Spatial allocation of selected socio-economic indicators and standardized Social Vulnerability Index by municipality.



Appendix D. Example maps of photovoltaic and wind capacity by municipality from processed energy production registry data.

Data availability

Supplementary data related to this article can be found online at 10.17632/v8cv52frdh.5

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