Development of an Integrated Tool for the Assessment of Regional Vulnerability to Energy Poverty: The Case of Greece

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Abstract

Families that cannot afford basic energy amenities are considered to live in energy poverty. Socioeconomic and environmental factors such as income inequality, building inefficiency, and climate change exacerbate this condition. This study proposes an innovative composite index that measures vulnerability by combining four different aspects of vulnerability: building, climatic, social, and economic. The regional composite index incorporates sub-indexes such as household income, residential energy cost, and housing characteristics to map the areas affected mostly by energy poverty. Official data from sources such as Hellenic Statistical Authority (ELSTAT) and Eurostat is used to establish these indicators. To assign objective weights to the various criteria, the study employs the entropy-weighted technique. This ensures that the research accurately represents regional vulnerability levels. The findings highlight significant regional disparities, with Eastern Macedonia and Thrace showing the highest levels of vulnerability while Attica exhibits the lowest. By providing decision-makers with a helpful tool, this composite metric seeks to address the structural and immediate causes of energy poverty while also helping policymakers develop targeted policies and initiatives.

Keywords: Composite Index, Energy Poverty, Policy Mitigation, Spatial Analysis, Vulnerability Assessment

1. Introduction

An additional aspect of poverty, known as "energy poverty," poses difficulties for today's societies [1]. Since 2010, scientists and decision-makers have been systematically addressing energy poverty [2]. The inability of a household to afford an adequate level of thermal comfort in their homes is referred to as "energy poverty" [3]. Climate change also affects the extent of energy poverty [4]. Therefore, ensuring adequate levels of cooling inside dwellings is considered crucial, especially in regions of Southern Europe that are faced with high temperatures, particularly during the summer season, threatening both the health of citizens and the general level of well-being [5].

There are significant differences in the prevalence of energy poverty across Europe [6]. Of all Member States, the countries of Eastern and Southern Europe are at the top when it comes to energy poverty [7]. Lower disposable income and high unemployment rates are exacerbating the problem in southern Europe [8] and [9]. In particular, declining household income during the financial crisis led to increased vulnerability as severe austerity measures were enforced [10]. The COVID-19 pandemic and the energy crisis resulting from the conflict between Russia and Ukraine led to an increase in energy poverty [11]. In the wake of the energy crisis, energy prices rose significantly, which led to an increase in energy costs [12]. The proportion of people unable to adequately heat their homes increased by 20% in the first year of the COVID-19 pandemic [13]. In response, several EU states have taken measures to reduce energy poverty and support low-income households in the wake of COVID-19 and during the 2021-2022 energy crisis [14].

Therefore, the level of energy poverty is directly related to the economic stability of society and is influenced by the distribution of energy expenditure and the financial resources available to the population [15]. Most studies conducted in Greece mainly used simple objective or subjective measures to quantify the extent of energy poverty at the national level [16] and [17]. A few researchers have also focused on studying the socioeconomic characteristics of energy-poor households at national and regional levels [18].

In Greece, energy poverty is reinforced by several socio-economic determinants such as disposable income, educational level and the demographic composition of household members. It is estimated that approximately 10% of households face chronic energy deprivation [18]. Furthermore, in literature studies highlight the social dimension of energy poverty with significant inequalities recorded among vulnerable population groups with limited access to economic resources and burdened health conditions [19]. Vulnerability to energy poverty is more acute, in the mountainous areas of Greece which is attributed to the degraded and poorly upgraded building stock, increased energy cost and inadequately efficient heating systems, resulting in energy poverty levels that exceed the national average [20]. Energy poverty mainly affects the elderly population of Greece who face more difficulties in paying utility bills, highlighting the need for the adoption of targeted strategies aimed at this demographic group [21]. To improve the quality of life of Greek households and achieve the sustainable goal of equal access to green and affordable energy, it is necessary to strengthen Community energy initiatives [22]. Since until recently no composite measure has been proposed to quantify vulnerability levels at a smaller spatial scale beyond the national level, this point highlights a significant gap in the literature. While most existing research has focused on national-level assessments or household-level determinants, few studies have attempted to analyze regional disparities of the energy poverty vulnerability through the construction of composite indexes [23][24] and [25]. To provide a comprehensive tool to capture, track, and assess Greece's vulnerability over time, this study proposes a novel composite indicator. Its main advantage is the possibility of identifying areas that are more likely to be negatively affected by the phenomenon and suffer from energy deprivation. In addition, it serves as a useful decision-making tool, allowing decision-makers to propose targeted mitigation and adaptation plans in areas where vulnerability is increasing.

The main objective of the present study is to fill the gap identified in the existing literature by: (a) constructing a composite and innovative index that captures the spatio-temporal dynamics of energy poverty in Greece; (b) identifying regions where vulnerability levels increase or decrease over time; and (c) formulating evidence-based policy recommendations to mitigate the adverse impacts of energy poverty.

2. Literature Review

Vulnerability to energy poverty is influenced by several factors [26]. These variables include, among others, income, energy costs, and whether household members live in apartments that have not been energy-efficiently modernized [27] and [28]. In addition, since some population groups such as the elderly, children, renters, single parents, etc. are naturally more vulnerable than others, socioeconomic and demographic factors also contribute to and shape the level of vulnerability [29][30] and [31]. The location of the apartment should be considered [29]. Rural areas are naturally more vulnerable due to aging building stock, energy-inefficient housing, and limited access to modern energy resources [32] and [33].

The extent of energy poverty is determined primarily by two methods: (a) the energy expenditure approach, which is an objective approach, and (b) the consensual approach, which is a subjective approach [34]. In the first case, the distribution of energy expenditure in relation to disposable income is examined [35]. Households are classified as energy poor if the ratio of energy expenditure to income exceeds a predefined threshold [36]. By considering qualitative factors, drawn mainly from European surveys (EU-SILC) that capture participants' attitudes and perceptions regarding the level of energy deficiency they observe in their homes, the subjective approach assesses energy poverty levels [37]. The simplicity of calculation is the main advantage of using objective measurements [38]. The expenditure approach has been used in several studies to calculate the extent of fuel poverty. The arbitrary use of the threshold without documentation is the main disadvantage of the objective method for estimating energy poverty in a region [39].

Subjective methods have the advantage of enabling comparative analyses between the areas under consideration [40]. Since this data collection method relies on questionnaire surveys, its main flaw is exclusion bias [41]. Therefore, individuals often conceal their actual situation to avoid being classified as energy poor [42]. Many scholars argue that using single metrics to measure the extent of energy poverty does not adequately capture all facets of the problem due to its complexity [13] and [14]. Composite measures address the issues posed by previous measurement techniques and should be used to measure and analyze the extent of energy poverty [41] and [43]. A composite indicator was developed to measure the extent of energy poverty in the Italian provinces [44].

To estimate vulnerability levels, the proposed index considered the characteristics of the building stock, energy prices and household disposable income. Similarly, to capture the complexity of energy poverty and measure the level of vulnerability in European countries, a composite index was proposed that considered factors such as the lack of natural light, household financial distress, thermal comfort, and the home's energy efficiency [45]. To assess the vulnerability levels of Irish households to energy poverty, a composite index consisting of ten sub-indices categorized into three thematic dimensions household composition, building characteristics, and dwelling heat demand was developed [46].

In Poland, a composite index was created to determine the vulnerability of households to energy poverty. This index combined objective and subjective measurements to assess the extent of energy poverty. The data required to construct this index came from the Household Budget Survey and the European Union Survey of Household Income and Living Conditions [47]. Additionally, the policy dimension, which captures European-level measures to reduce energy poverty, was integrated into the composite metric to estimate vulnerability levels [48]. Policy dimension refers to a series of actions for the alleviation of energy poverty. These interventions can be categorized as either short-term, which include allowances for low-income households to cover their basic energy needs, or long-term, which encompass energy retrofit programs aimed at upgrading the housing sector and increasing the penetration of renewable energy sources to ensure affordable energy for all citizens [49].

3. Material and Methods

3.1 Study Area

Greece is divided into 13 regions corresponding to NUTS 2 level and 51 prefectures corresponding to NUTS 3 level according to the classification proposed by Eurostat [50] as illustrated in Figure 1. Greece covers an area of 132000 sq. km, and its population is estimated at 10,500.000 inhabitants. More than 30% of the total population of the country resides in the region of Attica and almost 20% resides in the Region of Central Macedonia. In total, the population of these two regions accounts for more than 50% of the country's population [51].

3.2 Construction of a Composite Indicator for the Assessment of Regional Energy Poverty Vulnerability

The creation and use of composite indicators has become increasingly common in the global literature in recent years [52]. They can be useful evaluation and decision-making aids and can help ensure that the comparative analysis and classification of the spatial units under consideration is successful [53].

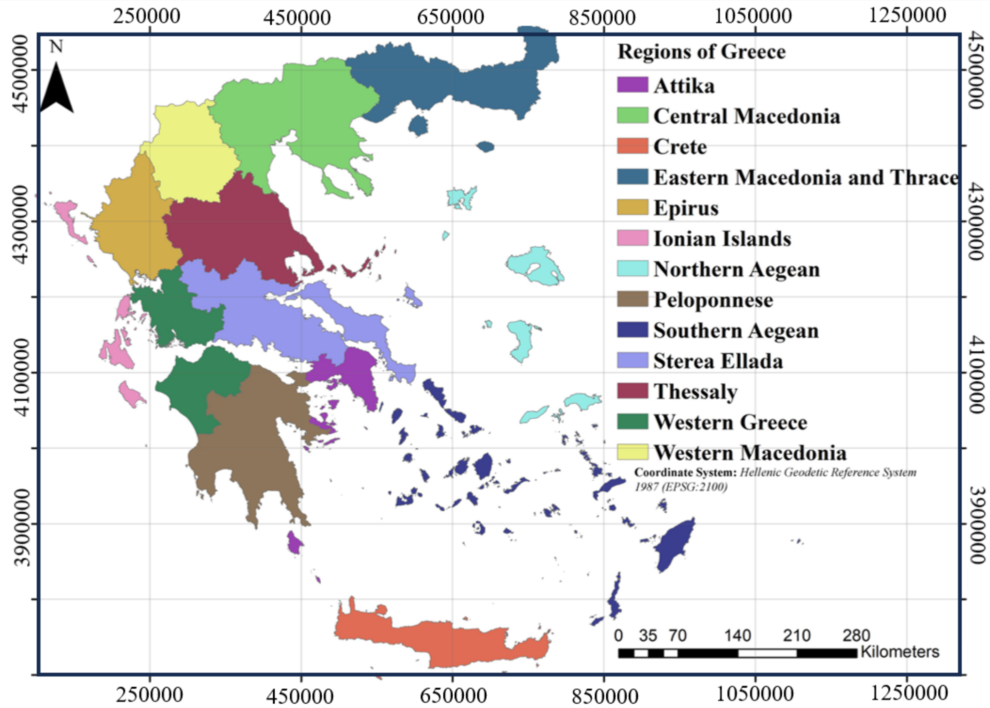

Figure 1: Administrative boundaries of Greece's Regions

A theoretical framework that serves as a basis for measuring the phenomenon under consideration should consider dimensions that are either directly or indirectly related to it [54]. To study the multidimensional nature of vulnerability in the Selangor region of Malaysia, a composite index was proposed by [55]. Figure 2 shows the basic procedures for creating the Composite Regional Energy Poverty Vulnerability Index. This systematic approach provides a comprehensive framework to detect energy poverty at the regional level. The assessment of regional vulnerability to energy poverty (REVPOV) starts with the definition of vulnerability and the identification of factors that exacerbate it. The most important indicators are chosen across four thematic fields: Economic, Building, Social, and Location & Climatic. The list of indicators that capture different aspects of vulnerability is presented in Table 1.

Furthermore, analytical techniques, including outlier identification using the Interquartile Range (IQR) method and normalization with the Min-Max approach, are implemented on the set of indicators during the data processing. Weights are assigned to the selected indicators according to the Shannon Entropy approach. The weighted indicators are combined using a linear weighted average method to generate composite sub-indicators for each dimension. In the end, these composite sub-indicators are merged into an overall composite index (REVPOV), which operates as an integrated tool for evaluating vulnerability levels across time and space.

3.3 Selection of Indicators

Official databases (ELSTAT, Eurostat and OECD) provide data that quantify and track the extent of regional vulnerability to energy poverty over time. Table 1 presents the indicators used to assess the level of vulnerability in the regions of Greece. Due to the lack of data at intra-regional level (NUTS 3), the composite indicator was structured at regional level (NUTS 2). Table 1 provides an overview of the four thematic dimensions that capture the multidimensional nature of energy poverty vulnerability. Specifically, the Economic Dimension encompasses indicators that reflect the economic hardship of the population. Among these indicators, disposable income (DHINCC) is one of the most important factors. As income decreases, the likelihood of a household to face energy deprivation rises [56]. Income-poor households (AROP) are more likely to experience energy deprivation conditions as they lack the financial capacity to cope with potential increases in energy prices [57]. Similarly, unemployed households (UNER) are prone to energy insecurity due to limited income resources [58]. Gross Domestic Product (GDPC) serves a proxy indicator of a region’s economic growth; a decline in GDPC increases the risk of transitioning into energy poverty [18]. Lastly, income inequality (INCDIS) is a crucial factor that exacerbates energy poverty by increasing the income gap between socio-economic groups [59]. The Building Dimension brings together indicators whose presence or absence can exacerbate the levels of energy poverty vulnerability.

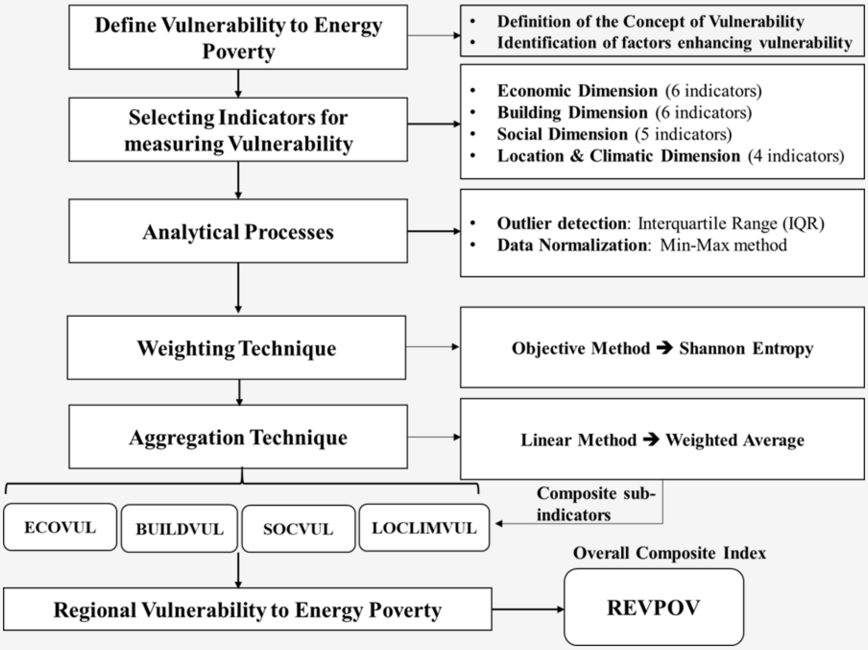

Figure 2: Regional vulnerability to energy poverty study workflow

Table 1: List of indicators included in the construction of the composite indicator

Dimension of Vulnerability	Description of sub-indexes	Abbreviation	Unit	Impact on Vulnerability	Data Sources
Economic Dimension	Disposable household income per capita	DHINCC	pps/cap	Negative impact	EUROSTAT
	Gross domestic product per capita	GDPC	pps/cap	Negative impact	EUROSTAT
	Unemployement rate	UNER	%	Positive impact	EUROSTAT
	High share of energy expenditures	HSENEXP	%	Positive impact	ELSTAT
	Income inequality	INCDIS	%	Positive impact	EUROSTAT
	At risk of poverty rate	AROP	%	Positive impact	EUROSTAT
Building Dimension	Detached dwellings	DTCH	%	Positive impact	ELSTAT
	Average size of dwellings over 100 m^2	ASIZE	%	Positive impact	ELSTAT
	Construction period before 1980	CONST	%	Positive impact	ELSTAT
	Households equipped with wood stoves for space heating	STOVHEAT	%	Positive impact	ELSTAT
	Energy Performance Certificates	EPC	%	Positive impact	ELSTAT
	Households using LPG appliances for cooking	LPGSTVE	%	Positive impact	ELSTAT
Social Dimension	Households with 5 or more members	MEMB	%	Positive impact	ELSTAT
	Single-parent households	SINGPA	%	Positive impact	ELSTAT
	Households of elderly persons	ELDHH	%	Positive impact	ELSTAT
	Low educational attainment	LEDU	%	Positive impact	ELSTAT
	Tenant households	TENTH	%	Positive impact	ELSTAT
	Part time employment incidence	PTEMP	%	Positive impact	OECD
Location & Climatic Dimension	Population Density	POPDEN	Pop/km^2	Negative impact	ELSTAT
	Household density	RUR_HH	%	Positive impact	ELSTAT
	Climatic risk	CLIMRISK	Degree days	Positive impact	OECD
	Number of days with strong heat stress (>38°C)	HEATSTR	Number of days	Positive impact	OECD

The age of the dwelling (CONST) is a crucial parameter that enhances the risk of a household experiencing energy deprivation, as it is associated with the energy efficiency and the living conditions inside the dwelling [60]. The size of the dwelling (ASIZE) can influence the residential energy cost, leading many households to not ensure adequate heating and cooling conditions inside their dwelling [61]. Households using wood stoves for heating (STOVHEAT) and LPG for cooking (LPGSTVE) are more prone to experiencing energy poverty due to the lack of access to modern and environmentally friendly sources of energy [62]. Low energy-efficient dwellings (EPC) are more vulnerable to energy poverty as they record increased energy consumption levels compared to energy-upgraded dwellings [63]. The presence of detached households (DTCH) is a crucial factor that increases vulnerability to energy poverty, as it is associated with higher levels of material deprivation [64]. The Social Dimension includes indicators that capture the vulnerability of the population to energy poverty. Large households (MEMB) are by nature more vulnerable to experiencing energy deprivation as their energy expenditures increase significantly [65]. Single-parent households (SINGPA) are unable to cope with unforeseen expenditures due to their limited financial resources [61].

Households of elderly people (ELDHH) are prone to energy poverty as they spend most of the day inside the dwelling, so a large share of their income is spent on ensuring adequate levels of heating and cooling [66]. Households living in rental properties (TENTH) cannot afford to carry out substantial and long-term interventions inside the dwellings (changes to the heating system, energy efficiency upgrades, etc.) [58]. People with a low educational attainment (LEDU) are vulnerable, as their income is inadequate to cover energy costs, and they also lack the capacity building to adopt sustainable energy-saving practices [65]. Residing in job-insecure households (PTEMP) is a crucial parameter to consider while approaching the issue of energy poverty, as they experience economic hardship due to their constrained income [67].

The Location and Climatic Dimension incorporate a set of determinants used to quantify the vulnerability. Population density (POPDEN) is a parameter used in the assessment of vulnerability levels [68]. A higher risk of energy poverty is linked to lower population density levels. The percentage of the population residing in rural areas (RUR_HH) exhibits higher vulnerability to energy poverty due to limited access to modern energy resources [69]. The climate risk indicator (CLIMRISK) incorporates the number of days when heating and cooling of dwellings is required [70]. The heat stress index (HEATSTR) captures the number of days where the temperature exceeds 38°C. The higher the values of this indicator, the higher the risk of energy poverty [71].

3.4 Data Treatment and Selection of Normalization Method

When dealing with missing values in the pre-processing phase of the indicators, we follow the methodology of [72]. We also examine the presence of outliers at the high and low ends of the variable distribution. The interquartile range (IQR) method is used to detect outliers [73]. The construction of the composite index to assess vulnerability levels to energy poverty in Greece was conducted at the NUTS-2 level (regional scale). Until now, most studies in Greece have not focused on the geographical dimension of the phenomenon, despite its recognition in the existing literature. The study aims to map the levels of vulnerability to energy poverty to highlight the uneven geographical distribution of the phenomenon. Most of the indicators covering aspects of the multidimensional nature of vulnerability to energy poverty are derived from the ELSTAT’s Annual Family Budget Survey (HBS), which provides data at the NUTS-2 level. This constitutes the main limitation of this study, as it fails to capture the intra-regional disparities. These disparities are represented at the NUTS-3 scale, where the Eurostat typologies adopted by Member States are typically applied. Nevertheless, the analyses carried out at the regional level are considered crucial for the design and development of effective strategies to address energy poverty. Table 2 illustrates the outliers and extreme values for all sub-indicators that form the composite indicator for assessing energy poverty vulnerability for the study period (2018-2020). We replace the outliers at the top and bottom of the sub-indicator distribution with the values of the upper and lower outer bounds, respectively, to reduce statistical noise. The indicators were normalized using the min-max normalization technique [74]. Applying this normalization technique has several advantages. The most important are their ease of use, their ability to preserve the relationship between the original data and their ability to perform comparative analyzes between the spatial units considered [72]. In order to take both positive and negative criteria into account in the calculation, the min-max method was modified [49]. To facilitate cross-time comparisons, we set the maximum value for each sub-index in the normalization phase as the highest value of all spatial units considered for the analysis period (2018-2020). To determine the lowest value, we used a similar procedure [46].

Normalize the sub-indicators that positively affect vulnerability levels using Equation 1:

$$r_{ij_{(pos)}} = \left[\frac{X_{ij} - \min_j\left(X_{ij}\right)}{\max_j\left(X_{ij}\right) - \min_j\left(X_{ij}\right)}\right] \times 100$$

Equation 1

Normalize the sub-indicators that negatively affect vulnerability levels using Equation 2:

$$r_{ij_{(neg)}} = \left[1 - \frac{X_{ij} - \min_j(X_{ij})}{\max_j(X_{ij}) - \min_j(X_{ij})}\right] \times 100$$

Equation 2

Where:

$r_{ij(pos)}$ = The normalized value of the indicator positively impacts vulnerability

$r_{ij(neg)}$ = The normalized value of the indicator negatively impacts vulnerability

$min_j(X_{ij})$ = The indicator's minimum value corresponds to criterion j

$max_j(X_{ij})$ = The indicator's maximum value corresponds to criterion j

Table 2: Presentation of outliers per indicator for the investigation period 2018 to 2020

Thematic Dimensions/sub-indexes		Outliers Lower Bound (LB) & Upper Bound (UB)		
		2018	**2019**	**2020**
Economic Dimension	DHINCC	Non outlier detected	Non outlier detected	Non outlier detected
	GDPC	**Attica-UB** (27400 pps/cap)	**Attica-UB** (28300 pps/cap)	**Attica-UB** (25700 pps/cap)
	UNER	Non outlier detected	Non outlier detected	**Peloponnese-LB** (11.4%)
	HSENEXP	Non outlier detected	Non outlier detected	Non outlier detected
	INCDIS	Non outlier detected	Non outlier detected	Non outlier detected
	AROP	Non outlier detected	Non outlier detected	Non outlier detected
Building Dimension	DTCH	**Attica-LB** (12.1%)	Non outlier detected	Non outlier detected
	ASIZE	Non outlier detected	Non outlier detected	Non outlier detected
	CONST	Non outlier detected	Non outlier detected	Non outlier detected
	STOVHEAT	**East Macedonia & Thrace-UB** (30.1%)	Non outlier detected	Non outlier detected
	EPC	Non outlier detected	Non outlier detected	Non outlier detected
	LPGSTVE	Non outlier detected	Non outlier detected	Non outlier detected
Social Dimension	MEMB	Non outliers detected	Non outliers detected	**Attica-LB** (5.4%); **Crete-LB** (5.3%)
	SINGPA	Non outliers detected	Non outliers detected	Non outliers detected
	ELDHH	**Ionian Islands-UB** (24.2%)	**Ionian Islands-UB** (32.8%)	**Ionian Islands-UB** (28.6%)
	LEDU	**Attica-LB** (17.2%)	Non outliers detected	**Attica-LB** (13.3%)
	TENTH	Non outliers detected	Non outliers detected	Non outliers detected
	PTEMP	Non outliers detected	Non outliers detected	Non outliers detected
Location/ Climatic Dimension	POPDEN	**Attica-UB** (984.6 Pop/km^2)	**Attica-UB** (981.2 Pop/km^2)	**Attica-UB** (980.3 Pop/km^2)
	RUR_HH	Non outliers detected	**Attica-LB** (1%)	Non outliers detected
	CLIMRISK	Non outliers detected	Non outliers detected	Non outliers detected
	HEATSTR	Non outliers detected	Non outliers detected	Non outliers detected

Note: The interquartile range (IQR) method is used to detect possible outliers. The presence of outliers and extreme values could negatively influence the calculation process of the composite indexes. To avoid this misinterpretation, we replaced extreme values with the corresponding lower or upper bound to maintain statistical consistency and ensure comparability across regions. This capping technique minimizes distortion in the vulnerability assessment while retaining meaningful variation among regions.

3.5 Shannon's Entropy Weighted Method

Using the entropy-weighted method, weights are assigned to the relevant criteria according to the extent of their diversification [75]. The degree of diversification increases with the variance of the values in the criteria examined [76]. In this case, the criterion examined has a higher weight [77]. This weighting technique was chosen due to its objective results, which are insensitive to disagreements between decision makers involved in the process [78]. Shannon's objective method of entropy is extensively used in the construction of composite indices, as it offers several advantages over both objective and subjective weight assignment methods [79]. A key advantage of the method is its ability to assign greater weights to criteria that exhibit higher variance by utilizing the information contained in the data itself [80]. Moreover, unlike the equal weighting (EW) method, which assigns equal weights to each criterion, Shannon's method allows for a deeper understanding of the differences between decision-making units (DMUs) [81]. The main advantage of the entropy method over the objective Benefit-of-the-Doubt (BoD) method lies in its computational simplicity and the assignment of common weights to all DMUs, which facilitates comparative analysis [81]. Finally, the comparative advantage of the entropy method over the subjective Analytical Hierarchy Process (AHP) is found in its elimination of the need for expert judgment in assigning weights to criteria, making it simpler to implement and more suitable when quantitative criteria are being weighted [82]. We discuss the five implementation stages of the method below [77]:

Step 1: Building the matrix of "criteria-alternatives" for the multi-criteria problem using Equation 3:

$$\begin{pmatrix} X_{11} & \cdots & X_{1n} \\ \vdots & \ddots & \vdots \\ X_{m1} & \cdots & X_{mn} \end{pmatrix}$$

Equation 3

Where:

X_{mn} = The value of the indicator in relation to region (n) and criteria (m).

Step 2: Normalize the criteria according to the way they positively or negatively impact the multi-criteria problem:

Normalizes the criteria that have a positive impact on the multi-criteria problem using Equation 4:

$$s_{ij(pos)} = \frac{X_{ij}}{\max_j \left(X_{ij} \right)}$$

Equation 4

Normalizes the criteria that negatively impact the multi-criteria problem Equation 5:

$$s_{ij(neg)} = \frac{\min_j \left(X_{ij} \right)}{X_{ij}}$$

Equation 5

Where:

$s_{ij(pos)}$ = The normalized value of the indicators has a positive impact on the multi-criteria problem

$s_{ij(neg)}$ = The normalized value of the indicators has a negative impact on the multi-criteria problem

$min_j(X_{ij})$ = The minimum value of the indicator corresponds to criterion j

$max_j(X_{ij})$ = The maximum value of the indicator corresponds to criterion j

Step 3: Calculating the ratio R_{ij} using Equation 6:

$$R_{ij} = \frac{s_{ij}}{\sum_{i=1}^{n} s_{ij}}$$

Equation 6

Where:

R_{ij} = Divide the normalized index

S_{ij} = The normalized values of criteria j

Step 4: Determine the entropy using Equation 7:

$$E_{nj} = -Y \sum_{i=1}^{n} \left(R_{ij} \times \ln\left(R_{ij} \right) \right)$$

Equation 7

Where:

E_{nj} =The entropy coefficient takes values from the closed interval [0, 1]

$Y = 1/\ln(n)$ where (n) corresponds to the set of spatial units considered

Here, a simplifying assumption to streamline the mathematical calculation. More precisely, when calculating entropy coefficient E_{nj}, if $R_{ij} = 0$ it is assumed that both $R_{ij} \times \ln(R_{ij}) = 0$

Step 5: Calculation of the degree of deviation (Div_j) and weighting of the criteria (Ew_j) using Equations 8 and 9, respectively:

$$Div_j = |1 - E_{ij}|$$

Equation 8

Where:

Div_j = The degree of differentiation of the criteria (j) involved in the multi-criteria problem:

$$Ew_j = \frac{Div_j}{\sum_{i=1}^{n} Div_j}$$

Equation 9

Where:

Ew_j = The weight corresponding to criterion j

3.6 Aggregation Method for the Synthesis of Regional Composite Indicator

Combining the normalized and weighted sub-indicators that help measure the phenomenon is the final step in creating composite indicators. Each analyst comes to a different conclusion depending on the method chosen [83]. This study uses the linear aggregation technique to create the composite regional index that measures the degree of vulnerability to energy poverty [84]. From the weighted average of the normalized indicators categorized in each topic dimension, we derive the four composite indicators. The arithmetic mean of the four composite indicators serves as the basis for our overall assessment of the vulnerability level, since in our opinion each dimension contributes equally to the final vulnerability level. The overall composite regional energy poverty vulnerability index is expressed in Equation 10:

$$REVPOV_c = \frac{1}{4} \times \left[ECOVUL_c + BUILDVUL_c + SOCVUL_c + LOCLIMVUL_c \right]$$

Equation 10

Where:

$REVPOV_c$ = The arithmetic mean that represents a region's c overall vulnerability to energy poverty

The classification methodology used to map the vulnerability levels of the four composite indicators SOCVUL, BUILDVUL, ECOVUL, and LOCLIMVUL each capturing different dimensions of the multidimensional energy poverty, as well as for the overall index of REVPOV, is based on the equal interval approach. This classification scheme divides the range of attribute values into five equally sized classes, ranging from very low to very high vulnerability, and has been applied to assess energy poverty vulnerability in urban neighborhoods of Oberhausen, and can be serve as an effective tool to support evidence-based policymaking [85]. Moreover, the approach can be generalized to other case study areas, including Greece.

3.7 Sensitivity Analysis of Weighting Schemes

We conducted a simple sensitivity analysis to assess the REVPOV's response to changes in different weighting schemes [86]. The composite index was recalculated using different weight options, such as equal weights for the baseline scenario and the Shannon entropy weighted method for an alternative scenario, and we examined how the scores for each DMU, which are the 13 administrative regions of Greece, changed. In order to evaluate the sensitivity of our composite index we examined the following parameters: a) The Mean Absolute Difference (MAD) measures the average absolute deviation of the composite scores from the baseline scenario and provides a straightforward metric for sensitivity b) Spearman's rank correlation coefficient (ρ) was calculated to assess the degree of agreement between the rankings, and c) rank shifts were analyzed to capture the number and magnitude of changes in position.

4. Results and Discussion

Figure 3 presents the weight distribution across four thematic axes reflecting the multidimensional aspects of vulnerability to energy poverty for the years 2018, 2019 and 2020.

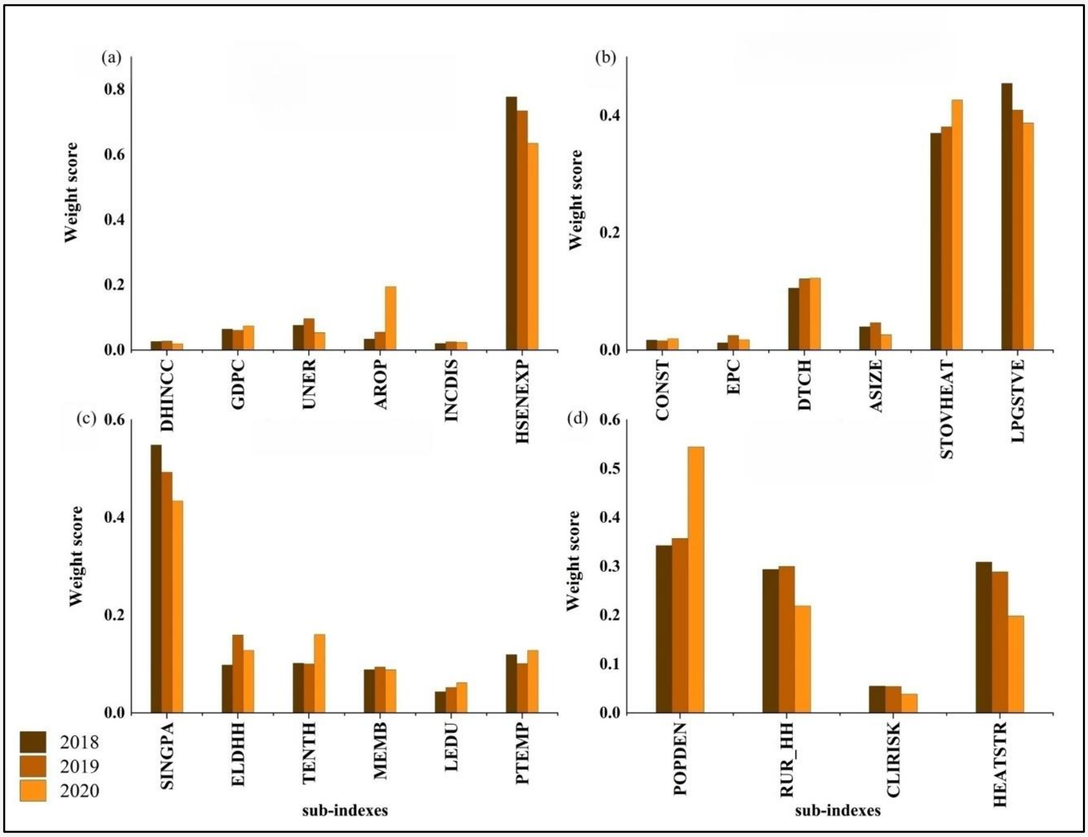

Figure 3: Vulnerability weight distributions based on Shannon's entropy: (a) economic vulnerability (b) building vulnerability (c) social vulnerability (d) location and climatic vulnerability

The objective weighting method prioritizes the High Energy Costs (HSENEXP) criterion, assigning it a weight of 78% in 2018, establishing it as the main factor influencing economic vulnerability (ECOVUL) for that year. By 2020, the importance of this criterion had decreased, resulting in a reduction in its weight by 18 percentage points. We use the objective, data-driven Shannon Entropy method to determine the weights of indicators. Higher weights are distributed to these indicators that present greater variability, and therefore, they carry more information. The HSENEXP is a dominant criterion in our case since the high variance recorded between examined regions led to a lower entropy value and therefore to greater weight [79]. The criterion for assessing the share of the population in poor income (AROP) has gained importance over time, with its weight increasing to 20% in 2020, a significant increase compared to previous years. Throughout the three-year period, the criteria for assessing household disposable income (DHINCC) and income inequality (INCDIS) consistently demonstrated limited validity as their weights remained below 5%, indicating a small contribution to overall economic hardship.

The Building Vulnerability Assessment Index (BUILDVUL) highlights two important factors: reliance on energy-inefficient appliances for household activities such as cooking and heating, and limited access to modern energy resources. In 2018, the proportion of households using LPG stoves for cooking (LPGSTVE) was 45.5%, while traditional use of heating devices such as wood stoves (STOVHEAT) was assigned a weight of 37 percent. By 2020, STOVHEAT's weight rose by 15 percentage points, while LPGSTVE's weight fell in line with that. The weighting of the construction period (CONST) and apartment size (ASIZE) criteria remained low throughout and did not exceed 5% in any year, which limited their influence on the overall vulnerability index.

The Composite Social Vulnerability Index (SOCVUL) consistently prioritized the criterion related to the proportion of single-parent households (SINGPA) across all three years. In 2018, SINGPA received a weighting of 55%, making it the dominant factor in the index. However, by 2020, its weight had declined by 21 percentage points, reflecting a shift in the distribution of vulnerability factors. In contrast, the weights for the criteria measuring the proportion of older households (ELDHH) and renter households (TENTHH) increased significantly in 2020, with an increase of 30 and 58 percentage points, respectively, compared to their values in 2018. The low educational attainment criterion (LEDU), on the other hand, had a smaller influence on the construction of the composite index and contributed minimally to the assessment of social vulnerability throughout the study period. The results of the entropy-weighted method highlight the lower influence of the LEDU criterion. This indicator exhibited low variation across different regions, which means it carries less information and ultimately receives less weight [79].

The Composite Index for Location and Climatic Vulnerability (LOCLIMVUL) includes four key criteria that measure vulnerability resulting from residential location and regional climatic conditions. Two criteria cover geographical aspects - population density (POPDEN) and the proportion of rural households (RUR_HH) - while the other two are climate-related and focus on climate risks (CLIMRISK) and heat stress (HEATSTR)**.** In 2018, the POPDEN criterion was the most influential with a weighting of 34%. By 2020, its contribution had increased dramatically, increasing by 59 percentage points, underscoring the growing importance of population density in determining vulnerability. Conversely, the CLIMRISK criterion consistently contributed less to the overall vulnerability index, with its weight remaining below 5% in 2020, suggesting that it played a relatively minor role in assessing vulnerability over the three-year period.

The composite indicators ECOVUL, BUILDVUL, SOCVUL, and LOCLIMVUL capture different aspects of vulnerability to energy poverty (Figure 4). The values of the composite indicators vary from 0 (very low vulnerability) to 100 (very high vulnerability). Regions recording high values in the composite indexes (>80) are depicted in dark red, indicating increased levels of vulnerability, while areas with low values (<20) are depicted in light red, indicating increased resilience. Figure 4 (a) shows the spatial distribution of the ECOVUL composite index for the year 2018 in the 13 administrative regions of Greece. The region of South Aegean records the lowest vulnerability (10.5) in contrast to the region of Western Macedonia, which shows the highest vulnerability (95.1). The high levels of economic hardship recorded by the region of Western Macedonia are due to increased energy expenditure and the unemployment rate, while the contribution of other economic factors to the deterioration of vulnerability levels is limited. Figure 4(b) shows the values of the BUILDVUL index for the year 2018 in the 13 regions of Greece. The region of Eastern Macedonia and Thrace records the highest levels of vulnerability (91.6).

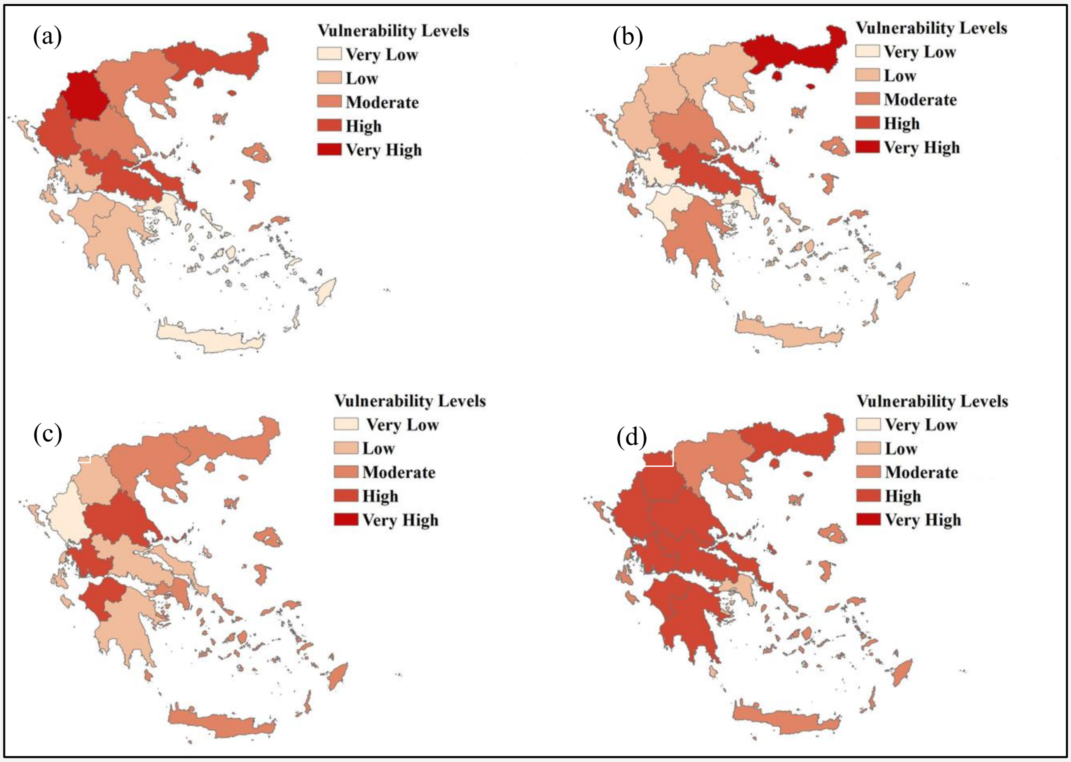

Figure 4: Energy poverty vulnerability of Greece in 2018 (a) economic vulnerability, (b) Social vulnerability, (c) building vulnerability, (d) location and climatic vulnerability

The Attica region has the lowest vulnerability levels (7.1) in comparison to the other regions. Factors that increase building vulnerability in Eastern Macedonia and Thrace include the types of houses and the use of outdated energy sources for basic household needs. Furthermore, the regions of Sterea Ellada, South Aegean, and Central Macedonia exhibit low vulnerability. The values of the SOCVUL index are depicted in Figure 4(c). Out of the 13 regions of Greece, the region of Western Greece is the one that shows the highest levels of social vulnerability (62.8), while the region of Epirus is the one that presents the most improved picture, recording the lowest value for the year 2018. The high levels of social vulnerability recorded in the regions of Thessaly and Western Greece are mainly attributed to the increased presence of single-parent households and labor insecurity.

The LOCLIMVUL indicator (Figure 4 (d)) for 2018 assesses the vulnerability levels in relation to location and climatic conditions. The region of Peloponnese showed the highest vulnerability (72.3), while the region of Attica showed the lowest levels of vulnerability (32.5). The main determinants that contributed to the strengthening of vulnerability levels were population density, heat stress, and the households residing in rural areas.

Urban overheating and climatic risk are crucial parameters that significantly exacerbate cooling energy demand and increase the energy burden of low-income households in Athens [71]. For instance, low-income households were found to be more vulnerable in excess heating and climatic variations since they consume more energy per unit area for cooling compared to wealthier households due to poor building insulation and lack of cooling systems. Moreover, during heatwaves, indoor temperatures in such energy deprived households reached critical levels, exposing residents to extreme health risks [5]. Based on the spatial analysis presented in Figure 5, the following observations can be made regarding regional disparities in energy poverty vulnerability. More specifically, the regions of Eastern Macedonia and Thrace (70.8), Sterea Ellada (59.6), Thessaly (59.1), and West Macedonia (58.3) showed the highest levels of vulnerability, while the regions of Attica (26.7), South Aegean (33.7), and Crete (39.7) recorded the lowest. The prevalence of vulnerability to energy poverty in these regions is mainly due to the presence of high vulnerability scores across the four key thematic dimensions that compose the REVPOV. The maximum value is presented in the region of Eastern Macedonia and Thrace, which geographically belongs to Northern Greece.

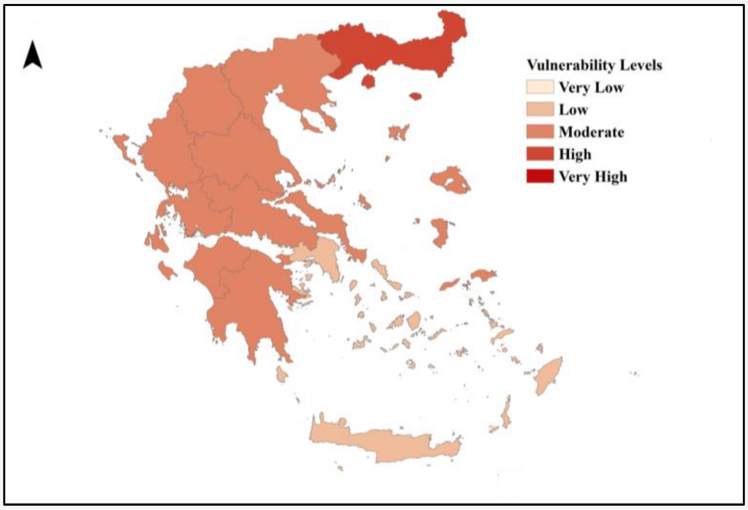

Figure 5: Spatial distribution of regional energy poverty vulnerability of Greece in 2018

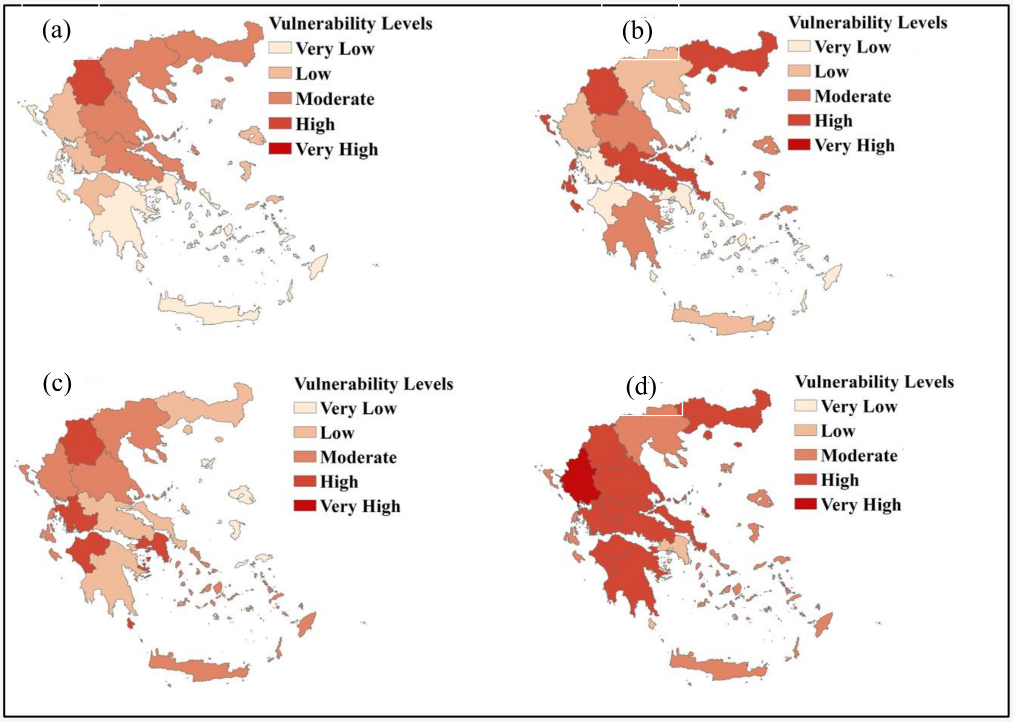

Figure 6: Energy poverty vulnerability of Greece in 2019 (a) economic vulnerability, (b) social vulnerability, (c) building vulnerability, (d) location and climatic vulnerability

Although social vulnerability (SOCVUL) in this region is at medium levels, the combined burden of the other dimensions leads to an overall high vulnerability to energy poverty (Figure 4). These findings confirm the trend recorded in previous studies, which point to the increased vulnerability of the regions of Northern Greece to energy poverty [24] and [25]. In contrast, the island regions of the South Aegean and Crete have the lowest values of the index, which may be linked to higher employment in the tourism sector, milder climatic conditions [50]. Figure 6 illustrates the four combined indicators, which are added together to create the overall energy poverty vulnerability assessment index. More specifically, the composite index ECOVUL for the year 2019 (Figure 6(a)) assesses the financial distress of households in the 13 regions of Greece. The lowest levels of vulnerability are recorded in the regions of Attica (7.8), South Aegean (7.3), and Crete (9.0).

While high levels of vulnerability (>70) are found in the region of Western Macedonia, which continues to maintain its top position in the ranking of regions in Greece. Increased energy expenditure, which is more than twice the median national energy expenditure, seems to significantly contribute to the final levels of economic vulnerability compared to the other economic sub-indices. Figure 6(b) shows the spatial distribution of the BUILDVUL index for the year 2019 in the regions of Greece. The regions of Eastern Macedonia and Thrace (75.8), Ionian Islands (64.6), and Central Greece and Western Macedonia (70.1) have the highest levels of building vulnerability. Attica (7.7), Western Greece (16.2), South Aegean (19.3), and Central Macedonia (21.4) have the lowest levels of building vulnerability. The factors that make up the overall measure of building vulnerability show that the inability of households to access modern energy sources for basic needs significantly affects the final vulnerability levels [62].

The SOCVUL indicator (Figure 6(c)) captures social vulnerability spatially in the 13 regions of Greece. Increased levels of social vulnerability were found in the regions of Western Macedonia (69.9), Western Greece (61.7), and Attica (60.5), while the lowest values in the composite index were found in the regions of South Aegean (17.0), Sterea Ellada (28.8), and Peloponnese (36.5). The presence of single-parent households is the most important determinant that shapes, to a significant extent, the levels of social precariousness between regions [61]. Furthermore, the LOCLIMVUL index (Figure 6(d)) assesses the levels of vulnerability associated with the location of the dwelling and climatic conditions. More specifically, among the 13 regions, high values (>70) in this indicator were found in the regions of Epirus (80.9), Western Macedonia (78.4), Peloponnese (76.1), and Sterea Ellada (75.2), while low levels of vulnerability (<30) were found in the region of Attica. Households living in rural areas, heat stress, and population density all influenced the vulnerability levels of LOCLIMVUL in 2019.

The spatial distribution of energy poverty vulnerability, as illustrated in Figure 7, reveals significant regional disparities across Greece. The regions of Attica, Crete, and South Aegean have the lowest levels of vulnerability to energy poverty, occupying the last positions in the ranking. These regions register high values in the LOCLIMVUL and SOCVUL indicators related to the socio-demographic conditions of households, the climatic conditions that shape electricity consumption patterns, and the challenges posed by living in rural areas. In contrast, low performance is recorded for the ECOVUL and BUILDVUL indicators, which assess the economic situation of households and living conditions. On the contrary, the region of Western Macedonia has a high value in the overall REVPOV indicator (around 70), indicating a strong vulnerability to energy poverty. This deterioration is attributed to the coexistence of unfavorable conditions in all structural indicators: limited financial resources, old and non-modernized building stock, socially vulnerable groups, unfavorable climate, and the challenge of living in rural areas. Figure 8 depicts the spatial distribution of the four composite indexes that capture different aspects of vulnerability to energy poverty across the 13 administrative regions of Greece in 2020.

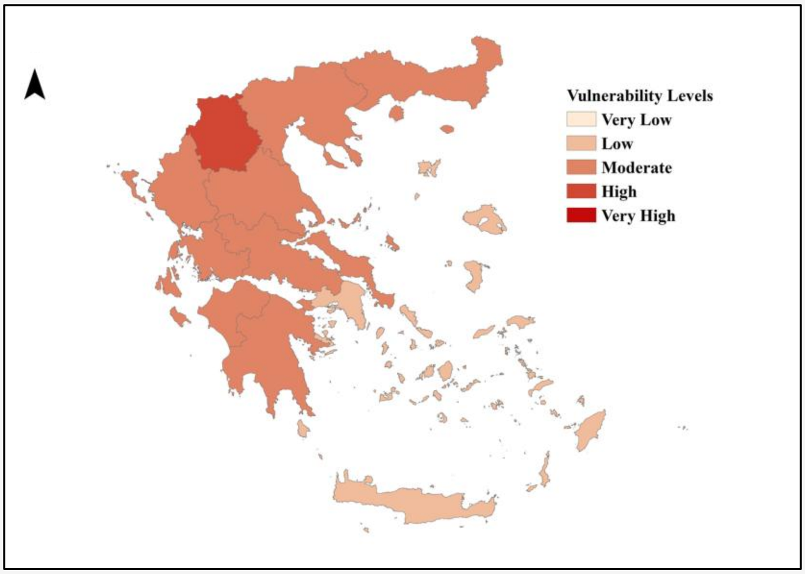

Figure 7: Spatial distribution of regional energy poverty vulnerability of Greece in 2019

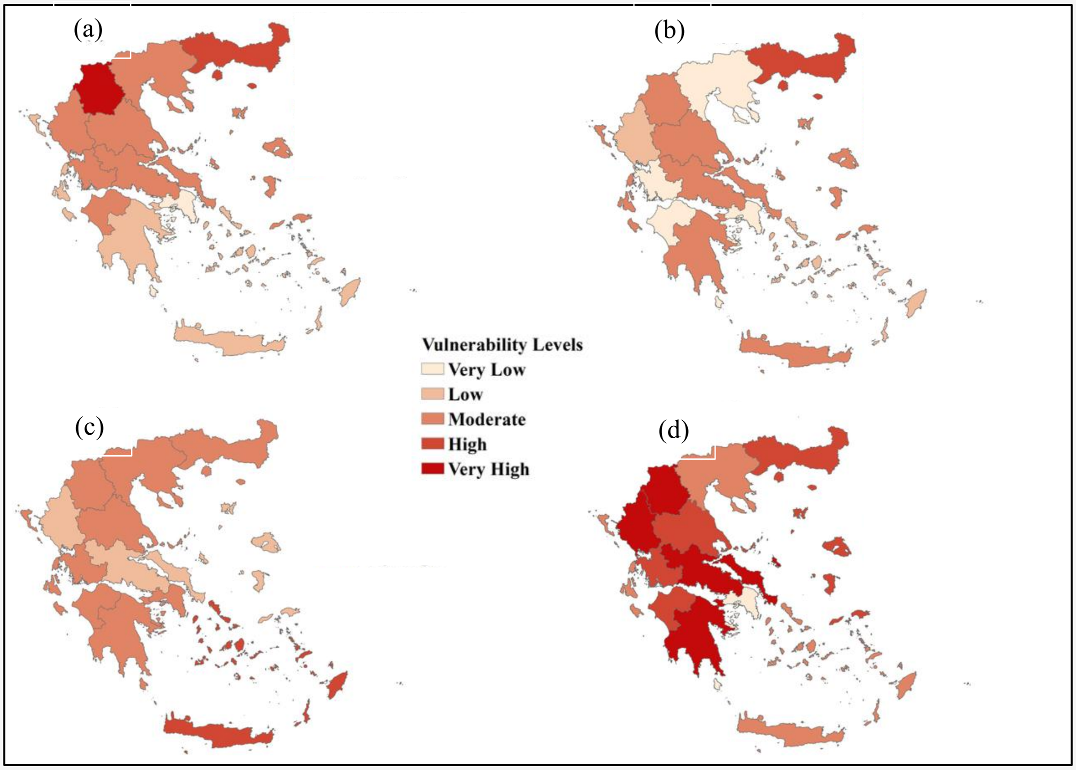

Figure 8: Energy poverty vulnerability of Greece in 2020 (a) economic vulnerability, (b) social vulnerability, (c) building vulnerability, (d) location and climatic vulnerability

Economic vulnerability (Figure 8(a)) appears particularly high in the regions of Western Macedonia (81) and Eastern Macedonia and Thrace (74.3), while Attica, on the contrary, shows a very low value of the index (<20). 46.2% of the regions (6 out of 13) fall into the category of medium economic hardship. The high vulnerability observed, mainly in the regions of Northern Greece, is primarily attributed to the high rate of energy expenditures and the proportion of households at risk of poverty and social exclusion (see Figure 3).

The BUILDVUL index (Figure 8(b)) captures the levels of building vulnerability in the regions of Greece in 2020. The spatial analysis shows high levels of vulnerability (>70) in the region of Eastern Macedonia and Thrace. In contrast, low values of the index (<20) were recorded in the regions of Attica, Central Macedonia, and Central Greece. Approximately 7 out of 13 administrative regions recorded medium levels of vulnerability (between 40 and 60 percentage points) in the given year. Considering the factors that compose the BUILDVUL index, it is worth noting that the accessibility of residents to conventional energy sources for covering basic household needs appears to have a significant impact on building vulnerability levels. Social vulnerability levels vary spatially across the 13 regions of Greece in 2020 (Figure 8(c)). The regions of the South Aegean and Crete recorded the highest values (>60) compared to the other regions. Conversely, the regions of Sterea Ellada (26.3) and North Aegean (29.7) demonstrate the lowest levels of social vulnerability and rank in the last two positions. Furthermore, single-parent households, renting homes, and unstable jobs are among the factors that significantly influence the final scores of the SOCVUL index in the regions being studied during the reference year [65] and [69]. Figure 8(d) illustrates the spatial distribution of the LOCLIMVUL index in 2020 in the 13 regions of Greece. The regions of Epirus (84.6), Western Macedonia (82.4), Central Greece (83.3), and Peloponnese (82.5) recorded high levels of vulnerability. In contrast, in 2020, the Attica region (18.9) demonstrated exceptionally low values of vulnerability. Living in rural areas and facing high temperatures are key factors that raise vulnerability levels related to climate and location, which ultimately affects the LOCLIMVUL index [69] and [71]. Figure 9 presents the results of the REVPOV. In 2020, the 13 regions of Greece recorded different levels of vulnerability, which demonstrates the uneven geographical distribution of the phenomenon [1] and [3].

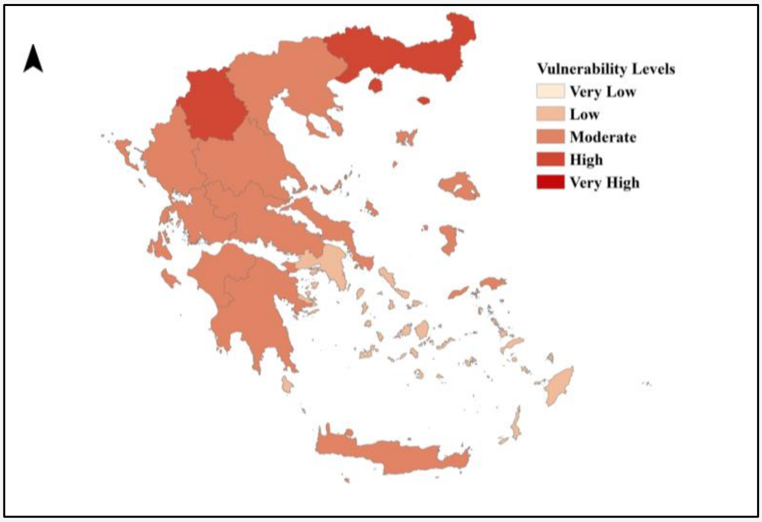

Figure 9: Spatial distribution of regional energy poverty vulnerability of Greece in 2019

Table 3: Descriptive Statistics of REVPOV index in Greece across the study period (2018-2020)

Descriptive Statistics		Years of Analysis		
		2018	2019	2020
REVPOV	Min	26.7	26.3	23
	Max	70.8	69.9	67.9
	Average	48.2	45.3	49.3
	Median	46.8	45.3	48.9
	1st Quartile (Q1)	44.2	37.8	45.6
	3rd Quartile (Q3)	58.3	51.2	54.7
	Skewness	0.09	0.32	-0.50
	Kurtosis	0.20	0.26	1.33

The regions of Eastern Macedonia and Thrace (67.9) and Western Macedonia (66.3) showed the highest levels of vulnerability. The REVPOV registered low values (<40) in the Attica and South Aegean regions. Moreover, most of the regions (10 out of 13) recorded moderate levels of vulnerability to energy poverty in 2020. The high scores in the four key indicators, which aggregate the overall index, account for the high vulnerability values observed in Northern Greece (Figure 8). The regions of Eastern Macedonia, Thrace, and Western Macedonia in Northern Greece exhibit the highest vulnerability to energy poverty during the examined period (see Figures 5, 7 and 9). The highest vulnerability is reinforced by the co-existence of causal factors that deteriorate the levels of energy security between the two examined areas. Firstly, economic instability and the poor quality of existing dwellings contribute to the prevalence of energy precarity in Eastern Macedonia and Thrace [25]. Furthermore, the geographical isolation of Eastern Macedonia and Thrace deteriorates economic development and enhances inequalities between societal groups. On the other hand, the high levels of vulnerability in Western Macedonia are mainly related to decarbonization transition, which, despite its multiple benefits for the environment and well-being, has socio-economic impacts associated with job losses and the gradual deindustrialization of the energy market [23] and [25].

The robustness of the REVPOV was evaluated through a sensitivity analysis comparing the two alternative weighting schemes during the study period 2018-2020. The results showed that the MAD ranged from 4.5 to 5.3, and Spearman's rank correlation remained high (≥0.88) during this period. These findings indicate strong agreement between the two weighting scenarios. Furthermore, it is worth mentioning that the rank shifts of regions were limited, with a mean shift below 1.3 and maximum shifts not exceeding 4 ranks. The composite index remains relatively stable at weight changes, and this indicates that it could be used as a trustworthy and credible tool for policy making [86]. The descriptive statistics of the REVPOV for the overall assessment of energy poverty vulnerability present the following findings (see Table 3).

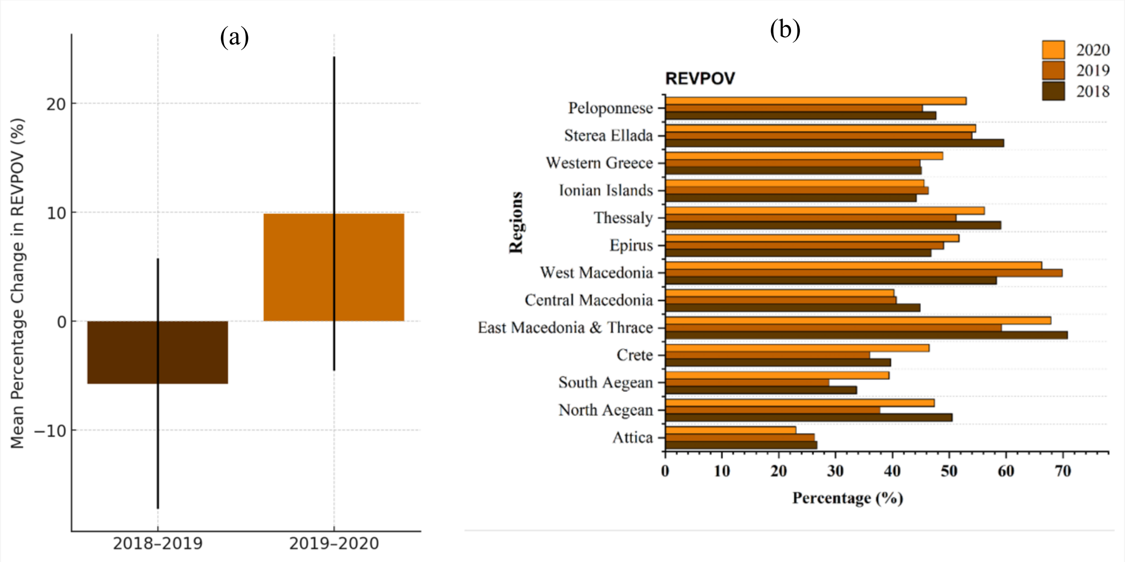

Figure 10: (a) Mean percentage change in REVOPOV across Greek regions by period (2018–2019 vs. 2019–2020), with standard deviations as error bars
(b) Temporal evolution of energy poverty vulnerability in Greece's regions from 2018 to 2020

In 2018, the average energy poverty vulnerability value was 48.2 and the median 46.8, while in 2019, there was a decrease in both values. In 2020, however, there was an increase in the average (49.3) and median (48.9). The change in asymmetry is noteworthy: from slightly positive in 2018 (0.09) and 2019 (0.32), it becomes negative in 2020 (-0.50), indicating that more regions showed values higher than the average. Overall, the evidence suggests a worsening of inequalities and an increase in uncertainty in 2020. These findings align with the seminal work of assessing energy poverty levels in Greece [24].

A paired-sample t-test was performed to compare the average percentage change in the REVOPOV index in the 13 administrative regions of Greece between 2018-2019 and 2019-2020 (Figure 10(a)). The results showed that there was a statistically significant difference between the two time periods, $t(12) = 2.41$, $p = .033$, $d = 0.67$, suggesting a moderate effect size. The mean percentage change for the 2018-2019 period was $M = -5.76$, $SD = 11.49$, while for the 2019-2020 period was $M = 9.85$, $SD = 14.43$. A Shapiro-Wilk test of normality was performed beforehand, which revealed no significant deviation from the normal distribution ($W = 0.972$, $p = 0.919$), confirming the validity of the use of the parametric test. During the period 2019-2020, a significant increase in the values of the composite index REVPOV was recorded compared to 2018-2019 in all the regions of Greece. The percentage increase was particularly pronounced in the island regions (North Aegean, South Aegean, Crete), which showed an increase of more than 20 percentage points compared to the mainland regions (Figure 10(b)). The outbreak of the Covid-19 pandemic further increased the levels of socio-economic vulnerability, especially in regions with a high dependence on tourism activities. The imposition of restrictive measures led to a significant reduction in income for businesses, increasing the risk of transition to energy poverty during the period under review [87].

5. Conclusions

The study presented the creation of an innovative composite indicator for the regional assessment and evaluation of energy poverty levels in Greece. This index incorporates a set of determinants that capture aspects of the phenomenon in terms of household economic hardship, building, and social vulnerability, as well as various climatic factors. The composite index results emphasize the phenomenon's spatial heterogeneity, which contributes to the intensification and strengthening of regional inequalities. For the study period (2018-2020) the regions of Eastern Macedonia and Thrace, Western Macedonia, Thessaly, and Sterea Ellada appear to have higher levels of vulnerability, in contrast to the regions of Attica and South Aegean. The composite indicator plays a dual role. On the one hand, it enables decision-makers to identify areas affected by the harmful effects of the phenomenon, allowing them to design more effective strategies aimed at addressing the structural causes of energy poverty. On the other hand, by monitoring vulnerability levels over time, it helps policymakers evaluate existing interventions and adjust strategies accordingly.

Future research is recommended to better understand and address the challenges of energy poverty. First of all, future research should focus on assessing vulnerability levels at the intra-regional scale (NUTS-3) to highlight the spatial disparities between urban and rural areas. Additionally, future studies should explore the interaction between energy poverty and climate change by identifying areas that are becoming vulnerable due to climate variability. Finally, case studies should also be conducted to investigate the benefits of renewable energy penetration in mitigating energy vulnerability by ensuring that all socio-economic groups have equitable access to affordable and environmentally friendly energy.

6. Policy Recommendations

The study's findings suggest that strategies to reduce vulnerability levels should concentrate on specific measures. Furthermore, it is recommended to provide subsidies, as short-term measures, to regions with significant economic vulnerability to mitigate the immediate effects of energy poverty and assist households with a high share of energy expenses. Upgrading the energy efficiency of the building stock in areas with high building vulnerability and providing subsidies to equip households with energy-efficient household appliances, is also proposed. Adapting such measures shall contribute significantly to mitigating long-term energy poverty levels.

From 2012 onwards, heating allowances will be granted to specific categories of consumers to cover their energy costs. During the energy crisis, it is foreseen that these allowances will be extended to cover other groups of consumers and different types of energy sources. One of the most important measures to mitigate energy poverty has been the protection of vulnerable consumers through the provision of social household tariffs. From 2017, low-income households received financial support to prevent electricity cuts due to unpaid debts. At the same time, since 2011 to date, energy upgrading programs for residential buildings, such as the “‘Energy Savings at Home, have been implemented, which aim to provide financial support to households for the energy upgrading of their homes. It is worth noting that incentives are foreseen to support the installation of Renewable Energy Sources (RES) projects by energy communities to meet the energy needs of both their members and vulnerable consumers. These actions are aligned with the Greek National Energy and Climate Plan (NECP), which emphasizes equitable access to clean energy. A quantitative target has been set to reduce energy poverty levels, as defined in the NECP, by at least 50% and 75% in 2025 and 2030 respectively.

Finally, the study highlights the necessity of strengthening social support mechanisms, particularly in areas with high levels of social vulnerability, by offering financial support to elderly people and single-parent households to significantly reduce their vulnerability. To address the growing threat of exposure to extreme weather events, it is recommended that national and regional energy poverty policies integrate climate change adaptation strategies, including the promotion of renewable energy sources and energy-efficient technologies.

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