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Energy Poverty Scenarios with Endogenous Thresholds: A Class of Distributional Indicators Based on the Beta Distribution

Scenari di povertà energetica con soglie endogene: una classe di indicatori distributivi basati sulla distribuzione Beta

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TABLE OF CONTENTS

INTRODUCTION 1
CHAPTER 1 5
1.1: THE HISTORICAL EMERGENCE OF ENERGY POVERTY 5
1.2 The Emergence And Evaluation Of Fuel Poverty Measurement 9
1.3 The Boardman Framework and the Evolution of Fuel-Poverty Measurement 12
1.4 The Multidimensional Turn: Capability Approach and Energy Justice 16
1.5 Synthesis and the Transition to Multi-Level European Governance 21
CHAPTER 2: 23
2.1 Introduction and Conceptual Framework 23
2.3 The Italian Policy Framework: From Fragmented Welfare to Regulated Energy Protection 32
2.4 Chapter Conclusions 40
CHAPTER 3 42
3.1 Measuring Energy Poverty: The Methodological Problem 42
3.2 Conventional Expenditure-Based Approaches to Measuring Energy Poverty 43
3.3 Beta Distribution and the Experimental Identification of an Endogenous Upper-Tail Threshold 50
3.4 From the Energy-Burden Tail to the Joint Energy-Poverty Framework 57
3.5 Empirical Validation and Robustness Strategy 62
3.6 Critical Assessment and Methodological Limitations 65
3.7 Conclusion 68
CHAPTER 4: EMPIRICAL RESULTS AND ASSESSMENT OF THE ENDOGENOUS THRESHOLD 70
4.1 Data and empirical implementation 70
4.2 Regional energy-burden distributions and Beta estimates 72
4.3 Regional endogenous thresholds 74
4.4 Comparison of the four energy-poverty indicators 77
4.5 The changing geography of Italian energy poverty 82
4.6 Spatial evidence and empirical assessment 85
4.7 Discussion, robustness and limitations 91
4.8 Conclusion 95
CONCLUSION 97
REFERENCES 101

INTRODUCTION

Energy poverty has progressively emerged as a distinct dimension of socioeconomic vulnerability, reflecting the difficulty experienced by households in securing adequate domestic energy services without compromising other essential needs. Although concerns over household energy affordability became particularly visible following the energy-price shocks of the 1970s, the concept has subsequently developed far beyond its initial interpretation as a problem of excessive fuel expenditure. Contemporary approaches increasingly recognise energy poverty as a multidimensional phenomenon arising from the interaction between household economic resources, energy prices, dwelling characteristics, energy efficiency, climatic conditions and the broader institutional environment in which energy services are provided.

This conceptual evolution has important consequences for both public policy and empirical analysis. Access to adequate heating, cooling, lighting and other domestic energy services affects living conditions, health, social participation and the capacity of individuals to achieve acceptable standards of well-being. Energy poverty therefore cannot be understood exclusively as a particular manifestation of general income poverty. Households with similar economic resources may face substantially different energy requirements, while households experiencing severe constraints may reduce their consumption to levels at which observed expenditure no longer reveals the actual extent of deprivation. The identification of energy-poor households consequently depends not only on the underlying socioeconomic condition but also on the criteria through which that condition is measured.

The policy relevance of this issue has increased considerably within the European Union. The progressive liberalisation and integration of European energy markets was accompanied by growing recognition of consumer vulnerability and, subsequently, by the incorporation of energy poverty into the wider framework of European energy and climate governance. The Clean Energy framework, the European Green Deal, the Renovation Wave, the “Fit for 55” package and the introduction of the Social Climate Fund illustrate the increasing connection between decarbonisation and social protection. This relationship is particularly important because the costs and benefits associated with the energy transition are not necessarily distributed uniformly across households and territories. Policies designed to accelerate decarbonisation may therefore require complementary mechanisms capable of protecting households with limited economic resources or structurally high energy needs.

Italy provides a particularly relevant context in which to examine these questions. National policy combines traditional affordability instruments, including the social electricity and gas bonuses, with

measures directed toward energy efficiency, renewable-energy access and structural transformation of household energy consumption. At the same time, substantial territorial differences in climate, housing characteristics, expenditure levels and socioeconomic conditions complicate the identification of a uniform profile of energy vulnerability. The Italian case therefore highlights a central tension in energy-poverty analysis: comparable national criteria are useful for policy monitoring, but uniform measurement rules may conceal important differences in the circumstances faced by households across regions.

Against this background, the central problem addressed by this thesis concerns the measurement of energy poverty and, in particular, the role played by threshold construction and geographical calibration in determining which households and territories are identified as vulnerable. Existing expenditure-based approaches provide different answers to this problem. Fixed thresholds offer transparency and comparability, while relative indicators adapt to the characteristics of the reference population; measures based on required energy expenditure attempt to capture underlying energy needs, whereas indicators based on realised expenditure are more readily applicable to standard household-budget data but remain sensitive to under-consumption and differences in consumption behaviour. Consequently, no individual expenditure indicator provides a complete representation of energy poverty, and differences among alternative measures may reflect substantive differences in what each methodology makes statistically visible.

The thesis investigates this measurement problem by combining established expenditure-based indicators with an experimental distributional approach. The household energy-expenditure share is treated as a bounded variable and modelled through the Beta distribution. The central methodological experiment examines whether the rightmost admissible stationary-curvature point of the fitted distribution can provide a candidate endogenous boundary for delimiting the upper expenditure-burden tail. Rather than imposing the same numerical energy-burden threshold independently of the observed distribution, this procedure allows the candidate boundary to respond to regional distributional characteristics.

Importantly, the proposed criterion is not assumed to constitute a theoretically or normatively established energy-poverty threshold. Its geometric identification within the fitted distribution and its substantive interpretation as a poverty boundary represent distinct questions. The methodology is therefore developed as an empirical investigation: the rightmost stationary-curvature point is treated as a candidate criterion whose behaviour, stability and implications for household classification must be assessed against alternative measurement specifications. This distinction is central to the

contribution of the thesis and prevents the statistical geometry of the expenditure distribution from being interpreted, by construction, as evidence of socioeconomic deprivation.

To connect energy burden with the household's broader economic position, the candidate threshold is combined with an economic-vulnerability condition based on 60% of median total expenditure. The framework is organised into four specifications that contrast fixed and endogenous energy-burden thresholds under national and regional economic reference structures. This design makes it possible to investigate two related dimensions of measurement choice: whether the energy-burden boundary is imposed or derived from the fitted distribution, and whether economic vulnerability is evaluated relative to a common national benchmark or to regional expenditure conditions. The resulting indicators are not intended to replace conventional energy-poverty measures, but to provide a systematic framework for examining how alternative methodological choices affect measured vulnerability.

The empirical application uses microdata from the Italian Household Budget Survey (HBS). Annual files covering the period 2014–2023 are harmonised to construct consistent expenditure variables, while the regional Beta-threshold application focuses on the 2023 cross-section across the twenty Italian regions. Household energy expenditure is related to total consumption expenditure, and differences in household composition are addressed through equivalence scaling. Survey weights are used where required to ensure that distributional benchmarks reflect the represented population. The analysis subsequently examines regional expenditure-share distributions, fitted Beta densities, candidate endogenous thresholds, the incidence generated by the four measurement specifications and their geographical representation. Spatial econometric evidence is additionally employed as a diagnostic tool to examine whether alternative indicators are associated with different territorial statistical structures.

The empirical analysis is consequently diagnostic rather than causal. Its purpose is not to establish the determinants of regional energy poverty or causal transmission between neighbouring territories, nor to demonstrate that the endogenous criterion constitutes a uniquely correct poverty threshold. Instead, it evaluates how the proposed candidate boundary behaves when confronted with observed regional distributions and whether allowing the threshold and economic reference structure to respond to territorial conditions reveals information that may remain hidden under a uniform measurement rule. The analysis therefore places particular emphasis on robustness, geographical sensitivity and the distinction between formal statistical properties and substantive socioeconomic interpretation.

The thesis is organised into four chapters. Chapter 1 reconstructs the historical and conceptual emergence of energy poverty, from the energy shocks of the 1970s and the early expenditure-based literature to the contributions of Boardman and Hills and the subsequent development of multidimensional perspectives based on capabilities and energy justice. Chapter 2 examines how this conceptual evolution was translated into European and Italian policy, considering the progressive recognition of vulnerable consumers, the integration of energy poverty into European climate governance and the development of national instruments for affordability protection and structural intervention.

Chapter 3 turns from conceptual and institutional development to the methodological problem of measurement. It reviews the principal expenditure-based indicators relevant to the analysis and develops the Beta-based experimental methodology, the candidate endogenous threshold and the four-indicator architecture combining alternative energy-burden boundaries and economic reference structures. It also establishes the validation and robustness strategy through which the proposed criterion is subsequently assessed. **C**hapter 4 applies this framework to the Italian regional data, examining regional distributions and Beta estimates, candidate thresholds, alternative estimates of energy-poverty incidence, geographical patterns and spatial statistical evidence. The chapter ultimately evaluates both the information provided by the endogenous approach and the limitations that prevent its formal geometric criterion from being interpreted as a uniquely valid socioeconomic boundary.

Taken together, the four chapters address energy poverty as simultaneously a conceptual, institutional and measurement problem. The underlying argument of the thesis is that identifying energy vulnerability is not a neutral statistical exercise: choices concerning expenditure variables, thresholds, economic reference populations and geographical calibration influence the households and territories that become visible through an indicator. By combining the historical and policy evolution of energy poverty with an experimental regional measurement framework, the thesis therefore seeks to contribute to the broader question of how energy vulnerability can be identified in a manner that remains empirically informative while making its underlying methodological assumptions explicit.

CHAPTER 1

1.1: THE HISTORICAL EMERGENCE OF ENERGY POVERTY

Prior to the 1970s, the economic expansion experienced by Western industrialized countries during the post-war "Golden Age" rested on the widespread assumption that fossil fuels would remain abundant, affordable, and continuously available. Energy was therefore regarded as a low-cost production input and an almost invisible household necessity rather than a potential source of social vulnerability [1]. Within macroeconomic modeling and social policy frameworks, the risk of a household's inability to secure sufficient domestic warmth or power was virtually absent. Poverty was conceptualized almost exclusively through broader rubrics of income deficiency or general material deprivation [2].

The first major disruption emerged in 1973, when the Arab-Israeli conflict was followed by restrictions on oil supplies imposed by Arab oil-exporting countries. The resulting contraction in supply produced an abrupt increase in international oil prices, which rose to approximately four times their pre-crisis level between late 1973 and early 1974 [1]. For oil-importing industrialised economies, the shock revealed the extent to which post-war growth had become dependent on access to relatively inexpensive petroleum. Its consequences extended beyond the immediate shortage: higher energy costs intensified the inflationary pressures already affecting advanced economies and contributed to a deterioration in macroeconomic conditions during the decade [3]. Although the embargo itself was subsequently terminated, oil prices did not return to their earlier levels, leaving energy costs and security of supply as persistent economic and policy concerns [1].

A second oil crisis occurred in 1979, resulting from the Iranian Revolution. High levels of social unrest severely damaged the Iranian oil industry, leading to a large loss of global output and a corresponding rise in prices. The situation worsened following the outbreak of the Iran-Iraq War in 1980, which further added to the level of instability throughout the region. By 1981, the price of oil was stabilized at an unprecedented $32 per barrel [1].

The geopolitical cataclysms of the 1970s did not merely represent temporary spikes in a volatile market; rather, they engineered a permanent, structural upward shift in the global energy price baseline. When the dust of the immediate diplomatic and military crises settled, global economies discovered that they could not revert to the status quo. Rather, they were forced to adapt to a new economic paradigm where energy was a persistently expensive, heavily financialized, and politically contested resource. This enduring inflation of the energy baseline acted as a continuous, systemic tax on the entire global architecture of production and consumption, fundamentally altering how capital, labour, and resources were allocated across industrialized economies. Far from representing a

temporary disruption, the first oil crisis exposed the structural dependence of industrialized economies on inexpensive energy. This vulnerability became even more evident following the second oil shock only a few years later [3].

From a macroeconomic perspective, the persistence of high energy prices after 1979 institutionalized a profound supply-side shock that crippled prevailing economic theories and monetary policies. Because energy is a primary, non-substitutable input embedded within every stage of the global supply chain, its elevated cost immediately inflated production overheads, raw material processing, and international transportation logistics. This led to the emergence of stagflation—a toxic economic environment where slow growth and high unemployment coexisted with runaway inflation.

The inflationary consequences of the oil shocks were also shaped by the monetary and institutional environment in which they occurred. In the United States, Goodfriend (2007) characterises monetary policy during the 1970s as being in "disarray", highlighting the difficulties faced by the Federal Reserve in reconciling price stability with concerns about employment and output [4]. More broadly, the persistence of inflation across advanced economies cannot be attributed to energy prices or monetary policy in isolation. Gomellini, Pellegrino and Corsello (2025) [5] emphasise that the oil shocks interacted with the breakdown of the Bretton Woods monetary framework and with institutional mechanisms affecting wage formation and fiscal policy. Their analysis also documents substantial differences across countries, indicating that similar external energy shocks could generate different inflationary outcomes depending on domestic institutions and policy responses. The experience of the 1970s therefore illustrates how a sharp increase in energy costs can interact with existing macroeconomic structures rather than producing uniform effects across economies.

Persistently high energy prices also encouraged structural adjustments in the energy use of industrialised economies. Governments and firms increasingly pursued energy conservation, improvements in efficiency and substitution away from oil towards other energy sources, including natural gas, coal and nuclear power. These changes gradually reduced the oil intensity of economic activity and weakened the dependence of advanced economies on imported petroleum. By the early 1980s, declining oil demand in industrialised countries coincided with additional production from non-OPEC sources, contributing to a substantial easing of the international oil market. The shortages that had characterised the previous decade therefore gave way to markedly weaker market conditions, while the experience of the two oil shocks had already established energy efficiency and security of supply as persistent policy concerns.

While firms gradually adapted through technological improvements and energy efficiency

investments, residential consumers possessed far less flexibility. The consequences of the new price environment became more evident at the domestic level.

On a microeconomic and human scale, the ramifications of this persistently high-cost environment were felt acutely, shifting from an abstract corporate concern to an intimate, everyday financial hardship for ordinary citizens. The historical transition to a high-energy-price regime meant that utilities—such as electricity, residential heating, and domestic fuel—were transformed from cheap, invisible background necessities into dominant, non-negotiable household expenditures. As the inflated costs of crude oil trickled down into consumer price indices, everyday staples, and public utility bills, families experienced a prolonged, severe squeeze on their discretionary income.

This economic pressure was distributed in a regressive and highly disproportionate manner across socio-economic demographics. Because lower-income households must allocate a significantly higher percentage of their total income to meet baseline subsistence needs, the permanent elevation of energy tariffs systematically eroded their purchasing power and standard of living. As these macroeconomic price shocks reached the domestic level, they encountered a residential infrastructure that was wholly unequipped to handle them, unlike firms, residential energy users could not easily substitute away from domestic energy consumption, making residential energy demand particularly exposed to higher utility costs. The post-WWII housing boom across Europe and North America had prioritized rapid construction and low initial capital expenditure over thermal efficiency. Due to the historical legacy of cheap fuel, homes built in the 1950s and 1960s featured minimal insulation, single-glazed windows, and highly inefficient heating systems.

When retail utility tariffs escalated, many households found themselves locked into energy-intensive consumption patterns due to the physical realities of their housing stock. Because domestic energy is a textbook example of an economically inelastic good—meaning households cannot easily or immediately reduce consumption of heating, cooking, or lighting without compromising basic survival—consumers had to absorb the additional costs. The compounding effects of the 1973 and 1979 oil crises had permanently redefined energy from a cheap commodity into a strategically important necessity.

As the economic consequences of the oil crises gradually became embedded in everyday life, attention shifted from national economic performance to household welfare. By the early 1980s, this sudden financial pressure prompted massive behavioral changes among the public. In the United States, over 12 million homeowners rushed to caulk their homes, and millions more installed weatherstripping and storm windows to trap heat. Yet, researchers and economists quickly realized that behavioral modifications and basic insulation were minor band-aids. The underlying problem

was rooted in deeper economic and housing-related conditions. The escalating costs exposed a stark disparity: high-income families could absorb the price hikes or invest in major energy-efficient retrofits, whereas low-income families were trapped in poorly insulated housing stock, forced to cut back on food and medical care just to afford heat.

This intersection of soaring prices, stagnant incomes, and inefficient housing proved that energy hardship was no longer just a temporary side effect of broader macroeconomic inflation. It had crystallized into a unique, systemic form of deprivation. Data compiled by the Institute for Fiscal Studies (IFS) shows that by 1985, domestic energy expenditure in the UK reached an all-time high, consuming an average of 10% of total household budgets. For the poorest decile of the population, that burden was nearly double, forcing vulnerable families to allocate almost 20% of their entire income just to keep the lights and heat on.

A similar economic shock unfolded across the Atlantic. A longitudinal analysis by the Federal Reserve Bank of Chicago revealed that direct household energy spending soared to an average of 11% of total expenditures during the early years of the 1980s. Historical reporting from *The New York Times* highlighted that between 1978 and 1980 alone, the average American household's fuel bill jumped from $724 to $917, driven by a staggering 105% increase in fuel-oil prices.

As the late 1980s progressed, researchers and social scientists recognized that traditional poverty metrics—which looked strictly at generalized income thresholds—completely failed to capture this specific crisis. The empirical data proved that a household could technically sit above the official poverty line but still freeze during the winter because the characteristics of their homes required an astronomical, unaffordable amount of energy to stay warm. These empirical findings raised a crucial question: why were some households disproportionately affected despite not necessarily falling below conventional poverty thresholds? Early foundational work by researchers like Alan Lewis in 1982 began mapping how high baseline utility costs strictly limited the core energy consumption of vulnerable groups, showing that the poor were forced to under-consume energy to their own physical detriment. By the end of the 1980s, the available evidence came to suggest that energy hardship could no longer be interpreted simply as a manifestation of general poverty. Instead, it represented a distinct form of deprivation arising from the interaction between household income, energy prices, and housing conditions. Existing poverty measures proved unable to capture this new reality, creating the need for analytical frameworks specifically designed to identify households vulnerable to excessive energy costs. It was within this intellectual and policy context that the first systematic attempts to define and measure energy poverty emerged.

1.2 The Emergence And Evaluation Of Fuel Poverty Measurement

The oil crises exposed a new form of household vulnerability that conventional poverty indicators failed to capture. Although policymakers increasingly recognized that rising utility costs were placing pressure on low-income households, existing welfare metrics continued to interpret domestic energy expenditure as merely another consequence of income poverty. As global fuel tariffs quadrupled and stagflation settled across primary product markets, domestic energy ceased to be an invisible, background overhead. Instead, it transformed into a dominant, non-negotiable household expenditure that directly threatened the budgets of low-income families [3].

Early welfare economics treated domestic fuel consumption through an expenditure-centric lens, operating on the implicit assumption that energy hardship was merely a secondary symptom of general low income. Under standard poverty definitions, policy responses relied on broad welfare transfers, assuming that general income support would naturally alleviate domestic strain.

This analytical gap created the conditions for the first systematic attempt to isolate energy-specific vulnerability. It was in this context that Baron C. Isherwood and Ruth M. Hancock undertook the first systematic attempt to identify households facing disproportionate domestic energy costs [4].

A household could sit technically above the official income poverty line yet experience severe material deprivation because an exorbitant, unavoidable share of its budget was consumed by utility bills. A new analytical framework was therefore required to connect macroeconomic energy shocks with household-level financial vulnerability. It was within this transitional vacuum that Baron C. Isherwood and Ruth M. Hancock executed the first systematic attempt to quantitatively isolate households facing disproportionate energy costs.

In 1979, working within the Economic Adviser's Office of the UK Department of Health and Social Security, Isherwood and Hancock produced the internal working paper *Household Expenditure on Fuel: Distributional Aspects*. At a time when fuel poverty still lacked a formal definition, their objective was to identify the demographic groups most exposed to rising domestic energy costs. To do so, they used microdata from the 1977 UK Family Expenditure Survey (FES), which provided detailed information on household income, composition and actual expenditure on fuel, light and power [4].

Their approach was based on relative expenditure strain rather than on physical housing conditions or theoretical heating requirements. A household was classified as fuel-vulnerable when its recorded expenditure on fuel, light and power exceeded twice the median expenditure of households with a comparable composition. Rather than applying a single threshold to the entire population, Isherwood

and Hancock differentiated between household types, including single pensioners, couples and families with children, and also examined expenditure patterns across income deciles. This stratification allowed them to account for differences in household size and baseline energy needs [4].

The analysis revealed that households exceeding the twice-the-median threshold devoted approximately 12% of their disposable income to domestic energy expenditure. The burden was strongly regressive: fuel costs absorbed a much larger share of available resources among lower-income households than among wealthier groups. These findings provided early quantitative evidence that rising energy costs did not affect all households uniformly. More importantly, they demonstrated that domestic energy expenditure could generate a specific form of vulnerability that conventional income-poverty indicators were unable to identify [4].

Isherwood and Hancock's work was principally pioneering because it transformed domestic energy spending from an unexamined sub-category of general consumption into an independent object of microeconomic analysis. By demonstrating that domestic energy expenditure generated forms of socio-economic vulnerability that conventional poverty indicators failed to identify, their study provided some of the earliest empirical proof that energy-related hardship warranted analysis as a distinct dimension of household deprivation [4].

Despite its immense historical and empirical merit, the Isherwood and Hancock framework contained a fundamental conceptual limitation that ultimately restricted its utility as a long-term policy diagnostic. Because their model was built entirely on retrospective ledger accounting—evaluating actual recorded money spent on fuel—it contained an analytical blind spot regarding severe physical deprivation [2].

Under severe budget constraints, low-income households often respond to rising energy prices by reducing their consumption rather than maintaining adequate heating. Faced with competing essential expenses such as food and housing, many households deliberately under-heat their homes to avoid unaffordable utility costs [2].

This behavioural response exposed the principal weakness of expenditure-based indicators. Because vulnerability was measured through observed expenditure, households that reduced their energy consumption despite living in inadequate thermal conditions appeared to have low energy costs. Consequently, those experiencing the greatest deprivation could remain statistically invisible, since under-heating artificially reduced observed expenditure despite persistent thermal deprivation [2].

The model also failed to distinguish between high expenditure caused by inefficient housing and high expenditure resulting from voluntary consumption. An affluent household occupying a large, energy-inefficient dwelling could exceed the expenditure threshold without experiencing deprivation, whereas a low-income household living in an inadequately insulated home could remain undetected simply because it restricted its energy use.

The metric diagnosed retrospective financial transactions, but remained blind to the built environment, thermal insulation, system efficiencies, and human health requirements [2].

The limitations of Isherwood and Hancock's expenditure-based framework became increasingly apparent during the 1980s. As research progressed, scholars recognized that an accurate assessment of energy deprivation could not rely solely on observed expenditure, but also had to consider the energy necessary to maintain adequate living conditions [2].

This conceptual shift was formalized by Brenda Boardman in her landmark 1991 study *Fuel Poverty: From Cold Homes to Affordable Warmth*. Building upon the empirical foundations established by Isherwood and Hancock, Boardman proposed replacing actual expenditure with an estimate of the expenditure required to achieve an adequate standard of indoor warmth [2].

This represented more than a methodological refinement. It marked a fundamental change in how fuel poverty was conceptualized, shifting attention from household spending behaviour to the interaction between income, housing conditions and essential energy needs [2]. Although limited, Isherwood and Hancock's framework established the empirical foundations upon which Boardman developed this new understanding of fuel poverty. Their work transformed energy hardship into a measurable social issue, while Boardman's contribution redefined how that hardship should be assessed [2, 4].

By the late 1980s, the academic framework surrounding domestic energy consumption found itself at an analytical impasse. As established by early expenditure-based models, most notably Isherwood and Hancock’s 1979 study for the UK Department of Health and Social Security, energy hardship was initially quantified using actual recorded outlays from household budget surveys. While these early studies successfully proved that low-income families bore a regressive energy burden, relying on retrospective financial transactions introduced a significant diagnostic flaw [2, 4].

She explicitly rejected actual expenditure as a valid indicator of fuel poverty because it failed to capture families that responded to financial hardship by reducing their domestic fuel use. As discussed in the previous section, this under-heating paradox meant that the most deprived

households often appeared to have low energy costs despite living in inadequate thermal conditions [2].

Because their real-world spending dropped to near zero, these self-rationing households fell far below spending-based thresholds like Isherwood and Hancock's "twice-the-median" indicator. Under an actual expenditure framework, the most critically deprived households were systematically misclassified as non-vulnerable, while affluent households living in large, thermally inefficient mansions were flagged as energy-poor simply because they chose to pay for high fuel consumption [2].

Against this backdrop, Brenda Boardman published her landmark 1991 monograph *Fuel Poverty: From Cold Homes to Affordable Warmth*, fundamentally redefining how the condition of fuel poverty would be understood and measured [2].

Her contribution emerged during a period in which British social policy largely emphasized income-based approaches to poverty alleviation. Boardman argued that fuel poverty also reflected structural deficiencies in the residential housing stock, highlighting the limitations of relying exclusively on income support [2].

Under Boardman's approach, a household was considered fuel poor when the cost associated with securing sufficient domestic energy services represented more than 10% of household income [2]. By framing fuel poverty around the concept of "affordable warmth," Boardman shifted the analytical focus from what households *actually spend* to what they *need to spend* to maintain a healthy home environment. This definition established energy access as a basic human right and positioned the physical condition of the dwelling as a central determinant of economic welfare [2].

1.3 The Boardman Framework and the Evolution of Fuel-Poverty Measurement

To operationalize her normative definition, Boardman constructed a precise mathematical formula that decoupled energy deprivation from actual ledger spending. The Fuel Poverty Ratio was established as necessary energy costs divided by net disposable income, with the threshold set at 10% [2]:

$$\text{Fuel Poverty Ratio} = \frac{\text{Total Required Energy Costs}}{\text{Total Net Income}} > 0.10$$

The numerator of this ratio—Total Required Energy Costs—is estimated through thermodynamic modeling rather than utility bill collection. Instead of asking how much fuel families actually

purchase, her model calculates the energy input needed to heat a specific dwelling to a standardized thermal baseline. The calculation incorporates the dwelling's physical characteristics, insulation quality, heating-system efficiency, fuel type, and local climatic conditions [2].

In addition to space heating, required costs include baseline allowances for water heating, cooking, lighting, and essential domestic appliances, assuming standardized occupancy schedules [2].

The choice of the 10% threshold was directly grounded in the empirical baseline established by Isherwood and Hancock. Analyzing data from the 1988 UK Family Expenditure Survey, her work observed that the median British household allocated approximately 5% of its net income to fuel, light, and power. Drawing on established economic principles of relative hardship, Boardman argued that dedicating more than twice the national median income share to a non-discretionary utility constituted an unreasonable financial burden [2, 4].

Rounding Isherwood and Hancock's finding—that vulnerable, high-spending families allocated roughly 12% of their budgets to fuel—Boardman established 10% as the boundary where energy spending becomes disproportionate [2, 4].

To define "adequate warmth," Boardman integrated medical standards established by the World Health Organization (WHO). The WHO recommended indoor temperatures of 21°C in main living areas and 18°C in secondary occupied rooms, such as bedrooms and hallways, to prevent cold-related morbidity. She incorporated these temperature thresholds as non-negotiable normative parameters in her required-expenditure model [2, 5].

Under this approach, a home was not evaluated based on the cold temperature the occupants tolerated, but on the energy required to maintain 21°C in the living room for nine hours on weekdays and sixteen hours on weekends [2, 5].

For the denominator of her ratio—Total Net Income—Her framework used net disposable income rather than gross income. Net income accounts for income tax, National Insurance contributions, and local property taxes, reflecting the actual cash resources available to a household for living expenses [2].

She argued that because energy is an absolute survival necessity, required fuel expenditures must be evaluated against disposable income to capture the severe trade-offs families face between utility payments, food, and other essential goods [2].

Boardman’s fundamental conceptual contribution was the formal decoupling of fuel poverty from general income poverty. Before 1991, economic literature generally treated the problem as a simple

subset of low income—assuming that poor people suffered from high energy bills merely because they were poor. Boardman illustrated that while income is a critical factor, this condition is driven by an interaction between three distinct variables: low household income, high energy prices, and structural energy inefficiency in the housing stock [2].

This framework revealed that fuel poverty was not simply income poverty in disguise. A low-income family residing in a modern, highly insulated housing unit equipped with an efficient heat pump or gas boiler might easily maintain WHO thermal standards while spending only 4% of its net income on fuel, thereby avoiding this situation entirely [2].

Conversely, a household with a moderate income sitting above the official poverty line, trapped in a large, uninsulated stone cottage with inefficient electric resistance heating, could be forced to spend 15% of its disposable income to achieve adequate warmth. In this way, Boardman showed that housing inefficiency acts as an independent driver of socio-economic vulnerability [2].

This conceptual redefinition positioned the built environment and public health at the heart of economic deprivation. Boardman highlighted how energy-inefficient housing acts as a physical trap: poor insulation and obsolete heating systems leak energy, forcing low-income occupants into a choice between financial insolvency or living in dangerously cold environments [2].

By incorporating WHO temperature standards, Boardman directly linked housing quality to medical outcomes, showing that cold homes were responsible for thousands of excess winter deaths each year from cardiovascular and respiratory conditions [2, 5]. Consequently, her model demonstrated that this condition could not be eradicated solely through cash welfare payments; long-term resolution required long-term investment in improving the energy efficiency of the housing stock [2].

The clarity and normative authority of Boardman's 10% Rule led to its widespread adoption by policymakers seeking an objective metric to guide public intervention [2]. In the United Kingdom, intense lobbying by academic coalitions, health organizations, and environmental groups culminated in the passage of the Warm Homes and Energy Conservation Act 2000. This legislation placed a legal obligation on the UK government to formulate a national strategy to eradicate the problem [6].

When the official UK Fuel Poverty Strategy was published in 2001, the 10% Rule was formally adopted as the national statutory metric [7]. Governments favored the 10% Rule because it provided a clear, intuitive headline indicator that could be easily communicated to the public, tracked over time using standardized housing surveys, and tied directly to measurable energy efficiency targets, such as Standard Assessment Procedure (SAP) housing ratings [7].

Following its institutionalization in the United Kingdom, her methodology became the dominant reference point for fuel poverty measurement across Europe and influenced the development of numerous national policy strategies [2, 7].

Despite its political success and intuitive appeal, the 10% Rule faced growing academic and methodological criticism throughout the 2000s. Critics argued that using a fixed 10% threshold calculated relative to 1988 income distributions created an arbitrary baseline that failed to adapt to changing macro-economic conditions. Because the numerator of the required-expenditure ratio depended on volatile retail energy prices, global spikes in oil and gas prices caused national fuel-poverty rates to fluctuate wildly, even when household incomes and housing insulation levels remained completely unchanged [8].

A major technical criticism centered on the misclassification of households under the 10% metric. Economists pointed out that Boardman's ratio generated significant false positives by capturing high-income households. An affluent family living in an exceptionally large, inefficient country estate might need to spend more than 10% of its net income to heat the property to WHO standards [8].

Under her formula, this high-income household was categorized as fuel poor, despite having ample remaining disposable income to maintain a high standard of living. Conversely, the metric generated false negatives among extremely poor households living in relatively small or moderately efficient homes whose required energy costs fell just below the 10% threshold, but who nevertheless suffered from severe income poverty [8].

These methodological limitations reached a crisis point in the UK during the late 2000s, when rising global fossil fuel prices caused official fuel poverty statistics to surge, creating the illusion that government energy efficiency investments were failing entirely. In response, the UK government commissioned independent economist Sir John Hills in 2011 to conduct a fundamental review of the national fuel poverty metric [8].

By the beginning of the 2010s, longstanding academic and policy concerns surrounding the 10% rule had become increasingly difficult to ignore. Rising domestic energy prices produced sharp increases in estimated fuel-poverty prevalence under Boardman’s threshold, even where improvements in the energy performance of the housing stock had reduced some of the underlying physical causes of deprivation [8].

The principal weakness of the 10% indicator lay in its reliance on a single expenditure-to-income ratio. Because energy costs formed the numerator and household income the denominator, rapid increases in retail energy prices could move substantial numbers of households above the 10%

threshold even when their underlying financial circumstances had not deteriorated to the same extent [8].

This generated important classification problems. Affluent households residing in large, energy-inefficient properties were classified as fuel poor despite retaining sufficient residual income to maintain an acceptable standard of living after meeting their energy costs. Conversely, some low-income households occupying relatively efficient dwellings could remain below the 10% threshold despite experiencing significant financial hardship. In practice, many reduced their domestic energy consumption below adequate levels in order to cope with constrained budgets, meaning that the indicator failed to capture important forms of hidden deprivation [8].

Recognizing that the 10% indicator was conflating rising domestic energy prices with persistent household vulnerability, the UK government commissioned independent economist Sir John Hills in 2011 to conduct an important review of the framework. The resulting Hills Review (2012) introduced the Low Income High Costs (LIHC) framework, replacing the single-ratio indicator with a two-criteria approach designed to improve the identification of fuel-poor households [8].

The principal methodological innovation of the Low Income High Costs framework was its dual-criteria structure, which evaluated the necessary

energy costs and household income as separate but complementary dimensions of fuel poverty. Under the LIHC framework, a household is classified as fuel poor only if it simultaneously satisfies two distinct economic criteria. First, its modelled needed energy costs must exceed the national median level of required energy expenditure. Second, after meeting those energy costs, its residual income would fall below the official poverty threshold. Only households satisfying both conditions were classified as fuel poor [8].

This framework was designed to address several limitations of the traditional 10% rule. Because the classification depended on relative rather than fixed expenditure thresholds rather than absolute expenditure ratios, the Low Income High Costs framework substantially reduced the distorting effects of macroeconomic energy price spikes [8].

1.4 The Multidimensional Turn: Capability Approach and Energy Justice

The development of the Low Income High Costs framework represented an important refinement in the measurement of fuel poverty, particularly by combining required energy costs with a residual-income criterion. Nevertheless, both the 10% Rule and LIHC remained primarily concerned with identifying deprivation through measurable relationships between household resources, energy requirements and housing conditions. Although these approaches improved statistical classification,

they offered only a partial account of what inadequate access to energy actually prevented individuals from being and doing [8].

This limitation prompted a broader theoretical question: why does energy deprivation matter beyond its effect on household expenditure? Domestic energy is not valuable solely as a commodity or budgetary input. It enables individuals to maintain adequate warmth, prepare food, preserve health, participate in social life and pursue education and employment. Understanding energy poverty therefore required a framework capable of examining not only the resources available to households, but also the real opportunities those resources created [8].

Despite representing an important methodological advance, this methodological refinement highlighted a broader limitation within quantitative energy economics. Both the 10% Rule and the LIHC framework continued to conceptualize energy poverty primarily through the interaction of needed energy costs, household income and housing characteristics. At the same time, these approaches provided only limited insight into the lived, multidimensional reality of energy deprivation. Energy fulfils functions that extend well beyond maintaining adequate indoor temperatures. It enables households to preserve health, nutrition, education, social participation and personal autonomy. Understanding energy poverty therefore required moving beyond the question of how deprivation should be measured toward a broader examination of what energy allows individuals to be and to do [8].

By defining deprivation strictly in terms of financial outlays or architectural heat-loss coefficients relative to median baselines, standard economic models reduced human welfare to resource availability. In doing so, they failed to account for how institutional structures, social marginalization, and geographic inequalities dictate a household's actual capacity to convert energy into a fulfilling life.

To address these conceptual gaps, an increasing body of literature turned toward normative human development frameworks, particularly the Capability Approach. Grounded in the theoretical framework of Amartya Sen and expanded by Martha Nussbaum, this perspective reconceptualizes the evaluation of well-being. Sen argued that social justice and economic welfare should not be measured by the resources an individual commands, such as real income or kilowatt-hour of electricity, nor by the subjective utility or satisfaction they derive from them. Instead, economic evaluation should focus on what people are actually able to be and do—their real freedoms to achieve valued states of human existence [9].
Rather than measuring well-being through the resources individuals possess, the Capability Approach evaluates the genuine opportunities those resources create.

Building upon this theoretical framework, a critical distinction is drawn between resources, functionings, and capabilities. Resources—such as natural gas, electricity, or physical heat pumps—are merely intermediate means to an end; they hold no intrinsic value in themselves. Functionings represent the realized states of being and doing that an individual achieves, such as being adequately warm, being healthy, being socially connected, or being able to cook a nutritious meal. Capabilities represent the broader set of real, substantive opportunities and freedoms an individual possesses to choose and achieve those valued functionings. A person who fasts voluntarily for religious reasons possesses the capability to eat but chooses not to, achieving the functioning of fasting; a person who starves due to poverty lacks the capability to obtain food [9].

Applying the Capability Approach to the field of energy economics, scholars such as Rosie Day and Gordon Walker reconceptualized domestic energy from an end-use commodity into a fundamental enabling service. Energy itself is not a primary capability; rather, it is an essential input required to support a wide range of human capabilities. From a capabilities perspective, energy poverty occurs when a household lacks access to affordable, reliable, and safe energy services necessary to achieve basic human capabilities [11].

When a family is trapped in an energy-inefficient home and forced to cut consumption, the deprivation extends far beyond thermal discomfort. Drawing upon Martha Nussbaum's list of Central Human Capabilities, scholars argued that energy vulnerability undermines multiple dimensions of human dignity [10].

First, chronic exposure to cold and damp living conditions can harm bodily health, increasing the risk of cardiovascular disease, respiratory illness, and excess winter mortality, thereby undermining the baseline capability to live a healthy life of normal length.

Second, it harms affiliation and social self-respect. Households experiencing severe energy stress frequently avoid inviting friends or family into cold, dark, or visibly degraded homes, giving rise to feelings of social shame, isolation, and thereby constraining relational capabilities

Third, it compromises emotional well-being and mental health. Persistent financial anxiety associated with rising utility debt and the risk of service disconnection generates severe, ongoing psychological distress, thereby undermining emotional well-being and personal agency.

Finally, it undermines practical reason and educational development, as children studying in unheated homes are often restricted to a single warm, overcrowded room, severely disrupting concentration, learning, and future educational and economic opportunities [10].

A central contribution of the Capability Approach is the concept of conversion factors. The personal, physical, structural, and social conditions that shape an individual's ability to transform a resource, like a kilowatt-hour of energy, into a valuable functioning such as adequate warmth or social inclusion. An elderly, bedbound citizen or a person living with a chronic illness requires substantially greater levels of domestic energy to maintain bodily health than a young, mobile adult. Similarly, a household residing in an uninsulated rural stone house faces substantially less favourable conversion factors compared to a family living in an urban insulated building. By focusing on these conversion factors, the capabilities perspective illustrates why flat-rate financial transfers or universal income support measures may prove insufficient to address energy poverty effectively: they treat unequals equally, overlooking the structural disparities that determine real human opportunities [9].

While the Capability Approach expanded the normative understanding of individual well-being, it also called for a complementary political framework capable of explaining the systemic and institutional mechanisms through which energy poverty is produced and sustained. This role was assumed by the emerging framework of Energy Justice. Pioneered by scholars such as Benjamin Sovacool, Darren McCauley, and Kirsten Jenkins, energy justice extends foundational principles of social, environmental, and spatial philosophy directly to the lifecycle of energy systems—from primary resource extraction and generation to household consumption and waste disposal [12]. Analytically, the framework is commonly structured around three interconnected dimensions: distributive justice, recognition justice, and procedural justice. Together, these three dimensions reframe energy poverty not merely as a market failure, but as a manifestation of structural injustice.

Each dimension therefore addresses a different question: how energy-related benefits and burdens are distributed, whose needs are recognised, and who has a voice in shaping energy decisions [12].

Distributive justice concerns the spatial and economic distribution of both the benefits and burdens of energy production and consumption. In the context of household energy poverty, distributive injustice occurs when vulnerable, low-income households bear a disproportionate financial burden for the energy system while gaining minimal access to its benefits. This is visible in how energy transition costs are frequently financed. When governments place green levies and grid maintenance tariffs onto consumer electricity bills as flat-rate charges rather than funding them through progressive income taxation, the economic burden falls regressively on low-income households. A further illustration of distributive injustice manifests when state subsidies for clean energy technologies—such as tax credits for rooftop solar panels, heat pumps, or electric vehicles—disproportionately benefit affluent homeowners, while low-income renters remain trapped in

inefficient housing, paying high retail tariffs to finance a grid decarbonization they cannot access [12].

Distributional justice therefore asks a fundamental question: not simply whether societies possess sufficient energy resources, but whether the costs and benefits of energy systems are shared in an equitable manner across different social groups.

Procedural justice focuses on the fairness, transparency, and inclusiveness of decision-making processes within energy governance. It demands that all citizens—regardless of income, social status, or geographic location—possess the political agency and institutional channels required to participate in shaping energy policies that directly affect their lives. Procedural injustice occurs when energy regulation is dominated by utility monopolies, technocratic regulatory bodies, and corporate lobbies, leaving vulnerable consumers without legal recourse, transparent pricing data, or protection against predatory practices such as involuntary pre-payment meter installations or winter disconnections. Procedural justice requires empowering local communities, tenant unions, and consumer protection advocates through participatory policymaking, ensuring that marginalized populations possess institutional voice and legal representation [12].

Yet meaningful participation cannot exist unless the specific identities, vulnerabilities, and needs of different social groups are first acknowledged. This broader question of visibility and representation lies at the core of Recognition Justice.

Recognition justice constitutes the foundational social prerequisite for both distributive and procedural justice. Grounded in political philosophy, recognition justice asserts that individuals and social groups must be acknowledged, respected, and understood according to their distinct identities, vulnerabilities, and social circumstances. In energy economic literature, misrecognition occurs when policymakers treat the population as a homogeneous consumer group with identical energy requirements. Recognition justice forces analysts to acknowledge that specific social cohorts—such as single mothers, elderly pensioners living alone, racial minorities, rural off-grid residents, and individuals suffering from chronic medical conditions—possess distinct, non-standard thermal, medical, and financial requirements. Failing to recognize these socio-demographic realities risks misallocating public resources while reinforcing existing forms of social exclusion.

Recognition justice therefore reminds policymakers that equitable energy transitions cannot be achieved through universal solutions alone. Effective interventions must first acknowledge the diversity of human needs before they can distribute resources fairly or design genuinely inclusive institutions [12].

1.5 Synthesis and the Transition to Multi-Level European Governance

The synthesis of the Capabilities Approach and Energy Justice marked a significant evolution in the understanding of energy poverty economics. Together, these frameworks shifted the academic discourse away from solely expenditure-based and econometric definitions toward an integrated, rights-based understanding of energy as an important public good. Rather than viewing energy poverty purely as an isolated market failure occurring within the household budget, the contemporary literature increasingly conceptualizes domestic energy deprivation as a multidimensional structural crisis located at the intersection of housing market failures, income inequality, systemic energy market design, and fundamental human rights [9, 11, 12].

From the retrospective expenditure observations of Isherwood and Hancock, through Boardman's required-expenditure framework and the methodological refinement introduced by the Hills Review, to the normative perspectives of the Capability Approach and Energy Justice, the literature progressively expanded both the measurement and the meaning of energy poverty. This theoretical transformation provided the intellectual foundation needed to inform multi-level governance, serving as the direct intellectual bridge to European Union energy and climate policy [2, 4, 8, 9 ,12]. As the European Union embarked on its ambitious climate-neutral targets—formalized under the European Green Deal, the Clean Energy for All Europeans Package, and the "Fit for 55" legislative framework—EU policymakers confronted a major political reality. Achieving rapid decarbonization through carbon pricing, such as the expansion of the Emissions Trading System to buildings and road transport (ETS2), risked imposing regressive financial costs on vulnerable, energy-poor households across Member States.

Consequently, contemporary energy poverty research no longer asks only whether households can afford sufficient energy, but also whether existing institutions enable all individuals to convert energy into genuine opportunities for human flourishing. Answering this broader question ultimately requires moving beyond theoretical evolution to examine how these principles have been translated into public policy—a challenge addressed in the following chapter through the evolution of European and Italian energy-poverty governance.

The evolution reconstructed throughout this chapter demonstrates that the understanding of energy poverty has progressively expanded beyond the measurement of household expenditure to encompass broader questions of human well-being, institutional responsibility and social justice. Contemporary scholarship no longer interprets domestic energy deprivation solely as an affordability problem, but as a multidimensional phenomenon shaped by the interaction between economic resources, housing conditions, individual capabilities and governance structures. This conceptual

evolution provides the theoretical foundation for examining how these principles have subsequently been translated into public policy at both the European and national levels, which forms the focus of the following chapter.

CHAPTER 2:

2.1 Introduction and Conceptual Framework

The theoretical framework developed in Chapter 1 established energy poverty not merely as a sub-component of general economic deprivation, but as an autonomous and multidimensional phenomenon driven by the interaction of low household income, inadequate residential energy efficiency and high energy costs. While the evolution of the academic literature has progressively isolated the microeconomic and social vectors of this vulnerability, it is now crucial to critically evaluate the process through which this multidimensional form of deprivation transitioned from an insufficiently monitored social condition into an explicit objective of public governance. This chapter aims to critically examine the evolution of the institutional responses and mitigation policies deployed both at the European Union level and within the Italian national context, highlighting the systemic frictions between market efficiency targets and distributive equity constraints.

The transition of energy poverty from a private, isolated domestic grievance into a headline priority of the international policy agenda was not immediate; rather, it reflects a shift in the conceptualization of the state's role within the economy. Historically, the universal availability of secure energy was treated as a fundamental prerequisite for social cohesion and industrial development. However, as this chapter will demonstrate, the significant deregulation waves and the transition toward market-driven mechanisms guided by competition significantly altered the traditional protection mechanisms of vulnerable consumers. Early responses suffered from severe methodological fragmentation: while specific welfare regimes, most notably the British model, anticipated this crisis by codifying the phenomenon as early as the 1990s, continental European and supranational responses largely addressed household vulnerability through general welfare and income-support instruments that were not specifically designed to capture energy-related deprivation.

The contemporary policy challenge is increasingly shaped by the distributive trade-offs associated with the decarbonisation process. Mandated by the global climate emergency and reinforced by recent geopolitical shifts, this process has introduced economic instruments designed to penalize carbon emissions, such as cap-and-trade permit markets. In the absence of adequate compensatory and adaptive measures, however, market-based environmental instruments may generate regressive distributional effects because lower-income households generally devote a larger share of their resources to essential energy services and possess less capacity to invest in low-carbon alternatives.

The theoretical frameworks developed in Chapter 1 provide the analytical basis for evaluating this policy evolution. Boardman's emphasis on the interaction between household income, energy prices and residential efficiency highlights the distinction between temporary affordability support and

interventions addressing the underlying drivers of energy poverty. The Capability Approach extends this assessment by asking whether households can convert available energy resources into adequate domestic services and valued functionings, while Energy Justice provides a framework for evaluating how the costs, benefits and decision-making opportunities associated with the energy transition are distributed across social groups.

Against this background, the chapter investigates whether contemporary European and Italian policy frameworks represent a genuine transition from reactive compensation toward structural prevention, and to what extent the growing integration of redistribution, energy efficiency and decarbonisation has succeeded in reconciling environmental objectives with the protection of vulnerable households.

The contemporary architecture of European energy markets is the direct outcome of a regulatory turning point initiated in the late 1990s. This process aimed to dismantle the traditional model of vertically integrated natural monopolies to establish a competitive, cross-border internal energy market. The liberalization process contributed to greater market integration, cross-border trading and price convergence across several segments of the European energy market. However, from a welfare and distributive standpoint, this transformation altered the exposure of retail consumers to market risks. By shifting energy from a state-guaranteed merit good into a commercially traded regulated commodity, the transition altered the microeconomic and institutional conditions under which household energy vulnerability was addressed.

To evaluate the distributive impact of this transition, it is first necessary to conceptualize the pre-liberalization baseline characterized by state-owned, vertically integrated monopolies. Until the mid-1990s, national energy sectors across Europe were dominated by historical state operators—such as ENEL and ENI in the Italian context—that controlled the entire industrial supply chain from generation and importation to transmission, distribution, and retail supply. Within this framework, energy policy served not only commercial and infrastructural objectives but also broader public-service and redistributive functions. Retail tariffs were extensively regulated, while cross-subsidisation and public intervention could partially cushion residential consumers from the immediate transmission of market shocks. As a result, household exposure to short-term retail volatility was more limited than under the subsequently liberalised market architecture. Consequently, access to energy was institutionally treated as a universal public service, comparatively more sheltered from direct retail-market volatility.

The dismantling of this monopolistic structure was executed at the European level through a progressive and legally binding sequence of three major legislative initiatives known as the Energy Packages. The First Energy Package, launched through Directive 96/92/EC, initiated the gradual

opening of national electricity markets to competition, introduced accounting separation between generation, transmission and distribution activities, and established system-access arrangements based on objective, transparent and non-discriminatory criteria [13].

The Second Energy Package, adopted through Directive 2003/54/EC, deepened this process by strengthening legal and functional unbundling, introducing regulated third-party access and progressively extending retail-market eligibility, first to all non-household customers by July 2004 and subsequently to all customers by July 2007. The Directive also strengthened the consumer-protection dimension of liberalisation by requiring Member States to adopt safeguards for vulnerable customers, including measures aimed at preventing disconnection [14].

The Third Energy Package, adopted in 2009, further strengthened the internal electricity market through stricter transmission-system unbundling requirements and reinforced consumer-protection provisions. Directive 2009/72/EC required Member States to adopt adequate safeguards for vulnerable customers and to define the concept of a vulnerable customer, which could explicitly refer to energy poverty. It also allowed measures such as national energy action plans, social-security benefits and support for energy-efficiency improvements to address energy poverty where identified [15]. At the institutional level, the Third Energy Package also established the Agency for the Cooperation of Energy Regulators (ACER) to strengthen cooperation among national regulatory authorities and support the integration of the internal energy market [16].

From a market-efficiency perspective, liberalisation facilitated organized wholesale trading, cross-border market integration and greater competition among generators and retail suppliers. Power exchanges and market coupling improved the coordination of generation and transmission resources, while the entry of new suppliers expanded the range of retail offers available to consumers. These developments constituted important achievements of internal-market integration, but they did not guarantee that all households possessed an equal capacity to benefit from competitive energy markets.

For vulnerable households, three dimensions of the liberalised market were particularly relevant: greater exposure to price volatility, unequal capacity to navigate retail competition, and the persistence of fixed or non-energy components within final bills. Despite these clear achievements, the liberalization process also exposed important distributive vulnerabilities, particularly among consumers with limited capacity to respond to price volatility and increasingly complex retail markets. This vulnerability was further compounded by acute informational asymmetries and transaction costs, which directly challenge the neoclassical assumption of the rational, utility-maximizing active consumer. These consumers struggle to decode the complexity of liberalized tariff

options, such as fixed versus variable or time-of-use rates. Lastly, the unbundling process contributed to a more fragmented composition of the final utility bill, loading the final retail price with extensive non-energy components designed to remunerate the decentralized supply chain. A further distributional concern arises from the structure of household electricity tariffs. Fixed components of electricity bills may have regressive effects because they are less closely related to actual consumption and can therefore increase the effective cost of electricity for poorer and low-consuming households [17].

Although electricity-market liberalisation was expected to increase competition and efficiency and thereby reduce consumer prices, the empirical relationship between regulatory reform and final electricity prices has remained more complex and contested [18].

Following the early liberalisation phases, European policy progressively developed a more explicit framework for addressing household energy vulnerability. The process began with consumer-protection provisions and subsequently expanded into common monitoring and reporting obligations within EU energy and climate governance.

The preliminary institutional breakthrough occurred with the adoption of the Third Energy Package in 2009, specifically through Directives 2009/72/EC and 2009/73/EC. For the first time in the history of supranational energy legislation, the European Union codified a binding requirement for Member States to formally address consumer vulnerability. However, rather than providing a unified, standardized definition of energy poverty, the Third Package introduced the legal category of the vulnerable consumer**.** This regulatory choice reflected a complex compromise between supranational market integration and national welfare sovereignty. Member States retained considerable flexibility to define vulnerability according to national socio-economic and health-related criteria. This preserved national welfare autonomy but produced substantial heterogeneity across the Union [15].

The structural limitations of this decentralized vulnerability framework became untenable as the EU transitioned toward its modern climate and energy strategies. The launch of the Energy Union strategy highlighted that a unified, secure, and low-carbon energy market could not maintain political legitimacy while leaving vulnerable households exposed to persistent thermal deprivation. This realization catalyzed the development of a highly formalized, multi-level governance model finalized through the Clean Energy for All Europeans Package in 2019. A further institutional development occurred with Regulation (EU) 2018/1999 on the Governance of the Energy Union and Climate Action, which integrated energy poverty into the National Energy and Climate Plans (NECPs). Under this governance framework, Member States must first evaluate the extent of energy poverty within their national territory, considering the energy services required to meet basic living standards

alongside the relevant domestic policy context and EU guidance. If this assessment reveals a significant incidence of energy poverty, the national plan must establish an indicative objective for its reduction and describe the measures intended to address it. For the Member States concerned, the framework further requires subsequent reporting on progress towards that objective and on the number of households affected [19].

Alongside these formal governance obligations, the European Commission developed a technical support infrastructure for measuring and addressing energy poverty. This began with the launch of the European Energy Poverty Observatory (EPOV) and evolved into the Energy Poverty Advisory Hub (EPAH). These centralized bodies provided the academic and statistical diagnostic tools necessary to standardize indicators across asymmetrical national administrative systems, supporting the development and comparison of multiple indicators, including expenditure-based and consensual measures of energy vulnerability. By the end of the decade, energy poverty had therefore become an increasingly formalized component of European energy governance. Yet recognition and monitoring alone could not address its underlying drivers. As European climate policy moved toward economy-wide decarbonisation, a new challenge emerged: ensuring that the transition itself did not reproduce or intensify existing forms of energy vulnerability.

A major development in this policy evolution occurred in December 2019 with the European Commission's European Green Deal. Presented as a new growth strategy for the Union, the Green Deal linked the objective of climate neutrality by 2050 to a broader transformation of the European economy towards greater resource efficiency, competitiveness and social inclusion. Crucially for the analysis of energy poverty, the Commission also stated that the transition should be just and inclusive, place people first and pay particular attention to the regions, industries and workers facing the greatest challenges [20]. The social dimension of this new regulatory era can be interpreted through the conceptual framework of Energy Justice developed in Chapter 1. From this perspective, the central question is no longer only whether decarbonisation reduces aggregate emissions, but also who bears its costs, who gains access to its benefits, and whether vulnerable groups are adequately recognised within transition policies. This theory demands that the benefits and burdens of the ecological transition be distributed equitably, ensuring that marginalized demographics do not bear a disproportionate cost for historical pollution. This distributive dimension was further developed through the Just Transition Mechanism (JTM), presented by the European Commission in January 2020 as part of the European Green Deal framework. The mechanism was designed to provide targeted financial and practical support to the regions, industries and workers facing the greatest socio-economic challenges from the transition toward a climate-neutral economy. In its original 2020 design, the Commission expected the mechanism to mobilise at least €100 billion of investment over

the 2021–2027 period, combining a Just Transition Fund, a dedicated scheme under InvestEU and a public-sector loan facility [21].

The structural dimension of energy vulnerability was addressed more directly through the Renovation Wave strategy, launched by the European Commission in October 2020. The strategy identified the poor energy performance of the European building stock as both an environmental and social challenge, noting that buildings accounted for approximately 40% of EU energy consumption and 36% of energy-related greenhouse-gas emissions. Against this background, the Commission sought to accelerate building renovation substantially by 2030, while directing particular attention towards energy-poor households and buildings with especially weak energy performance [22]regula.

In this respect, the strategy reflects the structural insight developed in Boardman's framework: reducing energy poverty requires not only supporting household purchasing power, but also lowering the energy requirement generated by inefficient residential conditions [2].

However, the acceleration of decarbonisation also introduced a different distributional challenge: while structural investment could reduce household energy requirements, the extension of carbon pricing risked increasing the immediate cost of fossil-fuel-based heating and mobility for households with limited adaptive capacity.

The next major step in the integration of climate and social policy occurred in July 2021 with the European Commission's "Fit for 55" package. The package translated the European Climate Law's objectives into a set of interconnected legislative proposals designed to reduce EU net greenhouse-gas emissions by at least 55% by 2030 compared with 1990 levels and to place the Union on a pathway toward climate neutrality by 2050. Alongside its environmental objectives, the Commission explicitly recognised that the distributional effects of the transition required particular attention to ensure that climate policies remained socially fair [23].

A particularly significant component of the reform was the establishment of a separate emissions-trading system for fuels used in buildings, road transport and certain additional sectors, commonly referred to as ETS2. Unlike the existing EU ETS, the new system places compliance obligations upstream on regulated fuel suppliers rather than directly on individual households or motorists. By incorporating the carbon content of fuels used for heating and transport into an emissions-trading framework, ETS2 extends carbon-pricing incentives to sectors in which emissions reductions have historically been more difficult to achieve [24].

While the creation of ETS2 functions as an efficient environmental policy tool by creating economic incentives for energy efficiency, its retail-level pass-through triggers distributive shocks. Fuel

suppliers operate in highly consolidated, price-competitive markets characterized by low operational profit margins. Economic theory suggests that a substantial share of allowance costs may be passed through to final consumers, although the magnitude of pass-through depends on market structure, contractual arrangements and competitive conditions. This cost pass-through reveals a structural asymmetry in welfare economics because the retail incidence of carbon pricing can display regressive characteristics when lower-income households devote a larger share of disposable income to fossil-fuel-based energy services. The distributional concern arises through two principal channels: the higher energy-expenditure share of low-income households and their lower capacity to invest in alternatives to fossil-fuel consumption.

The regressive nature of this mechanism is driven by two distinct socio-economic vulnerabilities. First, the expenditure share asymmetry dictates that although affluent households consume a larger volume of energy, low-income and energy-poor households dedicate a significantly higher share of their monthly disposable income to utility bills and basic heating requirements. Consequently, a uniform carbon price corridor applied across the retail market absorbs a disproportionately large percentage of a poor household's financial resources, functioning as a regressive penalty on low-income groups. Second, the inelasticity of essential energy demand limits the capacity of vulnerable households to adjust their consumption when fossil-fuel prices rise. Although standard environmental models assume that consumers respond to higher prices by switching to cleaner alternatives, such substitution requires financial resources and access to suitable technologies. This asymmetry can also be interpreted through the Capability Approach introduced in Chapter 1. Identical carbon-price signals do not imply identical adjustment opportunities: households differ substantially in the financial, physical and infrastructural conversion factors that determine whether they can substitute fossil-fuel consumption with lower-carbon alternatives.

However, vulnerable households generally possess substantially lower financial and technological adaptive capacity. Their ability to reduce or substitute essential heating and mobility consumption may be limited in the short term. Faced with rising retail prices from ETS2, these households cannot change their behavior. Instead, they are forced to absorb the higher costs by sacrificing other basic needs like food and healthcare, or by slipping into extreme forced self-deprivation. The market-based approach improves environmental efficiency by driving carbon out of the economy, but it concentrates the residual tax burden onto the lowest income deciles, directly worsening energy poverty.

The realization of this regressive carbon pricing paradox created a major political economy barrier for the Fit for 55 package. Policymakers recognized that if the ETS2 price corridor launched without

immediate social safeguards, the regressive cost shock could trigger severe public pushback and civil unrest across Member States, stripping the European Green Deal of its political legitimacy. To resolve this tension between environmental efficiency and distributive equity, the EU enacted Regulation (EU) 2023/955 establishing the Social Climate Fund (SCF).

Regulation (EU) 2023/955 established the Social Climate Fund as the principal EU instrument for mitigating the social consequences associated with the extension of emissions trading to buildings and road transport. Its support is directed towards vulnerable households, micro-enterprises and transport users, combining temporary income assistance with longer-term interventions in areas such as building efficiency, cleaner heating and cooling, renewable energy and sustainable mobility [25].

Implementation is organised through national Social Climate Plans, through which Member States define the interventions intended to protect vulnerable groups and the corresponding implementation objectives and costs. The Fund provides up to €65 billion of EU financing for 2026–2032, complemented by national co-financing of at least 25% of each Plan's estimated costs. Direct income support may form part of this response, but is limited to 37.5% of total estimated Plan costs, leaving a substantial share of resources for structural measures [25].

The governance framework of the fund mirrors the performance-conditioned disbursement methodology pioneered by the Recovery and Resilience Facility (RRF). To access their allocated funding envelopes, Member States are required to submit comprehensive National Social Climate Plans (NSCPs). These plans must be drafted in direct alignment with their existing National Energy and Climate Plans (NECPs). The governance architecture requires national authorities to identify precise vulnerable households, vulnerable transport users, and vulnerable micro-enterprises through multidimensional, data-driven indicators. Rather than receiving unconditional budgetary support, states are bound to a strict milestones-and-targets framework. The European Commission retains centralized oversight, evaluating the compliance of each NSCP and checking performance benchmarks before releasing bi-annual financial tranches. This multi-level governance framework constrains national discretion by linking access to EU resources to agreed plans, eligibility conditions and implementation requirements.

This short-term cushioning mechanism allows states to implement targeted utility bill discounts or fuel subsidies to absorb immediate price shocks at the pump or on gas bills. The limitation placed on temporary direct income support preserves a substantial role for structural measures and investments aimed at reducing vulnerability over the longer term. These permanent ex-ante measures prioritize deep building energy retrofits, the integration of decentralized renewable energy prosumership via solar installations, and the expansion of affordable, low-emission public transit networks. This

redistributive layout aims to systematically transition vulnerable citizens from passive subsidy dependency to active prosumership, permanently insulating their homes from the carbon price corridor.

From an analytical standpoint, the primary strength of the SCF is its ability to institutionalize a progressive fiscal loop. By ring-fencing carbon market revenues, the fund prevents environmental tax receipts from being absorbed into general national exchequers for deficit reduction. It guarantees that the financial yields of market efficiency are automatically recycled to correct the social imbalances those same markets create.

Despite this progressive architecture, the fund faces intense academic and institutional critiques within welfare economics literature. One potential tension can be described as a circular financing problem. The financial viability of the SCF relies mainly on the successful expansion and monetization of the ETS2 carbon market. Therefore, the financing capacity of the mechanism remains partly linked to revenues generated by the carbon-pricing system whose social effects the Fund is designed to mitigate. If carbon prices spike too rapidly, the €65 billion envelope will be quickly overwhelmed by the sheer scale of retail-level price shocks. Conversely, if emissions contract ahead of schedule, the fund will experience a severe capital shortfall. Furthermore, the 37.5% maximum cap on direct income support is heavily criticized for ignoring the short-term survival needs of households during unexpected winter price spikes, prioritizing long-term technical retrofits over immediate financial solvency.

Viewed through the Energy Justice framework, the SCF primarily addresses distributive concerns by recycling part of the fiscal value generated by carbon pricing toward vulnerable groups, while its requirement for nationally designed Social Climate Plans introduces a governance dimension concerning the identification and representation of affected populations. The Fund therefore illustrates how the justice principles discussed in Chapter 1 can be translated into concrete policy architecture, although their effective realization ultimately depends on national implementation.

Despite these limitations, the SCF constitutes an important development because it embeds social compensation and structural investment directly within the architecture of carbon pricing. Its effectiveness, however, will depend on the capacity of Member States to identify vulnerable beneficiaries accurately and convert available resources into timely and durable reductions in energy and transport vulnerability. This implementation challenge shifts the analysis from supranational policy design to national governance, where common European objectives interact with country-specific welfare systems, housing conditions and energy-market structures.

2.3 The Italian Policy Framework: From Fragmented Welfare to Regulated Energy Protection

The transposition of European Union energy directives into the Italian legislative framework has historically generated a distinct policy evolution, deeply conditioned by national constraints, high geopolitical dependency on natural gas imports, and structural socio-economic disparities. While the European Union provided the overarching regulatory milestones—moving from the early unbundling requirements to the modern eco-social mandates of the Green Deal—Italy's domestic execution developed through asymmetrical phases. The country transitioned from an era of fragmented, localized social welfare into a highly centralized, data-driven energy protection apparatus.

The core academic friction animating the Italian case study resides in the long-standing policy dualism between short-term compensatory mechanisms and long-term structural prevention. Historically, the Italian state relied heavily on ex-post financial relief and tariff manipulation to mask the immediate price signals of market liberalization, rather than deploying targeted capital investments to cure the thermodynamic deficiencies of its residential building stock. To understand how the modern Italian strategy operates under the pressures of accelerated decarbonisation, it is first necessary to critically evaluate the historical, regulatory, and microeconomic foundations of Italy's early defensive policy mix.

The Italian case therefore provides a national test of the broader European trajectory reconstructed above: whether energy policy has effectively progressed from compensating vulnerable consumers for high energy costs toward structurally reducing their exposure to those costs.

Italy's initial institutional response to the social externalities of retail energy market liberalization developed during the late 2000s. In compliance with the consumer protection mandates set forth by the EU's Second Energy Package, the Italian state established a reactive, compensatory framework. Rather than approaching energy deprivation as a distinct multidimensional form of vulnerability, early national policies treated the phenomenon merely as a standard monetary income deficit. This ideological baseline resulted in a defensive strategy anchored by two main pillars: targeted means-tested utility discounts and the preservation of a regulated retail market buffer.

The primary explicit safety net was established through the introduction of the social energy bonuses (*I Bonus Sociali*), developed under the centralized regulatory oversight of the national authority, known today as ARERA (*Autorità di Regolazione per Energia Reti e Ambiente*). The *Bonus Sociale Elettrico* was operationalized via the Interministerial Decree of December 28, 2007, followed by the implementation of the *Bonus Sociale Gas* under Decree-Law 185/2008.

Within this evolving framework, the Bonus Sociale became the principal Italian instrument for reducing the immediate energy burden of economically vulnerable households. Established through the interministerial decree of 28 December 2007 and effective from 1 January 2008, the mechanism operates as a bill discount for households satisfying specified economic or vulnerability criteria, thereby reducing energy expenditure without directly altering the structural energy performance of the dwelling [26].

The principal limitation of these early social bonuses lay in their limited sensitivity to energy-specific vulnerability driven by their reliance on the ISEE (*Indicatore della Situazione Economica Equivalente*) as the sole gateway for policy access. Eligibility was determined primarily through the ISEE means test, which established a common administrative criterion for economic vulnerability. As discussed in Section 2.3.4, however, an income-and-asset-based criterion does not necessarily coincide with energy-specific vulnerability.

This targeting failure was severely exacerbated by administrative and bureaucratic hurdles that triggered a large-scale non-take-up rate among the most vulnerable segments of the population. Under the original legislative framework, the energy bonuses were not applied automatically. Eligible low-income households were required to manually file a physical application through local municipal assistance offices (*CAF - Centri di Assistenza Fiscale*) and renew the bureaucratic paperwork every single year. Applied behavioral economics and institutional reports from ARERA reveal that fewer than 35% of eligible low-income households actually received the bonuses during the first decade of their operation. Administrative barriers therefore limited the effective reach of the scheme among eligible households.

A second pillar of the Italian protective architecture emerged with the Servizio di Maggior Tutela following the opening of the retail electricity market in 2007. The regime guaranteed continuity of electricity supply to eligible domestic customers and small businesses that had not selected a supplier on the liberalised market, under economic and contractual conditions determined by the national regulatory authority. It therefore operated as a regulated protective framework alongside the progressive development of retail-market competition [27].

Although originally designed as a temporary holding zone for residential clients transitioning toward the competitive market, the Maggior Tutela offered households unwilling or unable to navigate retail competition a standardized regulatory alternative, thereby reducing exposure to some of the informational and contractual risks associated with supplier choice.

A significant change in the accessibility of the Bonus Sociale occurred from 1 January 2021, when the system shifted from an application-based procedure to automatic recognition for households satisfying the relevant economic eligibility conditions. Article 57-bis of Decree-Law No. 124/2019, converted by Law No. 157/2019, established the automatic recognition of the electricity, gas and water social bonuses for eligible beneficiaries. Under the new system, households are no longer required to submit a separate application for these economic-hardship bonuses; instead, the information provided through the Dichiarazione Sostitutiva Unica (DSU) for the calculation of ISEE is used within the institutional data-exchange system to identify eligible beneficiaries [28].

The 2021–2023 energy crisis exposed the limits of Italy's pre-existing protective framework. After the initial post-pandemic recovery in energy demand, the shock intensified following Russia's invasion of Ukraine and the associated disruption of European energy markets. In Italy, the average electricity purchase price on the wholesale market (Prezzo Unico Nazionale – PUN) reached a historical high of €303.95/MWh in 2022, representing an increase of 142% compared with the previous year [29].

Faced with an economy-wide energy-price shock, the Italian government adopted a broad emergency response, mobilising tens of billions of euros in public resources through successive measures aimed at cushioning households and firms from exceptional increases in energy costs.

The emergency response combined broad bill-relief measures with reinforced protection for vulnerable consumers and support for firms. Between 2021 and 2023, the government progressively reduced and then temporarily eliminated general system charges for electricity and gas, while the VAT rate on natural-gas bills was reduced to 5%. At the same time, the social bonuses were strengthened through additional compensation and the government introduced tax credits and other measures to limit the impact of exceptional energy costs on businesses [30].

Simultaneously, the state recognized that the crisis was rapidly creating an important class of newly vulnerable lower-middle-class households who sat above traditional anti-poverty safety nets but lacked the disposable income to absorb the utility shocks. To prevent these demographics from slipping into energy poverty, the government introduced unprecedented regulatory elasticity to the *Bonus Sociale* by dynamically altering the means-tested ISEE ceilings. Through successive emergency provisions—culminating in Decree-Law 21/2022 (*DL Aiuti*) and the 2023 Budget Law (*Legge di Bilancio 2023*) for 2022, the government temporarily expanded access to the social electricity and gas bonuses by raising the ordinary ISEE eligibility threshold to €12,000 [31]. The expansion was continued in 2023, when the ordinary ISEE threshold for access to the social electricity and gas bonuses was raised to €15,000 for households with fewer than four dependent

children [32]. The temporary expansion substantially increased the reach of the protective mechanism. In 2022, more than 6.2 million electricity and gas social bonuses for economic hardship were recognised, including approximately 3.77 million electricity bonuses and 2.44 million gas bonuses. The expansion continued in 2023, when approximately 7.6 million electricity and gas bonuses were recognised [33].

The composition of the emergency response reveals a predominantly compensatory logic. Measures such as reductions in system charges, lower taxation, reinforced social bonuses and support for energy costs were designed primarily to limit the immediate transmission of wholesale-price shocks to household and business expenditure. While necessary to contain short-term vulnerability, these interventions did not by themselves reduce the underlying energy requirement of inefficient dwellings or permanently increase household capacity to withstand future price shocks.

From Boardman's structural perspective, such measures mitigate the immediate affordability dimension of energy poverty without necessarily addressing the energy inefficiency of the dwelling itself [2].

The episode demonstrated the practical limits of relying exclusively on competitive market mechanisms during exceptional price shocks and highlighted the continuing stabilizing role of public intervention.

Taken together, these measures marked a temporary expansion of the state's role from targeted welfare provider to economy-wide shock absorber during an exceptional energy-price crisis.

The normalization of energy prices following the 2021–2023 geopolitical shock catalyzed a transition within the Italian policy design. Confronted with a tightening fiscal landscape and the strict deficit-reduction targets imposed by European governance, the Italian state recognized that continuous deficit-funded bill subsidies were fiscally unsustainable. Consequently, the national strategy initiated a policy shift from ex-post emergency compensation to ex-ante structural prevention. This transition aims to cure the thermodynamic and infrastructural causes of energy poverty rather than masking its economic symptoms. It operates through the integration of the National Recovery and Resilience Plan (PNRR) resources, the institutionalization of collective self-consumption, and the final deregulation of the retail market.

Italy's post-crisis framework evolved along two parallel tracks: structural measures intended to reduce future energy dependence and regulatory safeguards designed to protect vulnerable consumers within the liberalised retail market.

A more explicitly structural approach to energy vulnerability emerged with the Fondo Nazionale Reddito Energetico, designed to facilitate access to renewable self-generation for households in economic hardship. The Fund was initially endowed with €200 million for 2024–2025, divided equally between the two years, with 80% of the available resources allocated to the regions of Southern Italy and 20% to the remaining regions and autonomous provinces. Eligible households could access the measure for the installation of photovoltaic systems in self-consumption configurations serving their residential properties [34]. Eligibility is restricted to households with an ISEE below €15,000, or below €30,000 for households with at least four dependent children [34]. A second structural instrument is represented by the development of Comunità Energetiche Rinnovabili (CER) and collective self-consumption configurations. Under the original PNRR framework for Mission 2, Component 2, Investment 1.2, €2.2 billion were allocated to promote renewable-energy communities and collective self-consumption, with capital grants covering up to 40% of eligible investment costs for qualifying renewable-energy installations [35]. The support architecture combines different instruments: the PNRR component provided a capital contribution of up to 40% of eligible investment costs under the applicable conditions, while the incentive framework for shared renewable energy operates through a tariff mechanism administered by the GSE [35].

These instruments also provide a direct connection between contemporary renewable-energy policy and the structural interpretation of energy poverty developed by Boardman. In Boardman's framework, vulnerability cannot be reduced to insufficient income alone, since the energy burden faced by a household also depends on the characteristics of the dwelling and on the amount of purchased energy required to secure adequate domestic energy services [2]. Distributed photovoltaic generation introduces a related structural mechanism: where households are able to self-consume electricity generated at their residence, part of their energy needs can be met without an equivalent purchase from the retail electricity market. Policies that facilitate access to photovoltaic self-generation may therefore reduce exposure to recurring electricity expenditure rather than merely compensate households after energy costs have been incurred. This interpretation does not imply that photovoltaic support is sufficient to eliminate energy poverty, since heating requirements, building efficiency, tenure conditions, income and other household characteristics remain relevant determinants of vulnerability.

The completion of electricity retail-market liberalisation in 2024 further differentiated the protective framework according to consumer vulnerability. From 1 July 2024, the Servizio di Maggior Tutela ceased to apply to non-vulnerable domestic electricity customers, who, where they had not selected a free-market supplier, were transferred to the Servizio a Tutele Graduali. By contrast, vulnerable

domestic customers retained access to the Maggior Tutela regime and may request regulated supply under that framework [36].

Under ARERA's updated criteria, this vulnerable cohort retains the statutory right, under the current regulatory framework, to regulated supply conditions, adjusted quarterly by the authority based on wholesale market indicators. For electricity-market purposes, vulnerable customers include individuals aged over 75, recipients entitled to the electricity social bonus on economic or serious-health grounds, persons with disabilities under Article 3 of Law No. 104/1992, customers supplied in emergency housing following disasters and customers located on non-interconnected minor islands [36]. This regulatory division illustrates the hybrid nature of contemporary Italian energy governance: the state has systematically moved toward an asset-based preventative framework powered by the PNRR and the *Reddito Energetico*, yet it maintains a robust, centralized regulatory floor to shield its most fragile demographics from the raw price dynamics of the fully liberalized market.

The emergence of these preventive and asset-based instruments therefore represents an important evolution in Italian energy policy, but it does not by itself establish that the benefits of the transition are distributed equitably or that vulnerable households are identified accurately. These unresolved questions form the basis of the critical assessment that follows.

The contemporary landscape of Italian energy policy reveals significant policy frictions when evaluated through the analytical frameworks of welfare economics and energy justice. Despite the legislative pivot toward a structural transition, the empirical reality exposes persistent limitations in policy design and targeting within the national strategies. This critical assessment deconstructs the two primary fault lines that define the modern Italian policy failure: the regressive distribution of universal efficiency incentives contrasted with targeted solar equity, and the limited sensitivity to energy-specific vulnerability of income-based welfare indicators when measured against multidimensional econometric metrics.

These weaknesses operate at two distinct stages of the policy process: first, in the distribution of public resources across households; and second, in the identification of the households that should qualify as energy vulnerable. The first problem concerns the design of policy instruments, while the second concerns the accuracy of policy targeting.

The Energy Justice framework developed in Chapter 1 provides a useful lens for interpreting both failures. The distribution of efficiency subsidies concerns distributive justice, since it determines which households capture the benefits of public decarbonisation expenditure. The design of

eligibility criteria concerns recognition justice, since effective targeting depends on whether policy instruments correctly identify the specific energy needs and vulnerabilities of different households. Procedural considerations further arise where access to support depends on financial literacy, property ownership or the capacity to navigate complex administrative requirements.

A major structural intervention in the residential sector was introduced in 2020 through the Superbonus 110%, which provided an enhanced tax deduction for qualifying expenditure on building energy-efficiency improvements, seismic-risk reduction and related interventions. In the energy domain, the measure sought to stimulate investment in the physical performance of the housing stock by subsidising interventions capable of improving building efficiency and reducing future energy requirements [37]. Low-income households are disproportionately affected by fiscal *incapienza*—meaning they pay little to no personal income tax (*IRPEF*) because their earnings fall below the minimum taxable threshold. Consequently, they lacked the tax liability required to directly absorb a multi-year deduction. When the secondary credit-transfer market (*cessione del credito* and *sconto in fattura*) saturated due to regulatory instability and banking blockades, vulnerable households were left unable to participate. Furthermore, the design of the scheme was more readily accessible to owners able to coordinate and finance eligible renovation projects or condominiums with greater organizational and financial capacity. In old, low-income multi-family apartment blocks with complex, fractured ownership structures, vulnerable tenants faced substantial bureaucratic and procedural barriers, lacking the liquid capital to finance initial technical feasibility studies or the consensus to approve complex renovations. As a result, a substantial share of public expenditure may have accrued to households with greater ownership, financial and administrative capacity, raising concerns about the distributive effectiveness of the scheme.

Conversely, the *Reddito Energetico Nazionale* operationalizes the principles of energy justice by abandoning the illusion of universality. By locking its resources to strict income thresholds via the ISEE, it directs public resources toward income-targeted households. More importantly, it eliminates the upfront capital and credit barriers through its public revolving fund structure: the GSE pays certified installation suppliers upfront, freeing the low-income consumer from the requirement of credit-worthiness or tax-deduction capacity. Compared with the broad tax-based architecture of the Superbonus, the Reddito Energetico more directly targets economically vulnerable households and addresses one structural dimension of energy vulnerability by improving access to distributed renewable generation.

From a capability perspective, the significance of this intervention lies not simply in transferring monetary resources, but in expanding the household's practical capacity to secure essential energy services with lower exposure to recurring market expenditure.

This does not imply that photovoltaic support resolves energy poverty in all its dimensions, since vulnerability may also derive from inefficient housing, heating requirements, tenancy conditions and other household-specific constraints.

The comparison therefore highlights a broader policy-design trade-off: large-scale decarbonisation incentives may mobilize substantial investment without necessarily concentrating benefits among energy-vulnerable households, whereas targeted instruments can improve distributive alignment but operate on a narrower scale and address only specific dimensions of deprivation.

ISEE and the Faiella–Lavecchia indicator serve different analytical and administrative purposes. ISEE measures household economic conditions for access to a broad range of means-tested benefits, whereas the Faiella–Lavecchia approach is specifically designed to identify energy-poverty conditions.

A persistent limitation of the Italian framework concerns the administrative tools used to identify and target energy-poor households. The national safety net relies predominantly on the ISEE index to determine access to utility-bill discounts and other means-tested forms of support. Reliance on a general means-tested indicator may therefore generate inclusion and exclusion errors when economic vulnerability does not coincide with energy-specific deprivation. A further limitation may arise from the retrospective nature of the economic information used in ordinary means testing, which can reduce responsiveness to sudden deteriorations in household circumstances unless more current assessment mechanisms are activated.

A more energy-specific approach to identifying vulnerability is provided by the indicator developed by Faiella and Lavecchia for the Italian context. Building on a modified Low Income–High Costs methodology, the indicator combines information on household economic resources and energy expenditure while also accounting for economically vulnerable households reporting no heating expenditure, thereby reducing the risk that severe under-consumption remains statistically invisible. Using this measure, Faiella and Lavecchia estimated that approximately 8% of Italian households experienced energy poverty over the period 1997–2012 [38].

The relevance of this methodology subsequently extended beyond the academic literature: the Faiella–Lavecchia indicator has been used in Italian government energy-policy documents since 2017, including the National Energy Strategy and the National Energy and Climate Plan [38].

The targeting problem therefore also constitutes a question of recognition justice. A welfare system may redistribute resources toward households classified as economically vulnerable while still misrecognising energy deprivation if its eligibility criteria fail to capture heterogeneous energy needs, dwelling conditions and exposure to energy costs.

Reliance on ISEE as the principal eligibility criterion may therefore produce mismatches where general economic vulnerability does not coincide with energy-specific deprivation. Households whose economic indicators remain above administrative thresholds may nevertheless experience substantial energy burdens, while economically eligible households do not necessarily face the same level of energy deprivation. A further limitation concerns the temporal structure of ordinary ISEE: income and asset information generally refers to the second calendar year preceding the submission of the DSU. This may reduce responsiveness to sudden deteriorations in household circumstances. However, the Italian framework partially addresses this limitation through the ISEE corrente, which allows more recent economic information to be considered when significant changes in household circumstances occur [39].

Taken together, the two comparisons reveal that the effectiveness of energy-poverty policy depends on two distinct but complementary forms of targeting. Public resources must first be distributed through instruments that vulnerable households can effectively access; at the same time, eligibility systems must identify energy-specific deprivation with sufficient accuracy. The Italian case therefore illustrates that the transition from compensatory relief toward structural prevention cannot be evaluated solely by the volume of resources mobilized or the technologies financed, but also by who is able to benefit from them and whether the households most exposed to energy vulnerability are correctly recognised.

2.4 Chapter Conclusions

The evolution of European energy policy examined in this chapter reveals a progressive change in the treatment of household energy vulnerability. Energy poverty moved from being addressed indirectly through general consumer protection and welfare mechanisms toward becoming an increasingly explicit component of energy and climate governance. This evolution became particularly significant as decarbonisation policies expanded beyond environmental objectives alone: the distribution of transition costs, the capacity of vulnerable households to adapt, and access to energy-efficiency investment increasingly entered the policy framework. The resulting European approach therefore combines market integration and climate mitigation with a growing recognition that the transition must also address its unequal social consequences.

The Italian case reflects this broader trajectory but also demonstrates the persistence of a hybrid policy model. Early instruments such as the Bonus Sociale and regulated retail protection primarily sought to mitigate the monetary consequences of energy vulnerability, while the 2021–2023 energy-price crisis temporarily expanded the state's role through exceptional fiscal and regulatory intervention. More recent measures, including targeted support for renewable self-generation and energy communities, indicate a gradual shift toward preventive and asset-based intervention capable of reducing future exposure to purchased energy. Italy has therefore moved beyond an exclusively compensatory approach, although this transition remains incomplete and continues to coexist with traditional income support and consumer-protection mechanisms.

The analysis nevertheless shows that the transition from compensation toward structural prevention cannot be evaluated solely by the volume of public resources mobilized or the technologies supported. The multidimensional framework developed in Chapter 1 indicates that household vulnerability depends on the interaction of income, energy costs, dwelling efficiency and the unequal capacity to convert available resources into adequate energy services. From this perspective, the Italian experience reveals two persistent policy challenges: ensuring that vulnerable households can effectively access the benefits of decarbonisation investment, and identifying energy-specific deprivation with greater precision than general economic indicators alone may permit. Effective energy-poverty governance therefore requires not only sufficient financial support, but also equitable distribution, accessible policy design and accurate recognition of heterogeneous household needs.

These remaining limitations also underline the importance of measurement. If energy poverty is multidimensional and heterogeneous across households, evaluating policy effectiveness requires analytical tools capable of moving beyond general income-based classifications and examining how vulnerability is distributed across the population. The following chapters therefore shift from institutional and policy analysis toward the quantitative dimension of the thesis, developing an empirical framework for examining the distribution and intensity of energy poverty and assessing the extent to which observed patterns are consistent with the vulnerabilities identified in the preceding theoretical and policy analysis.

CHAPTER 3

3.1 Measuring Energy Poverty: The Methodological Problem

As established in Chapter 1, energy poverty is a multidimensional form of deprivation arising from the interaction between household resources, energy costs, dwelling characteristics and the ability to secure adequate domestic energy services [11]. Because it cannot be observed directly through a single monetary variable, empirical measurement requires its translation into observable criteria capable of distinguishing energy-specific vulnerability from general economic disadvantage. This task has become increasingly important as the policy framework examined in Chapter 2 has strengthened the need to identify, monitor and protect vulnerable households.

Indicator design necessarily determines which manifestations of energy poverty become statistically visible. Alternative measures may emphasise high energy expenditure, unusually low consumption, residual economic resources or required energy needs and can therefore classify different households within the same population [38]. Measurement choice is consequently not neutral: it affects both estimated prevalence and the composition of the population identified as vulnerable.

A central difficulty concerns the distinction between observed expenditure and the energy services required to maintain adequate living conditions. Financially constrained households may suppress consumption, causing deprivation to appear as low expenditure, while high expenditure may reflect affordability pressure but also dwelling size, inefficiency, climatic conditions or voluntary consumption choices. Realized expenditure therefore provides useful information on energy burden without uniquely identifying its underlying cause.

A second methodological issue concerns threshold construction. Expenditure-based indicators generally convert continuous household characteristics into discrete classifications through fixed, relative or combined boundaries. Although such rules facilitate interpretation, classifications are sensitive to the selected threshold and reference population: households with similar circumstances may fall on opposite sides of a boundary, while relative thresholds may change as the reference distribution changes.

Geographical calibration introduces a related trade-off. National benchmarks facilitate comparison through a common standard, whereas regional benchmarks may better reflect territorial heterogeneity but reduce uniform comparability across areas. The reference population must therefore be treated explicitly as part of the measurement strategy.

These difficulties explain the plurality of energy-poverty indicators found in the literature [38]. Rather than representing interchangeable estimates of a directly observable condition, different

measures capture different dimensions of vulnerability. Section 3.2 therefore examines the principal expenditure-based approaches relevant to this thesis, their informational contribution and their methodological limitations, establishing the benchmark for the distributional methodology developed subsequently.

3.2 Conventional Expenditure-Based Approaches to Measuring Energy Poverty

Conventional expenditure-based indicators identify energy vulnerability by comparing household energy costs with available economic resources or with reference values derived from a selected population. They differ in the use of observed or required expenditure, threshold construction and the manifestation of vulnerability targeted: some identify high energy burdens, others potential under-consumption, while more complex approaches incorporate residual economic resources. Consequently, different indicators may classify different households even when applied to the same population. The following subsections examine the principal approaches relevant to this thesis: Boardman's fixed 10% rule, the relative 2M and M/2 indicators, the Low Income High Costs framework and the Italian Faiella–Lavecchia indicator.

Boardman's formulation represents one of the foundational approaches to the quantitative measurement of fuel poverty. As discussed in Chapter 1, its affordability criterion relates to the expenditure required to secure adequate domestic energy services rather than exclusively to realized household spending, thereby reducing the risk that households engaging in self-rationing are excluded because their observed energy expenditure is low [2].

Let E_i^{req} denote the expenditure required by household i to obtain an adequate level of domestic energy services and Y_i household income under the relevant implementation. The required expenditure-burden ratio is:

$$s_i^B = \frac{E_i^{req}}{Y_i}.$$

Under the conventional Boardman rule, household i is classified as fuel poor when:

$$\frac{E_i^{req}}{Y_i} > 0.10.$$

with the corresponding binary indicator:

$$I_i^B = \begin{cases} 1 \text{ if } \frac{E_i^{req}}{Y_i} > 0.10 \\ 0, \quad \text{otherwise} \end{cases}$$

Required energy expenditure reflects the estimated cost of adequate domestic energy services given factors such as dwelling characteristics, heating-system efficiency, energy prices and climatic conditions. The approach therefore distinguishes energy need from realized consumption and combines this conceptual advantage with a transparent 10% boundary. Historically, the threshold reflected UK expenditure patterns and approximated twice the median household fuel-expenditure share, building on the earlier approach associated with Isherwood and Hancock [2, 4].

Its principal limitation is the fixed numerical boundary. Because the 10% rule emerged from a specific historical and national context, it does not automatically adjust to changes in prices, resources, housing conditions or climate, while its binary construction can assign different statuses to households with almost identical burdens around the threshold. Moreover, if required expenditure cannot be estimated and actual expenditure is substituted, the interpretation changes substantially: high realized spending may reflect vulnerability but also voluntary consumption or other characteristics of economically secure households. These limitations motivate comparison with relative expenditure measures whose thresholds adapt to the observed distribution.

Relative expenditure indicators replace fixed numerical cut-offs with thresholds derived from the distribution of a selected reference population. Two widely used measures are “Twice the Median” (2M) and “Half the Median” (M/2). Despite their common reliance on medians, they operate on different variables and identify opposite manifestations of potential energy vulnerability: 2M captures unusually high energy-expenditure shares, whereas M/2 captures unusually low absolute energy expenditure.

2M — Excessive Realized Energy Burden

The 2M indicator identifies households whose energy-expenditure share exceeds twice the median value observed in the relevant reference population [40]. In the expenditure-based implementation adopted in this thesis, let E_i denote actual household energy expenditure and C_i total household consumption expenditure. The realized energy-expenditure share is:

$$s_i = \frac{E_i}{C_i}.$$

Let the corresponding median be:

$$M_s = \text{Median}(s_i)\,.$$

The 2M threshold is:

$$\tau_{2M} = 2M_s.$$

Household i satisfies the condition when:

$$s_i > 2M_s,$$

with binary classification:

$$EP_i^{2M} = \begin{cases} 1, & \text{if } s_i > 2M_s, \\ 0, & \text{otherwise.} \end{cases}$$

Unlike the fixed 10% rule, the 2M boundary varies with the expenditure-share distribution and therefore identifies households whose realized burden is unusually high relative to the reference population. Its advantages include simplicity, adaptability and limited data requirements. However, the multiplier of two remains externally imposed, and a population-wide increase in energy burdens may raise both household shares and the median benchmark. Moreover, a high realized share does not independently establish economic deprivation, since economically secure households may also record comparatively high energy expenditure.

M/2 — Potential Under-Consumption

M/2 instead identifies households with unusually low absolute energy expenditure, reflecting the possibility that financial constraints induce consumption suppression [40]. Let the median of actual household energy expenditure be:

$$M_E = \text{Median}(E_i)\,.$$

The M/2 threshold is:

$$\tau_{\frac{M}{2}} = \frac{M_E}{2}.$$

Household i satisfies the condition when:

$$E_i < \frac{M_E}{2}.$$

with binary classification:

$$EP_i^{\frac{M}{2}} = \begin{cases} 1, & \text{if } E_i < \dfrac{M_E}{2}, \\ 0, & \text{otherwise.} \end{cases}$$

The distinction from 2M is fundamental: 2M is based on the median of the energy-expenditure share, whereas M/2 uses the median of absolute monetary energy expenditure. The two measures therefore operate on different variables and cannot be interpreted as symmetric upper- and lower-tail thresholds on the same scale.

M/2 can reveal potential self-rationing that upper-burden measures may overlook, but low expenditure does not uniquely indicate deprivation; it may also reflect dwelling characteristics, energy efficiency, climate or genuinely limited energy needs. Taken together, 2M and M/2 provide

complementary information on excessive realized burden and potential under-consumption, but neither independently establishes insufficient economic resources.

The Low Income High Costs (LIHC) indicator combines comparatively high required energy costs with insufficient residual economic resources, addressing the limitation that high energy costs alone do not necessarily imply deprivation. The notation below represents its conceptual structure; the original UK implementation additionally incorporates equivalisation and specific treatment of housing costs and required fuel expenditure [8].

Let E_i^{req} denote required energy expenditure and let the relevant median required expenditure be:

$$M_{E^{req}} = \text{Median}\left(E_i^{req}\right).$$

The high-cost condition is:

$$E_i^{req} > M_{E^{req}}.$$

Let Y_i denote disposable household income. Residual income after required energy expenditure is:

$$Y_i^{res} = Y_i - E_i^{req}.$$

If P_Y denotes the relevant poverty threshold, the low-income condition is:

$$Y_i^{res} < P_Y.$$

A household is classified as energy poor only when both conditions hold:

$$E_i^{req} > M_{E^{req}} \text{ and } Y_i - E_i^{req} < P_Y.$$

with binary classification:

$$EP_i^{LIHC} = \begin{cases} 1, & \text{if } E_i^{req} > M_{E^{req}} \text{ and } Y_i - E_i^{req} < P_Y, \\ 0, & \text{otherwise.} \end{cases}$$

LIHC therefore links high required energy costs to the household's capacity to sustain them. The residual-income condition excludes households that retain sufficient resources after meeting energy requirements, while the use of required rather than realized expenditure reduces sensitivity to self-rationing.

This richer interpretation entails greater data and modelling requirements. Required energy expenditure must be estimated using information on dwelling characteristics, energy efficiency, household circumstances, climate and energy prices. LIHC also remains dependent on discrete high-cost and poverty thresholds, so households close to either boundary may change classification following relatively small changes in circumstances or methodological specification. These

requirements can limit direct application where sufficiently detailed dwelling-level information is unavailable, motivating approaches more closely aligned with standard household expenditure microdata.

In the Italian context, Faiella and Lavecchia developed an expenditure-based framework designed for application to household microdata. The indicator combines observed expenditure and economic vulnerability through two identification routes: the first captures comparatively high realized energy burden associated with insufficient residual resources, while the second addresses an extreme manifestation of potential under-consumption through zero heating expenditure [38].

Let C_i denote total household consumption expenditure, E_i actual household energy expenditure and H_i observed expenditure on space heating. The household energy-expenditure share is:

$$s_i = \frac{E_i}{C_i}$$

Let P_C denote the applicable relative consumption-poverty threshold.

First Identification Route: Excessive Burden and Residual Economic Vulnerability. The first route identifies households simultaneously experiencing high realized energy burden and insufficient residual consumption resources. Let $\bar{s}$ denote the national average energy-expenditure share. Residual household consumption after energy expenditure is:

$$C_i^{res} = C_i - E_i.$$

Household i satisfies the first route when its energy-expenditure share exceeds twice the national average and its residual consumption falls below the applicable relative consumption-poverty threshold [38]:

$$s_i > 2\bar{s}$$

and

$$C_i^{res} < P_c.$$

The corresponding classification is:

$$EP_i^{FL,1} = \begin{cases} 1, & \text{if } s_i > 2\bar{s} \text{ and } C_i - E_i < P_C, \\ 0, & \text{otherwise.} \end{cases}$$

The residual-consumption condition prevents high realized energy expenditure from being sufficient for classification, requiring it to coexist with material economic vulnerability.

Second Identification Route: Zero Heating and Severe Potential Under-Consumption. The second route captures potential hidden energy poverty through the absence of observed heating expenditure.

Let C_i^{eq} denote equivalised total household expenditure and $\tilde{C}^{eq}$ its national median. Household i satisfies this route when it reports zero heating expenditure and equivalised expenditure below the national median [38]:

$$H_i = 0$$

and

$$C_i^{eq} < M_C^{eq}.$$

with classification:

$$EP_i^{FL,2} = \begin{cases} 1, & \text{if } H_i = 0 \text{ and } C_I^{eq} < M_C^{eq} \\ 0, & \text{otherwise.} \end{cases},$$

The overall Faiella–Lavecchia indicator is the logical union of the two routes:

$$EP_i^{FL} = EP_i^{FL,1} \vee EP_i^{FL,2}.$$

Equivalently:

$$EP_i^{FL} = \begin{cases} 1, & \text{if } (s_i > 2\bar{s} \text{ and } C_i - E_i < P_C) \text{ or } (H_i = 0 \text{ and } C_I^{eq} < M_C^{eq}), \\ 0, & \text{otherwise.} \end{cases}$$

The framework therefore captures two distinct manifestations of vulnerability: high realized energy burden combined with insufficient residual resources, and an extreme form of potential under-consumption among economically vulnerable households reporting no heating expenditure. Its principal practical advantage is compatibility with household budget microdata, avoiding the detailed engineering information required by needed-expenditure models.

Important limitations remain. The first route depends on a relative high-cost benchmark based on twice the national average energy-expenditure share, while the second captures only an extreme form of potential under-consumption: households may substantially ration heating while still reporting positive expenditure. Both routes also retain discrete thresholds and the associated sensitivity of classifications around their boundaries.

The indicators reviewed above demonstrate that energy poverty can become statistically visible through different expenditure patterns and methodological assumptions. Boardman and LIHC emphasise required energy expenditure, with LIHC additionally incorporating residual economic resources; 2M and M/2 operate on opposite regions of observed expenditure distributions; and Faiella–Lavecchia combines realized burden, economic vulnerability and an additional route for extreme potential under-consumption. These measures should therefore be interpreted as

complementary rather than interchangeable representations of household energy vulnerability [2, 8, 38, 40].

A first methodological tension concerns threshold construction. Boardman employs a fixed numerical percentage; 2M and M/2 derive their boundaries from population medians while retaining predetermined multipliers; and LIHC and Faiella–Lavecchia combine multiple expenditure and poverty conditions. The indicators therefore operationalize the classification boundary through different mechanisms, whose consequences can be compared empirically.

A second tension concerns required versus observed expenditure. Boardman and LIHC reduce sensitivity to self-rationing through required-energy-cost estimates, whereas 2M, M/2 and Faiella–Lavecchia rely more directly on realized expenditure patterns. The comparison therefore involves a trade-off between richer representations of energy needs and greater compatibility with standard household expenditure microdata.

Under-consumption remains a particularly important source of divergence, since M/2 and the zero-heating route of Faiella–Lavecchia can reveal potential self-rationing that upper-burden measures may miss, while the underlying cause of low expenditure remains observationally ambiguous.

Finally, conventional approaches ultimately convert continuous household circumstances into threshold-based classifications. While this facilitates interpretation and policy monitoring, it discards information about households' relative positions within the underlying expenditure distribution: similar households can fall on opposite sides of a boundary, while households located very different distances beyond it may receive the same status.

These limitations do not imply that conventional expenditure indicators are methodologically inadequate. Each measure makes a particular manifestation of vulnerability observable while sacrificing some information in exchange for interpretability, feasibility or sensitivity to specific forms of deprivation. Disagreement across indicators may therefore contain substantive information about the dimension of vulnerability being captured rather than simply representing measurement error.

The unresolved question motivating the methodology developed in this thesis concerns the upper boundary itself. Existing high-burden approaches determine this boundary through a fixed percentage, a predetermined multiple of a reference statistic or a combination of explicit classification conditions. They do not generally investigate whether the geometry of a fitted continuous expenditure-share distribution may itself contain information useful for delimiting an unusually high-burden tail.

Section 3.3 therefore introduces the Beta distribution as a parametric representation of household energy-expenditure shares and investigates an experimental possibility: whether a characteristic point derived from the geometry of the fitted distribution can provide a candidate endogenous boundary for the upper tail. The objective is neither to assume that such a criterion constitutes the correct definition of energy poverty nor to replace the conventional approaches reviewed above. Rather, the proposed procedure examines whether a distribution-derived threshold can provide a meaningful complementary perspective whose performance can subsequently be evaluated against established benchmarks.

3.3 Beta Distribution and the Experimental Identification of an Endogenous Upper-Tail Threshold

The limitations of discrete classification identified in Section 3.2 motivate a complementary distributional perspective that preserves information on households' positions within the expenditure distribution and, in particular, its upper tail. Let E_i denote household energy expenditure and C_i total consumption expenditure. The household energy-expenditure share is:

$$s_i = \frac{E_i}{C_i}.$$

Provided that energy expenditure constitutes a component of total consumption expenditure, its natural domain is:

$$0 \leq s_i \leq 1.$$

Higher values of s_i indicate that energy absorbs a larger proportion of household consumption expenditure. They do not, however, constitute energy-poverty status in themselves, since high realized burdens may reflect affordability pressure, energy requirements, housing inefficiency or other household circumstances. Accordingly, s_i is treated as a continuous measure of realized energy burden.

Rather than immediately converting s_i into a binary classification, the proposed approach examines the shape and upper-tail behaviour of its distribution. A threshold remains necessary to delimit a specific high-burden group, but the methodological question changes from imposing an externally specified boundary to investigating whether a reproducible candidate boundary can be derived from the fitted expenditure-share distribution itself.

Given the bounded nature of s_i and the possibility of asymmetric empirical distributions, the Beta family provides a flexible parametric specification for this purpose. Its role is not to define energy poverty directly, but to represent the continuous expenditure-share distribution whose fitted geometry is investigated in the subsequent threshold construction.

The Beta distribution is characterised by two positive shape parameters, α and β, and provides a flexible parametric model for continuous variables on the unit interval [41]. Let Sdenote the random variable representing household energy-expenditure shares:

$$S \sim Beta(\alpha, \beta)$$

with:

$$\alpha > 0,\ \beta > 0.$$

For values strictly inside the unit interval, the probability density function is:

$$f(s; \alpha; \beta) = \frac{s^{\alpha-1}(1-s)^{\beta-1}}{B(\alpha, \beta)},\ 0 < s < 1,$$

where the Beta function is:

$$B(\alpha, \beta) = \frac{\Gamma(\alpha)\Gamma(\beta)}{\Gamma(\alpha+\beta)}.$$

and ensures normalization:

$$\int_0^1 f\ (s; \alpha; \beta)\ ds = 1.$$

The parameters α and β jointly determine the location, concentration and asymmetry of the fitted density. Its expected value and variance are:

$$\mathbb{E}[S] = \frac{\alpha}{\alpha+\beta}, \qquad Var(S) = \frac{\alpha\beta}{(\alpha+\beta)^2(\alpha+\beta+1)}.$$

These parameters also determine the local geometry of the density, which becomes central to the subsequent upper-tail construction.

$$F(s; \alpha; \beta) = P(S \leq s).$$

For any admissible threshold τ, the fitted probability mass above it is:

$$P(S > \tau) = 1 - F(\tau; \alpha; \beta).$$

At this stage, τ has no predetermined energy-poverty interpretation: the Beta distribution provides only the statistical representation on which the experimental threshold procedure is constructed.

A technical distinction concerns the boundaries of the support. Although the observed expenditure share may theoretically satisfy:

$$0 \leq s_i \leq 1,$$

the standard continuous Beta density is defined for

$$0 < s \quad < 1.$$

Observations exactly at zero or one therefore require explicit empirical treatment before estimation [41]. Since zero energy expenditure may remain possible at the sample-selection stage, the treatment of boundary observations is documented as part of the empirical data-processing and robustness procedure.

Given a sample of household energy-expenditure shares lying within the admissible support of the Beta distribution:

$$s_1, s_2, \dots, s_n,$$

let:

$$\theta = (\alpha, \beta)$$

denote the unknown parameter vector. Under the Beta specification, the likelihood is:

$$L(\alpha, \beta) = \prod_{i=1}^{n} f\,(s_i; \alpha; \beta).$$

and the corresponding log-likelihood is:

$$\ell(\alpha, \beta) = \sum_{i=1}^{n} \log f\,(s_i; \alpha; \beta)\,.$$

The maximum-likelihood estimates are:

$$\left(\hat{\alpha}, \hat{\beta}\right) = \arg\max_{\alpha,\beta>0} \quad \ell(\alpha, \beta)\,.$$

yielding the fitted density:

$$\hat{f}(s) = f\left(s; \hat{\alpha}; \hat{\beta}\right).$$

When survey weights are available, let w_i denote the annual survey weight of household i. The weighted log-likelihood is:

$$\ell_w(\alpha, \beta) = \sum_{i=1}^{n} w_i \log f\,(s_i; \alpha; \beta).$$

In the empirical implementation, survey weights are incorporated through frequency expansion before Beta estimation, so that sampled households contribute in proportion to their annual weights. The weighted-likelihood expression above provides the corresponding analytical representation of this population-weighted estimation criterion.

The estimated parameters $(\hat{\alpha}, \hat{\beta})$ are not measures of energy poverty; they determine the shape and local geometry of the fitted expenditure-share distribution. Because Beta estimation can be performed on different reference populations, the resulting parameters and candidate thresholds may vary with the population used for fitting.

In the empirical architecture developed in Section 3.4, endogenous specifications are estimated separately within regions after applying the relevant economic-vulnerability condition. The national variant applies a common Italian consumption benchmark to select the vulnerable population within each region, whereas the regional variant applies territory-specific benchmarks. Consequently, both variants generate region-specific conditional Beta distributions, while differing in the economic benchmark used to define the estimation population.

Once $(\hat{\alpha}, \hat{\beta})$ have been estimated, the analysis turns to the geometry of the fitted density and the identification of a characteristic upper-tail transition.

Once the Beta distribution has been fitted, its geometry can be examined for information useful in delimiting an unusually high expenditure-burden region. The experimental procedure considers the mode and successive derivatives of the fitted density, focusing on its decreasing right-hand side.

For the class of unimodal Beta distributions relevant to the proposed construction, the mode is:

$$s_m = \frac{\alpha - 1}{\alpha + \beta - 2},$$

provided that:

$$\alpha > 1,\ \beta > 1 \text{ [41]}.$$

The mode identifies the maximum of the fitted density. Moving to its right, progressively higher expenditure shares become less frequent, but the rate and curvature of this decline may vary. To express the successive derivatives compactly, define the logarithmic derivative:

$$\psi(s) = \frac{f'(s)}{f(s)}.$$

which, for the Beta density, becomes:

$$\psi(s) = \frac{\alpha - 1}{s} - \frac{\beta - 1}{1 - s}.$$

This function is used solely as an analytical device and has no independent economic interpretation.

The first derivative describes the slope of the density:

$$f'(s) = f(s)\psi(s).$$

To the right of the mode, $f'(s) < 0$, indicating a decreasing density. The second derivative describes its local curvature:

$$f''(s) = f(s)[\psi(s)^2 + \psi'(s)],$$

where:

$$\psi'(s) = -\frac{\alpha - 1}{s^2} - \frac{\beta - 1}{(1-s)^2}. \qquad f''(s) = 0$$

at which the sign of $f''(s)$ changes identifies an inflection point. The right-hand inflection point marks a change in curvature but is not imposed as the final upper-tail boundary.

The subsequent evolution of curvature is examined through the third derivative:

$$f'''(s) = f(s)[\psi(s)^3 + 3\psi(s)\psi'(s) + \psi''(s)],$$

with:

$$\psi''(s) = \frac{2(\alpha - 1)}{s^3} - \frac{2(\beta - 1)}{(1-s)^3}.$$

Since $f'''(s) = \frac{d}{ds} f''(s)$, a solution of:

$$f'''(s) = 0$$

identifies a stationary point of the second derivative. The experimental procedure investigates whether the rightmost admissible such point can provide a reproducible candidate boundary for the final right-hand regime of the fitted distribution. Its geometric identification does not, by itself, establish an economically valid energy-poverty threshold; that interpretation remains subject to empirical assessment.

The three-regime decomposition applies when the fitted Beta density exhibits the required interior geometric features, including a right-hand inflection point and at least one admissible third-derivative root. These conditions are not universal properties of the Beta family and must therefore be verified for each fitted distribution.

A useful set of sufficient conditions for the right-hand geometric configuration considered here is $\alpha > 1$ and $\beta > 3$. The first condition, together with $\beta > 1$, ensures that the Beta density has an interior mode $s_m = (\alpha - 1)/(\alpha + \beta - 2)$, at which $f''(s_m) < 0$. The stronger restriction $\beta > 3$ governs the behaviour of the density near the upper boundary. In particular, as $s \to 1^-$, the second derivative approaches zero from above, $f''(s) \to 0^+$. Since curvature is negative at the interior mode but positive in the right-hand tail, continuity implies the existence of a right-hand inflection point at which $f''(s) = 0$. Beyond this point, the positive curvature must subsequently decline towards zero

as the upper boundary is approached, implying the existence of at least one interior stationary point of curvature satisfying $f'''(s) = 0$. Thus, $\alpha > 1$ and $\beta > 3$ provide sufficient conditions for the mode–inflection–stationary-curvature sequence required by the proposed right-tail construction. They do not, however, establish the socioeconomic validity of the selected third-derivative root as an energy-poverty threshold, which remains an empirical question.

First regime, decreasing and concave. Immediately to the right of the mode s_{mode}, the relevant configuration is:

$$f'(s) < 0,\ f''(s) < 0.$$

This region remains associated with the main body of the fitted distribution and is not treated as the candidate upper-tail region.

Second regime, decreasing and convex transition. Let s_{infl} denote the right-hand inflection point satisfying:

$$f''(s_+) = 0.$$

Beyond it, the geometric configuration relevant to the proposed construction is:

$$f'(s) < 0,\ f''(s) > 0,\ f'''(s) > 0.$$

The change in the sign of $f''(s)$ marks the transition from concavity to convexity while the density continues to decrease. Because curvature is still evolving within this regime, the right-hand inflection point is treated as an intermediate geometric transition rather than directly as the candidate upper-tail boundary.

Third regime, final right-hand regime. Let s_3 denote the rightmost admissible solution of:

$$f'''(s) = 0,\ 0 < s < 1.$$

Beyond this point, the proposed geometric configuration is:

$$f'(s) < 0,\ f''(s) > 0,\ f'''(s) < 0.$$

Within this final regime, the fitted density remains decreasing and convex, while the evolution of its second derivative differs from that observed in the preceding transition regime. Under the experimental construction considered here, the interval extending from the selected third-derivative root towards the upper boundary is therefore investigated as a candidate distribution-derived right-tail region.

$$s \in (s^*, 1) \qquad\qquad s_m \to s_+ \to s^* \to 1.$$

If $f'''(s)$ has multiple admissible interior roots, the procedure selects the rightmost one, corresponding to the final admissible transition encountered when moving towards the upper

boundary. This selection provides a reproducible geometric rule, not a socioeconomic result: it identifies a candidate location within the fitted distribution but does not establish that households beyond it are necessarily energy poor. The empirical analysis must determine whether this transition provides a stable and economically interpretable boundary for unusually high realized energy burdens.

The geometric analysis above provides the basis for defining the endogenous threshold investigated in this thesis. Let the set of admissible interior roots of the third derivative of the fitted Beta density be:

$$\mathcal{R} = \{s \in (0,1): f'''(s; \hat{\alpha}; \hat{\beta}) = 0\}.$$

When this set is non-empty and the required right-hand geometric configuration is satisfied, the candidate endogenous threshold is defined as its rightmost admissible element:

$$\tau_{\text{endo}} = \max \mathcal{R}\,.$$

where the fitted parameters $(\hat{\alpha}, \hat{\beta})$ determine the location of the threshold through the geometry of the estimated distribution. The resulting boundary is therefore endogenous in the statistical sense that it is derived from the fitted expenditure-share distribution rather than fixed ex ante as a predetermined percentage or multiplier.

Because the Beta density is strictly positive within its interior support, the same condition can be expressed using the logarithmic-derivative representation introduced above. Since:

$$f'''(s) = f(s)[\psi(s)^3 + 3\psi(s)\psi'(s) + \psi''(s)],$$

and:

$$f(s) > 0 \text{ for } 0 < s < 1,$$

the roots of $f'''(s)$ are equivalently obtained by solving:

$$\psi(s)^3 + 3\psi(s)\psi'(s) + \psi''(s) = 0.$$

This representation facilitates numerical identification of the admissible roots. In the empirical implementation, candidate solutions are located over a dense grid on the interior of the unit interval by detecting sign changes in the third-derivative condition and subsequently refining the corresponding roots numerically. Only solutions satisfying the required right-hand geometric conditions are retained, and the rightmost admissible solution is selected.

The construction requires explicit safeguards because the relevant root need not exist for every fitted Beta distribution. A fitted density may lack the required interior geometry, may produce no

admissible third-derivative root or may generate candidate solutions too close to the boundaries to support a stable interpretation. Such cases must be identified rather than forcing the procedure to return a threshold.

The term *endogenous* should therefore be interpreted narrowly. It indicates that the numerical boundary responds to the estimated distribution and its reference population; it does not imply that the threshold is theoretically or normatively established as the point at which energy poverty begins. The rightmost root is investigated as a candidate endogenous boundary, whose empirical stability and substantive relevance are evaluated subsequently.

Once the candidate endogenous threshold has been identified, the fitted Beta distribution can be used to quantify the probability mass lying above it. For a fitted threshold τ_{endo}, the corresponding upper-tail probability is:

$$S > \tau_{\text{endo}},$$

where F denotes the cumulative distribution function of the fitted Beta model. In empirical applications, the corresponding observed population share can also be calculated directly from the weighted household data:

$$p_{\text{tail}} = P(S > \tau_{\text{endo}}) = 1 - F\left(\tau_{\text{endo}}; \hat{\alpha}; \hat{\beta}\right).$$

Comparing the fitted and empirical tail shares provides a direct diagnostic of how closely the Beta model reproduces the observed upper tail, which is particularly important because the candidate threshold is derived from fitted distributional geometry.

The resulting tail probability should not be interpreted as a complete measure of energy poverty. It identifies the prevalence of unusually high realized energy burdens according to the candidate distribution-derived boundary but does not establish whether households in that tail also lack sufficient economic resources. The next section therefore combines the expenditure-share condition with an explicit economic-vulnerability criterion.

3.4 From the Energy-Burden Tail to the Joint Energy-Poverty Framework

The endogenous threshold developed in Section 3.3 identifies a candidate upper-tail condition for realized energy burden, but this condition is not sufficient to define energy poverty. The empirical approach therefore combines the relevant energy-burden criterion with a separate measure of economic vulnerability, producing a joint identification rule represented by their intersection:

$$high\ energy\ burden \cap economic\ vulnerability$$

The energy-burden component is determined by the threshold specification, while the economic condition restricts identification to households characterised by comparatively limited consumption resources.

Let C_i denote the total consumption expenditure of household i. Economic vulnerability is operationalized through a relative expenditure benchmark equal to 60% of the median consumption expenditure of the selected reference population [42]. Denoting the relevant median by M_c, the vulnerability threshold is:

$$m_{60} = 0.60\, M_C.$$

Household i satisfies the economic-vulnerability condition when:

$$C_i < m_{60}.$$

This condition and the energy-expenditure-share criterion capture distinct dimensions of household disadvantage. The energy share $s_i$measures realized energy burden, whereas the low-consumption condition identifies households below the relevant consumption-resource benchmark. Combining them excludes economically secure households whose energy shares are high but whose broader consumption resources remain above the vulnerability threshold.

Because the 60%-of-median criterion is relative to the selected reference population, its value depends on the geographical scale of calculation. A national median provides a common benchmark across territories, whereas regional medians allow the vulnerability condition to reflect territory-specific consumption distributions.

For the endogenous specifications, this economic-vulnerability condition also determines the population used for Beta estimation within each region. Under the national specification, the common national 60%-of-median benchmark is applied in every region; under the regional specification, each region uses its own benchmark. The resulting candidate threshold is therefore derived from the conditional regional distribution of energy-expenditure shares among economically vulnerable households.

$$\{s_i > \tau\} \cap \{C_i < m_{60}\},$$

The combination of energy burden and economic vulnerability can be expressed probabilistically. Let S denote household total consumption expenditure, let:

$$A = \{S > \tau\}$$

denote membership in the high energy-burden tail, and let:

$$B = \{C < m_{60}\}$$

denote economic vulnerability. The conditional probability:

$$p_{\text{cond}} = P(A \mid B) = P(S > \tau \mid C < m_{60}).$$

measures the proportion of economically vulnerable households whose energy-expenditure share exceeds the selected threshold.

The joint probability instead measures the prevalence of households satisfying both conditions in the total population:

$$P(A \cap B) = P(A \mid B)P(B),$$

By the multiplication rule:

$$extent\ of\ economic\ vulnerability$$

and:

$$incidence\ of\ high\ energy\ burden\ within\ that\ vulnerable\ population$$

This identity does not require statistical independence between energy burden and economic vulnerability. It shows that joint prevalence depends on two components: the incidence of high energy burden within the economically vulnerable population and the population share satisfying the economic-vulnerability condition.

This distinction is useful empirically because changes in the final indicator may arise from either component. A high conditional incidence of excessive energy burden need not produce high joint prevalence when the economically vulnerable population is small, while a larger vulnerable population may raise joint prevalence even when the conditional high-burden probability is moderate.

The first methodological dimension concerns the definition of the energy-burden threshold. Two alternatives are considered: a fixed benchmark and the candidate endogenous boundary derived from the fitted Beta distribution.

Under the fixed specification, household i satisfies the high-burden condition when:

$$\tau_{\text{fix}} = 0.10. \qquad s_i > 0.10.$$

where τ_{fix} is predetermined and common across the relevant comparison. This specification provides a transparent benchmark whose numerical value does not respond to the observed expenditure-share distribution.

Under the endogenous specification, the high-burden condition is:

$$s_i > \tau_{endo,r}$$

The alternative specification replaces this fixed boundary with the endogenous candidate developed in Section 3.3:

$$\tau_{\text{endo}} = \max\{s \in (0,1): f'''(s;\hat{\alpha};\hat{\beta}) = 0\}.$$

where $\tau_{\text{endo},r}$ is the candidate boundary obtained from the fitted conditional Beta distribution for region r according to the procedure developed in Section 3.3. The comparison between fixed and endogenous specifications therefore isolates two different principles of threshold construction: an externally imposed common boundary and a distribution-derived, region-specific candidate boundary.

The second methodological dimension concerns the geographical scale used to construct the economic-vulnerability benchmark. Under the national specification, the 60%-of-median threshold is calculated from the national consumption distribution and applied uniformly across regions. Under the regional specification, the corresponding threshold is calculated separately from each regional distribution.

The national approach provides a common economic standard and facilitates territorial comparison, whereas regional benchmarks allow the vulnerability condition to adapt to differences in regional consumption distributions. Neither scale is intrinsically preferable: they answer different measurement questions concerning vulnerability relative to a common national standard or to the household's territorial context.

This distinction also affects the endogenous specifications because the economic benchmark determines which households enter each regional conditional Beta fit. Moving from national to regional conditioning can therefore change both the composition of the economically vulnerable population and the fitted parameters $(\hat{\alpha}_r, \hat{\beta}_r)$, with corresponding effects on $\tau_{\text{endo},r}$. Consequently, comparisons between national and regional endogenous indicators should not be interpreted as isolating the effect of changing only the energy-burden threshold.

Combining the two threshold specifications with the two economic-reference structures yields four indicators. They form a 2×2 architecture that separates, as far as the design permits, the role of threshold construction from the role of geographical calibration.

$$Fixed\ vs.\ Endogenous$$

while the second concerns the geographical reference structure:

$$National\ vs.\ Regional$$

the term produces the following analytical architecture:

	National reference	Regional reference
Fixed threshold	Π_1^N	Π_2^R
Endogenous threshold	Π_3^N	Π_4^R

The fixed-national specification combines the 10% energy-burden threshold with the national economic-vulnerability benchmark and therefore represents the most externally standardized configuration.

The fixed-regional specification retains the 10% energy-burden boundary while evaluating economic vulnerability relative to regional consumption benchmarks.

The endogenous-national specification replaces the fixed boundary with the candidate distribution-derived threshold while retaining a common national economic benchmark.

The endogenous-regional specification allows both the economic-vulnerability benchmark and, through regional Beta estimation, the candidate energy-burden threshold to vary territorially.

Here, the subscript identifies the threshold specification, while the superscript identifies the geographical reference used to construct the economic-vulnerability benchmark. Specifically, Π_1^N denotes the fixed-threshold specification with national economic conditioning, Π_2^R the fixed-threshold specification with regional economic conditioning, Π_3^N the endogenous-threshold specification with national economic conditioning, and Π_4^R the endogenous-threshold specification with regional economic conditioning. The superscripts N and R therefore refer exclusively to the geographical calibration of the economic-vulnerability benchmark. In particular, the superscript N in Π_3^N does not imply the use of a single national endogenous energy-burden threshold: the endogenous Beta distributions and their corresponding candidate thresholds remain region-specific, while economically vulnerable households are selected using the common national benchmark.

The four indicators therefore permit structured comparisons along two dimensions. Comparing Π_1^N with Π_2^R shows how geographical calibration affects the fixed-threshold specification. Comparing fixed and endogenous indicators within a given reference structure highlights the consequences of changing the energy-burden threshold rule, subject to the conditioning structure of the endogenous procedure. Finally, comparing Π_3^N with Π_4^R captures the combined consequences of changing the economic-vulnerability benchmark and the conditional regional Beta fit and should not be interpreted as a pure threshold effect.

These indicators are alternative measurement specifications rather than competing estimates expected to coincide. Their empirical comparison is used to assess how threshold construction and geographical reference choices influence measured energy vulnerability.

3.5 Empirical Validation and Robustness Strategy

The methodological framework developed above generates alternative measures of energy vulnerability, but their construction does not establish their empirical validity. This distinction is particularly important for the endogenous specifications, since the rightmost third-derivative root is investigated as an experimental distribution-derived criterion rather than an established socioeconomic threshold. Validation therefore assesses the internal consistency and empirical plausibility of the framework through the quality of the Beta representation, the stability of the candidate boundary, comparisons across threshold rules and geographical reference structures, correspondence between fitted and empirical quantities, and comparison with established energy-poverty measures. The objective is not to identify a universally correct indicator, but to determine whether the endogenous criterion produces stable and interpretable empirical patterns.

The first level of assessment concerns the statistical representation upon which the endogenous methodology is constructed. Since the candidate boundary is obtained from the geometry of a fitted Beta density, the usefulness of the resulting boundary necessarily depends on whether that distribution provides a reasonable representation of the observed energy-expenditure shares.

The fitted density can therefore be evaluated against the empirical distribution of:

$$s_i = \frac{E_i}{C_i}.$$

with particular attention to the upper tail. Perfect correspondence is neither expected nor required; the relevant question is whether the model reproduces the principal characteristics of the observed distribution sufficiently well for its right-hand geometry to support empirical interpretation.

A second internal diagnostic concerns the existence and numerical stability of the rightmost admissible solution of:

$$f'''(s) = 0.$$

used to define:

$$\tau_{\text{endo}}.$$

Failure to identify an admissible interior root, unstable selection among multiple roots, or disproportionate threshold movements following small parameter changes would indicate limitations

of the procedure. Conversely, recurrent identification of a stable admissible root would support its operational consistency, without establishing its socioeconomic validity.

A second level of assessment compares the externally fixed energy-burden threshold with the experimental endogenous boundary. The relevant threshold specifications are:

$$\tau_{\text{fix}} = 0.10,$$

and:

$$\tau_{\text{endo}} = \max\{s \in (0,1): f'''(s) = 0\}.$$

Their consequences are compared within the national and regional economic-reference structures:- share distribution.

$$\Pi_1^N \leftrightarrow \Pi_3^N, \qquad \Pi_2^R \leftrightarrow \Pi_4^R.$$

The analysis considers both the location of the alternative boundaries and the populations identified beyond them. Differences in measured prevalence can reflect not only movement in the threshold itself but also the amount of probability mass located beyond the corresponding boundary. The comparison therefore evaluates the empirical consequences of replacing a common externally specified criterion with a distribution-derived candidate threshold rather than assuming that either rule is intrinsically preferable.

The national and regional specifications provide a direct assessment of geographical sensitivity. The relevant comparisons are:

$$\Pi_1^N \leftrightarrow \Pi_2^R.$$

and:

$$\Pi_3^N \leftrightarrow \Pi_4^R.$$

The analysis examines whether changes in geographical calibration produce coherent differences in fitted parameters, candidate thresholds and measured prevalence. For the endogenous specifications, regional calibration can affect both the population entering the conditional Beta fit and the resulting distribution-derived threshold, so national–regional differences cannot be attributed to a single component in isolation.

Neither large nor small differences are interpreted as desirable by construction. Limited variation may indicate that a common national benchmark already captures the relevant patterns, whereas large or erratic movements may reflect genuine territorial heterogeneity but can also signal sensitivity to regional sample composition or parameter estimation. The relevant validation criterion is therefore whether geographical calibration reveals stable and interpretable territorial information.

A further level of assessment compares the four specifications developed in Section 3.4 with the conventional energy-poverty indicators reviewed in Section 3.2. This comparison is not based on the expectation that alternative measures should produce identical prevalence rates or household classifications, since they operationalize different dimensions of vulnerability and employ different threshold rules.

The analysis instead examines whether the experimental specifications display interpretable relationships with established measures. Similarities may indicate that the endogenous framework captures patterns also identified by conventional approaches, whereas differences may reveal the consequences of alternative threshold construction, economic conditioning or geographical calibration. Disagreement is therefore treated as an empirical result requiring interpretation rather than as evidence of measurement error by itself.

Comparison is conducted not only in terms of aggregate prevalence but, where the available data permit, also through the territorial distribution of measured vulnerability. This provides an external benchmark for assessing whether the experimental specifications generate plausible spatial patterns while preserving the conceptual differences between indicators.

An additional diagnostic compares the upper-tail probability implied by the fitted Beta distribution with the corresponding empirical population share observed in the weighted household data. For a candidate endogenous threshold $\tau_{\mathrm{endo},r}$, the fitted tail probability is:

$$p_{\mathrm{fit}} = 1 - F\left(\tau; \hat{\alpha}; \hat{\beta}\right).$$

while the empirical weighted tail share is:

$$s_i > \tau.$$

Their comparison assesses whether the fitted model reproduces the observed population mass beyond the candidate boundary. This diagnostic is particularly relevant because $\tau_{\mathrm{endo},r}$ is derived from the geometry of the fitted distribution itself: satisfactory representation of the centre of the distribution does not necessarily imply equally satisfactory representation of its upper tail.

Close correspondence supports the adequacy of the Beta representation in the region directly relevant to the threshold procedure, whereas persistent discrepancies indicate that fitted tail probabilities should be interpreted cautiously even when broader distributional fit appears satisfactory.

The final validation component concerns robustness to the principal methodological choices underlying the framework. Sensitivity analysis considers the treatment of boundary observations, the geographical reference used for economic vulnerability, the distinction between fixed and

endogenous energy-burden thresholds, the stability of the fitted Beta parameters and candidate roots, and the correspondence between fitted and empirical upper-tail probabilities.

Particular attention is given to whether moderate changes in specification produce proportionate and interpretable changes in estimated thresholds and prevalence. Substantial instability following minor methodological changes would weaken confidence in the operational robustness of the endogenous procedure, whereas broadly stable results across plausible specifications would provide supporting evidence for its empirical reliability.

Robustness is assessed jointly rather than through a single diagnostic. Statistical fit, root stability, threshold sensitivity, geographical calibration, comparison with conventional indicators and upper-tail correspondence address different aspects of the framework and should therefore be interpreted together. Positive performance across these dimensions supports the empirical usefulness of the candidate endogenous criterion, while remaining limitations define the conditions under which its results should be interpreted cautiously.

3.6 Critical Assessment and Methodological Limitations

The methodological framework developed in this chapter provides complementary perspectives on household energy vulnerability, but none offers a complete or assumption-free representation of energy poverty. Each indicator translates a multidimensional phenomenon into a restricted set of observable variables, thresholds and reference choices, thereby making some manifestations of vulnerability more visible than others. This qualification is particularly important for the experimental endogenous approach: although the fitted Beta distribution provides a formal representation of bounded expenditure shares and its rightmost admissible third-derivative root defines a reproducible candidate boundary, these mathematical properties do not establish a socioeconomic division between energy-poor and non-energy-poor households. The following limitations therefore define the scope within which the empirical results should be interpreted.

Conventional expenditure-based indicators involve different methodological trade-offs and should therefore be interpreted as complementary rather than interchangeable measures. High-burden indicators may identify economically secure households with unusually large energy requirements while missing constrained households that suppress consumption; low-expenditure measures can reveal potential self-rationing but cannot determine whether low spending reflects deprivation or genuinely limited energy needs. Approaches incorporating required energy costs and residual resources improve socioeconomic interpretation but demand richer data and additional modelling assumptions. The Faiella–Lavecchia indicator partly addresses these tensions by combining realized burden with economic vulnerability and an additional zero-heating route, although it remains

dependent on explicit thresholds and captures only an extreme manifestation of potential under-consumption.

The distributional methodology developed in this chapter is based on the realized energy-expenditure share s_i. Although this variable directly measures the proportion of household consumption expenditure absorbed by energy, it does not measure the energy services that a household requires or actually receives. Financially constrained households may suppress consumption and consequently remain outside the high-burden tail despite experiencing inadequate heating or other forms of energy deprivation. Conversely, high realized expenditure may reflect genuine affordability pressure but can also occur among households with sufficient economic resources. Combining the energy-burden criterion with the economic-vulnerability condition introduced in Section 3.4 reduces the latter problem but does not resolve hidden under-consumption. The resulting indicators should therefore be interpreted as measures of the realized expenditure-based dimension of energy vulnerability rather than complete measures of energy deprivation.

The Beta distribution is a flexible specification for the expenditure-share variable because its continuous support corresponds to the interior of the unit interval:

$$0 \leq s_i \leq 1,$$

while the standard continuous Beta density is defined on:

$$0 < s < 1.$$

This compatibility does not imply that the Beta family necessarily provides an adequate representation of every empirical expenditure-share distribution. Model adequacy depends on the observed shape of the data, while observations at the boundaries require explicit treatment. Because the candidate threshold is derived from higher-order local geometry, even an acceptable overall fit may coexist with discrepancies in the upper tail that affect the interpretation of the selected root.

A further limitation concerns the sensitivity of the candidate boundary to the fitted parameters:

$$(\hat{\alpha}, \hat{\beta}) \rightarrow \hat{f}(s) \rightarrow \hat{f}'''(s) \rightarrow \tau_{\text{endo}}.$$

Small changes in $(\hat{\alpha}, \hat{\beta})$ may alter the number or location of admissible third-derivative roots, particularly when regional samples provide weaker support for parametric estimation. The existence, uniqueness and numerical stability of the rightmost admissible root must therefore be treated as empirical properties of each fitted distribution rather than assumed by construction.

Most importantly, the geometric and socioeconomic interpretations remain distinct. The condition $f'''(s) = 0$ identifies a stationary point of the curvature of the fitted density, and the proposed

procedure selects the rightmost admissible solution as a reproducible **candidate** boundary for the final right-hand regime. No mathematical property of this root establishes that it is the uniquely appropriate boundary for energy poverty. The empirical analysis may support its usefulness, reveal that it performs meaningfully only under particular configurations, or identify limitations requiring further refinement.

The Beta methodology should therefore be understood as a complementary distributional extension to established indicators rather than their replacement. It investigates whether the geometry of realized expenditure burdens provides useful additional information for delimiting the upper tail; it does not independently identify hidden under-consumption or the structural causes of high energy expenditure.

The national-regional architecture introduces a trade-off between comparability and contextual sensitivity. National calibration provides a common reference population across territories but may conceal differences in regional expenditure distributions and economic conditions. Regional calibration incorporates such heterogeneity more directly, but households with similar characteristics may consequently be evaluated against different reference distributions.

The two approaches therefore answer different measurement questions: national calibration evaluates vulnerability relative to a common country-wide benchmark, whereas regional calibration evaluates it within territory-specific expenditure structures. Differences between the resulting indicators should consequently be interpreted as reference-scale sensitivity rather than evidence that either calibration is intrinsically preferable.

This trade-off is particularly relevant to the endogenous criterion because regional conditional estimation can produce different Beta parameters and candidate thresholds:

$$\left(\hat{\alpha}_r, \hat{\beta}_r\right) \rightarrow \tau_{\mathrm{endo},r}.$$

Territorial variation in $\tau_{\mathrm{endo},r}$ may reflect meaningful differences in expenditure distributions, but it may also become less stable where regional samples provide weaker support for parametric estimation. Interpretation must therefore consider both substantive heterogeneity and statistical reliability.

The integrated framework should ultimately be interpreted as an analysis of the expenditure-based dimension of energy poverty rather than as a complete household-level diagnosis. Monetary expenditure data do not directly observe thermal comfort, dwelling quality, adequacy of energy services, arrears or subjective experiences of affordability. The indicators developed here are

therefore better suited to measurement and monitoring than to determining individual eligibility for policy support without additional information.

Generalisation across territories and periods also requires caution. Relative and distribution-dependent classifications may change with the reference population, so variation in measured prevalence can reflect changes in household circumstances, the broader expenditure distribution, sample composition or their interaction. Meaningful comparisons consequently require harmonised variable definitions and consistent construction of the underlying reference populations.

More broadly, methodological sophistication does not eliminate judgement from energy-poverty measurement. Fixed, relative, combined and distribution-derived approaches all require explicit choices concerning thresholds, reference populations or interpretative criteria. The framework developed in this chapter makes these dependencies transparent by allowing alternative threshold rules and geographical references to be compared while retaining conventional indicators as complementary evidence. Greater confidence can therefore be attached to patterns that remain interpretable across plausible specifications, whereas divergence helps identify which methodological assumptions **drive** measured vulnerability.

3.7 Conclusion

This chapter has developed the methodological framework used to measure energy poverty in the empirical analysis. The review of conventional expenditure-based indicators showed that alternative measures capture different manifestations of vulnerability and that their classifications depend on the variables, thresholds and reference populations employed. These approaches therefore provide complementary benchmarks rather than interchangeable estimates of a uniquely observable condition.

Building on the household energy-expenditure share, the chapter then introduced a distributional methodology based on the Beta family. The central experimental component investigates the rightmost admissible stationary-curvature point of the fitted density as a candidate endogenous boundary for delimiting its upper expenditure-burden tail. Unlike a predetermined numerical threshold, this boundary responds to the estimated distribution; however, its formal geometric identification does not establish its socioeconomic validity, which remains an empirical question.

The candidate energy-burden criterion was subsequently combined with a 60%-of-median economic-vulnerability condition and organised within a four-indicator architecture contrasting fixed and endogenous thresholds under national and regional economic reference structures. This design makes

it possible to assess how measured vulnerability responds to both threshold construction and geographical calibration while preserving the distinct interpretation of each specification.

The resulting framework is proposed as a complementary methodological extension rather than a replacement for established energy-poverty measures. Its contribution lies in testing whether the distributional geometry of realized expenditure burdens provides additional information for identifying unusually vulnerable upper-tail conditions, while explicitly recognising the limitations associated with observed expenditure, parametric approximation, geographical calibration and the substantive interpretation of the candidate boundary.

Chapter 4 applies this framework to the available household data. The empirical analysis evaluates the behaviour of the candidate endogenous thresholds across Italian regions, compares the four measurement specifications and established benchmarks, and assesses whether the rightmost admissible stationary-curvature point provides a sufficiently stable and economically interpretable criterion to contribute to the empirical measurement of energy poverty.

CHAPTER 4: EMPIRICAL RESULTS AND ASSESSMENT OF THE ENDOGENOUS THRESHOLD

This chapter applies the methodological framework developed in Chapter 3 to the Italian regional context and examines the empirical behaviour of the candidate endogenous threshold. The analysis assesses whether allowing the energy-burden boundary to emerge from regional expenditure-share distributions provides information not captured by a uniform threshold, particularly in terms of estimated incidence and the territorial representation of energy poverty.

After describing the data and the implementation of the expenditure-based framework, regional energy-burden distributions and their corresponding Beta estimates are examined. The candidate endogenous thresholds derived from these distributions are then compared across regions and conditioning schemes. The analysis subsequently evaluates the four energy-poverty indicators introduced in Chapter 3, first through their numerical incidence and then through their geographical distribution. Finally, spatial econometric evidence is used to investigate whether the alternative measurement specifications are associated with different territorial statistical structures.

Consistent with the methodological discussion developed in the previous chapter, the rightmost admissible solution of $f'''(s) = 0$ is treated as a candidate endogenous boundary whose empirical relevance is to be assessed rather than assumed. The analysis therefore distinguishes between the formal geometric properties of the fitted Beta density and the substantive interpretation of the resulting threshold as an energy-poverty criterion. The objective is not to establish the endogenous threshold as a uniquely valid normative boundary, but to evaluate its empirical behaviour, sensitivity to regional distributional heterogeneity and consequences for the measurement of energy poverty.

4.1 Data and empirical implementation

The empirical application uses microdata from the Italian Household Budget Survey (HBS). The annual survey files covering 2014–2023 are harmonised to reconcile changes in variable coding and construct consistent household expenditure variables across survey vintages. The regional Beta-threshold application examined here focuses on the 2023 cross-section, for which the conditional distributions and corresponding indicators are estimated across the twenty Italian regions.

Residential energy expenditure is reconstructed from the survey components relating to electricity and heating sources, including natural gas, gas cylinders, kerosene or diesel, coal and wood, central heating and district heating. The active specification is restricted to expenditure associated with the household's principal residence, excluding secondary and other dwellings.

Differences in household size and composition are accounted for through the Carbonaro equivalence scale, whose coefficients range from 0.60 for a one-person household to 2.40 for households with seven or more members, with a coefficient of one for the two-person reference household. Equivalent expenditure measures are obtained by dividing household expenditure values by the applicable coefficient. This adjustment accounts for differences in consumption needs and economies of scale across household sizes.

Annual HBS survey weights are used in the calculation of expenditure quantiles so that the resulting distributional benchmarks reflect the represented population rather than the unweighted survey sample. This function is distinct from equivalence scaling: the latter adjusts expenditure for household needs, whereas survey weights determine the population representation of each observation.

The central distributional variable is the household energy-expenditure share $s_i = \frac{E_i}{C_i}$, where E denotes residential energy expenditure and C total household consumption expenditure. The ratio measures the proportion of household expenditure absorbed by residential energy and is bounded between zero and one, providing a natural basis for the subsequent Beta specification. Importantly, s is an expenditure-burden measure rather than a complete energy-poverty indicator, since the household's economic position must also be considered.

Economic vulnerability is defined using a cut-off equal to 60% of median total expenditure, calculated either relative to the national distribution (S_N) or separately within each regional distribution (S_R). The distinction therefore concerns the geographical reference used to identify economically vulnerable households.

Changing from S_N to S_R alters both the households satisfying the economic-vulnerability condition and the conditional population on which each regional Beta distribution is estimated. The resulting endogenous thresholds may therefore differ because they are derived from different conditional expenditure-share distributions.

Combining the fixed 10% or candidate endogenous energy-burden threshold with national or regional economic conditioning produces the four measurement specifications analysed in the chapter. This 2×2 structure allows the empirical consequences of changing the energy-burden threshold, the economic-vulnerability benchmark, or both simultaneously to be distinguished.Having defined the expenditure variables and the alternative conditioning schemes, the analysis can now turn to the regional energy-burden distributions from which the candidate endogenous thresholds are derived.

4.2 Regional energy-burden distributions and Beta estimates

The first empirical step examines household energy-expenditure shares within the economically vulnerable population, since the endogenous threshold is derived from the geometry of a fitted regional distribution rather than imposed directly on the observed data. Its empirical interpretation therefore depends on how adequately the Beta specification represents the conditional energy-burden distributions observed across Italian regions.

As established in Chapter 3, the energy-expenditure share is modelled conditionally on the household satisfying the relevant economic-vulnerability criterion:

$$s \mid S < m \sim \text{Beta}(\alpha, \beta),$$

where m denotes either the national benchmark S_N or the regional benchmark S_R. The parameters $\alpha$and $\beta$are estimated separately for each region under the two conditioning schemes. This region-specific estimation allows each conditional distribution to exhibit its own shape rather than imposing a common energy-burden distribution across Italy.

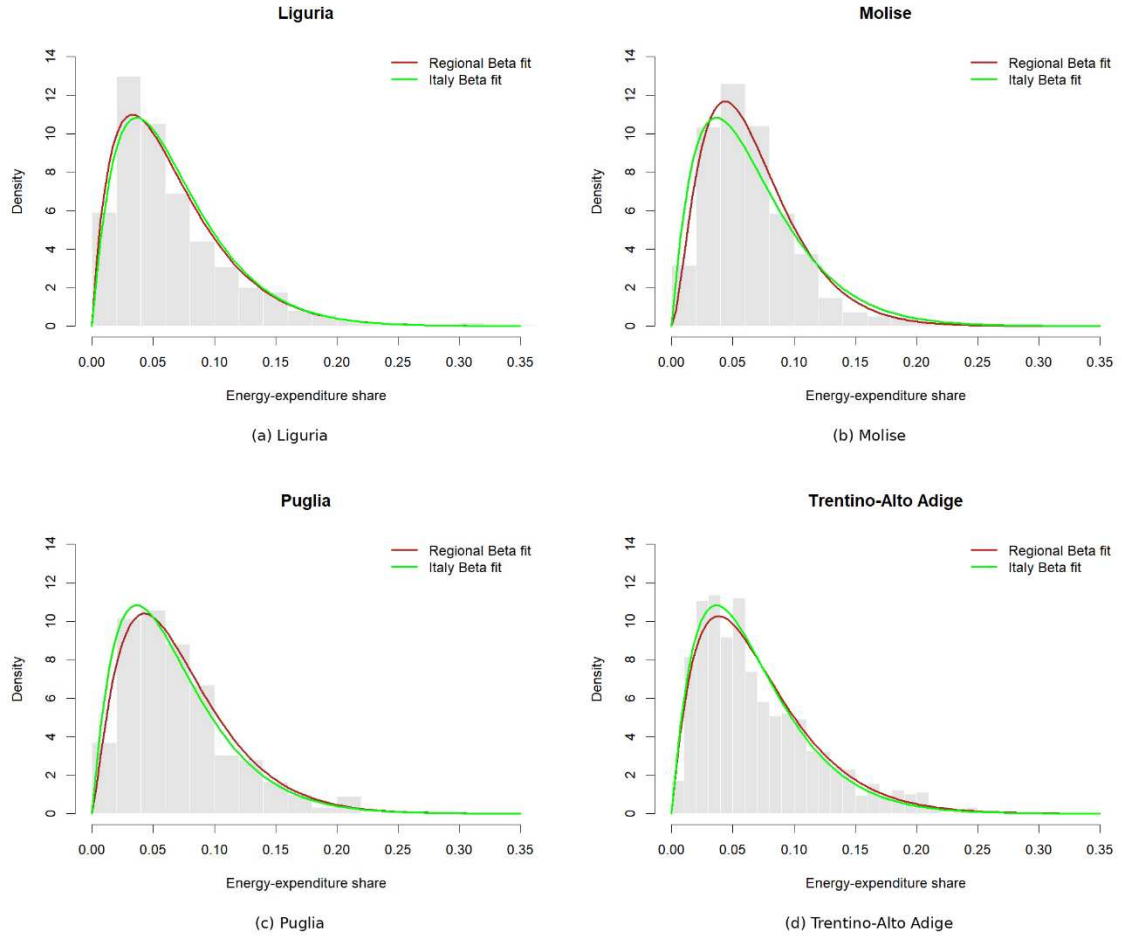
The estimated parameters display a common broad configuration across the regional samples, with β substantially larger than α, corresponding to strongly asymmetric fitted distributions concentrated at relatively low energy-expenditure shares and characterised by progressively lower density toward the upper tail.

All regional estimates under both conditioning schemes satisfy the sufficient conditions $\hat{\alpha} > 1$ and $\hat{\beta} > 3$ introduced in Section 3.3. The fitted distributions therefore exhibit the right-hand geometric configuration required for application of the endogenous-threshold procedure in the 2023 regional analysis.

Despite their broad common asymmetry, the estimated combinations of α and β vary across regions and conditioning schemes, producing region-specific differences in the concentration and shape of the fitted densities. The transition toward the upper tail may therefore occur at different expenditure shares across regions, providing the empirical basis for investigating a distribution-specific rather than uniformly imposed energy-burden boundary.

Regional heterogeneity must also be considered in relation to the economic-vulnerability benchmark used for conditioning. Under the national and regional specifications, the Beta parameters are estimated from households satisfying the corresponding national or regional vulnerability condition, respectively. Because these conditions may select populations of different size and composition within the same region, comparing the resulting fitted distributions reveals the sensitivity of the regional distributional representation to the definition of economic vulnerability.

Figure 4.1 — Representative regional energy-expenditure-share distributions and fitted Beta densities, 2023



Note: The grey bars represent the empirical distribution of the energy-expenditure share, while the fitted Beta densities represent the region-specific fit and the Italian aggregate fit. The horizontal and vertical scales are held constant across panels to facilitate comparison.

Figure 4.1 compares selected empirical regional distributions with their fitted Beta densities, providing a direct assessment of the parametric representation of the observed energy-share patterns. Representative cases are retained in the main text, while the complete set of regional plots can be provided in the Appendix to preserve regional coverage without overloading the empirical discussion.

The presence of asymmetric regional distributions with identifiable upper-tail structure provides the empirical setting in which the endogenous procedure can be investigated, but it does not by itself establish the substantive validity of the resulting threshold. The Beta estimates describe the statistical structure from which the candidate boundary is derived; whether that boundary produces an

informative energy-poverty classification must be assessed through the threshold and indicator results that follow.

These differences provide the empirical basis for examining in the next section the magnitude, regional dispersion and conditioning sensitivity of the corresponding candidate endogenous thresholds.

4.3 Regional endogenous thresholds

The candidate endogenous thresholds are obtained, as described in Chapter 3, from the rightmost admissible solution of $f'''(s) = 0$ for each fitted regional conditional Beta density. Applying the procedure under national and regional economic conditioning produces two sets of region-specific candidate thresholds, denoted by $\tau_{\mathrm{endo},r}$, with the relevant conditioning scheme specified where necessary.

The estimates reveal substantial cross-regional variation. Under national economic conditioning, the candidate thresholds range from approximately 11.1% to 18.7%, with a cross-regional mean of 14.88%; under regional conditioning, they range from approximately 11.1% to 19.1%, with a corresponding mean of 14.95%. The two ranges therefore span approximately 7.6 and 8.0 percentage points, respectively.

The proximity of the two cross-regional means indicates that changing the conditioning benchmark has little effect on the average candidate boundary, but does not imply stability at the regional level. The near-invariance of the mean may instead result from offsetting region-specific increases and decreases, making the regional comparison essential.

At the regional level, the candidate boundaries do not follow a simple geographical gradient. Under national conditioning, comparatively high thresholds are observed in Molise, Piemonte, Puglia and Calabria, while Liguria, Toscana, Trentino-Alto Adige/Südtirol and Lazio lie toward the lower end. The pattern remains broadly similar but not identical under regional conditioning, with Molise and Puglia reaching approximately 19.1% and 18.9%, respectively, compared with approximately 11.1% in Liguria and 11.3% in Toscana.

The effect of regional conditioning is also heterogeneous: the candidate threshold increases from approximately 17.4% to 18.9% in Puglia and from 14.3% to 14.9% in Marche, while declining from 13.8% to 13.1% in Friuli-Venezia Giulia and from 12.7% to 11.8% in Trentino-Alto Adige/Südtirol. Regional conditioning therefore produces neither a uniform upward nor a uniform downward adjustment in the endogenous boundary.

A further feature of the 2023 application is that every estimated candidate endogenous threshold exceeds the conventional 10% energy-burden benchmark, ranging from approximately 11.1% to 19.1%, with several regional values above 17%. The candidate upper-tail boundary therefore lies above the conventional rule in all twenty regions in this application.

This finding is specific to the estimated Italian regional distributions and should not be interpreted as a mathematical property of the methodology. The definition based on $f'''(s) = 0$ does not impose a threshold above 10% by construction. Different expenditure-share distributions, samples or geographical contexts could in principle produce different relationships between the endogenous boundary and the conventional benchmark.

Table 4.1 — Regional Beta parameter estimates and candidate endogenous thresholds under national and regional economic conditioning, 2023

Region	$\widehat{\alpha}$	$\widehat{\beta}$	$\tau_{\text{endo},r}$	$\widehat{\alpha}$	$\widehat{\beta}$	$\tau_{\text{endo},r}$
	National Conditioning			**Regional Conditioning**		
Abruzzo	2.480	22.518	0.166	2.467	21.878	0.170
Basilicata	2.284	22.989	0.150	2.241	21.934	0.155
Calabria	2.367	21.011	0.170	2.337	19.950	0.177
Campania	3.896	41.131	0.140	3.912	41.078	0.141
Emilia-Romagna	2.194	21.899	0.151	2.220	23.164	0.145
Friuli-Venezia Giulia	1.774	18.883	0.138	1.884	21.350	0.131
Lazio	2.125	24.602	0.130	2.311	26.667	0.132
Liguria	1.775	23.399	0.111	1.775	23.399	0.111
Lombardia	2.024	19.786	0.154	2.062	20.343	0.153
Marche	3.500	36.573	0.143	3.129	31.712	0.149
Molise	2.850	22.780	0.187	3.018	23.465	0.191
Piemonte	1.800	14.458	0.185	1.846	14.785	0.186
Puglia	4.097	34.074	0.174	3.705	28.657	0.189
Sardegna	1.966	18.707	0.157	2.047	19.214	0.160
Sicilia	2.656	31.510	0.128	2.554	29.395	0.132
Toscana	1.558	18.641	0.117	1.461	17.536	0.113
Trentino-Alto Adige/Südtirol	1.566	17.444	0.127	1.601	19.201	0.118
Umbria	2.263	25.141	0.136	2.200	24.773	0.134
Valle d'Aosta	2.456	23.213	0.160	2.593	24.595	0.159
Veneto	1.766	17.564	0.148	1.796	18.490	0.143

Note: Beta parameters are estimated separately for each region under the national and regional economic-vulnerability conditioning schemes. The candidate endogenous threshold $\tau_{\text{endo},r}$ is obtained from the rightmost admissible solution of $f'''(s) = 0$ for the corresponding fitted conditional Beta density. Thresholds are expressed as expenditure shares.

The magnitude of $\tau_{\mathrm{endo},r}$ should not be interpreted as a regional energy-poverty rate or as a direct ranking of energy vulnerability. It identifies the expenditure-share level associated with the candidate upper-tail boundary of the fitted conditional Beta density, not the probability mass lying beyond it. A comparatively high threshold may therefore coexist with limited probability mass in the relevant tail, while a lower threshold may coexist with greater tail mass.

$$P\big(s > \tau_{endo,r}, S < m\big) = P\big(s > \tau_{endo,r} \mid S < m\big)P(S < m)$$

Measured incidence therefore depends on both the conditional probability of exceeding the candidate threshold and the proportion of households satisfying the economic-vulnerability condition; the location of $\tau_{\mathrm{endo},r}$ alone cannot determine regional incidence.

The regional results illustrate this distinction clearly. Molise combines one of the highest regional candidate thresholds, approximately 19.1%, with an endogenous joint incidence of about 2.76%, whereas Liguria combines the lowest threshold, approximately 11.1%, with an incidence of about 3.14%. Trentino-Alto Adige/Südtirol provides an even clearer contrast, with a threshold of approximately 11.8% and a fully regional endogenous incidence of about 4.28%. Threshold location and measured prevalence therefore capture distinct features of the regional measurement framework.

Taken together, the 2023 estimates show that the procedure generates region-specific candidate boundaries rather than a common rescaling of the conventional 10% rule: cross-regional means remain similar across conditioning schemes, while individual thresholds vary substantially and respond heterogeneously to the conditioning benchmark.

This result remains distinct from establishing the substantive validity of the rightmost stationary-curvature point as an energy-poverty threshold. The threshold estimates show how the proposed geometric criterion behaves when applied to the observed regional distributions; their relevance for energy-poverty measurement ultimately depends on the classifications they produce and on how those classifications compare with alternative indicator specifications.

The analysis therefore turns from the location of the candidate thresholds to their consequences for measured energy-poverty incidence through the four-indicator framework.

4.4 Comparison of the four energy-poverty indicators

The regional threshold estimates become substantively relevant through their consequences for the identification of energy-poor households. The four-indicator framework combines fixed or endogenous energy-burden thresholds with national or regional definitions of economic

vulnerability, allowing the empirical consequences of the two methodological dimensions to be compared separately and jointly.

The four specifications are defined as:

$$\Pi_1^N = P(s, > 0.10S < S_N),$$
$$\Pi_2^R = P(s, > 0.10S < S_R),$$
$$\Pi_3^N = P\left(s > \tau_{endo,r}, S < S_N\right)$$

and

$$\Pi_4^R = P\left(s > \tau_{endo,r}, S < S_R\right)$$

The 2×2 structure permits three controlled comparisons. Comparing Π_1^N with Π_2^R holds the 10% energy-burden threshold constant and changes only the economic-vulnerability benchmark; comparing Π_1^N with Π_3^N holds national economic conditioning constant and changes only the energy-burden threshold; and comparing Π_2^R with Π_4^R performs the corresponding threshold comparison under regional conditioning. By contrast, Π_3^N and Π_4^R differ in both dimensions and therefore identify their combined rather than isolated consequences.

Before comparing the joint indicators, it is useful to examine how the two expenditure benchmarks alter the population classified as economically vulnerable. The national benchmark applies a common expenditure reference across Italy, whereas the regional benchmark evaluates households relative to the expenditure distribution within their own region.

Under national conditioning, the proportion of households satisfying the low-expenditure criterion reaches approximately 37.5% in Calabria, 32.8% in Puglia, 32.7% in Molise and 30.8% in Basilicata, compared with approximately 11.6% in Trentino-Alto Adige/Südtirol and 11.7% in Toscana. Under regional conditioning, the reported shares are concentrated within a considerably narrower cross-regional interval.

The difference reflects the geographical reference embedded in each measure: the national benchmark preserves regional differences relative to a common Italian expenditure standard, whereas the regional benchmark emphasises relative economic vulnerability within each territory. The resulting reclassification is therefore a consequence of measurement design and does not imply that underlying regional living standards have changed.

The survey-weighted numbers of economically vulnerable households illustrate the same reclassification. Moving from national to regional conditioning reduces the estimated vulnerable population from approximately 540,227 to 248,893 households in Puglia, from 304,737 to 174,754 in Calabria and from 192,015 to 117,797 in Sardegna. The direction is reversed in several Central and Northern regions, with Lombardia increasing from approximately 629,934 to 863,425 households, Toscana from 196,083 to 289,737 and Trentino-Alto Adige/Südtirol from 54,907 to 91,875.

These differences show that moving from $S_N$to $S_R$can substantially alter the size and composition of the population to which the energy-burden criterion is applied, so differences between nationally and regionally conditioned indicators cannot be attributed exclusively to the energy threshold.

Under the endogenous specification with national economic conditioning, Π_3^N ranges from approximately 1.36% to 4.63%, with a cross-regional mean of 2.69%. The highest values occur in Basilicata (4.63%), Molise (4.21%), Sardegna (4.08%) and Calabria (4.03%), while the lowest occur in Valle d'Aosta/Vallée d'Aoste (1.36%), Veneto (1.73%), Emilia-Romagna (1.80%) and Friuli-Venezia Giulia (1.86%).

The persistence of comparatively high values in several Southern and insular regions is consistent with the common national economic benchmark, since regions containing relatively large populations below $S_N$can retain high joint incidence even after the fixed 10% rule is replaced by region-specific candidate thresholds.

The geographical ranking changes markedly under the fully regional specification Π_4^R, which ranges from approximately 1.26% to 4.28% with a cross-regional mean of 2.49%. The highest values occur in Trentino-Alto Adige/Südtirol (4.28%), Toscana (3.61%) and Liguria (3.14%), followed by Basilicata (2.98%) and Molise (2.76%), whereas Puglia records the lowest value (1.26%), followed by Marche (1.44%) and Campania (1.78%).

The transition from Π_3^N to Π_4^R is associated with substantial regional reclassification. Incidence falls from 3.20% to 1.26% in Puglia, from 4.03% to 2.20% in Calabria, from 4.08% to 1.95% in Sardegna, from 4.63% to 2.98% in Basilicata and from 4.21% to 2.76% in Molise. Conversely, it rises from 2.65% to 4.28% in Trentino-Alto Adige/Südtirol, from 2.50% to 3.61% in Toscana, from 1.86% to 2.71% in Friuli-Venezia Giulia and from 1.73% to 2.56% in Veneto.

These changes should not be interpreted as the isolated effect of the endogenous threshold. Moving from $\Pi_3^N$to Π_4^Rsimultaneously changes the economic-vulnerability benchmark and re-estimates the candidate threshold on the newly conditioned regional population. The observed differences

therefore capture the combined consequences of regionalising both the economic and energy-burden dimensions.

A central empirical result is the contrast between aggregate stability and regional reclassification: the cross-regional mean decreases only from approximately 2.69% for Π_3^N to 2.49% for Π_4^R, a difference of 0.20 percentage points, while individual regional movements exceed one or even two percentage points. The largest reported shift, Sardegna's 2.13-percentage-point decline, is approximately ten times the change in the cross-regional mean, showing that modest aggregate variation can conceal substantial territorial reclassification.

Liguria provides a useful internal comparison: the weighted population satisfying the national and regional vulnerability conditions is identical, the candidate threshold remains approximately 11.1% under both specifications, and endogenous incidence consequently remains unchanged at approximately 3.14%, showing that regionalisation does not mechanically alter the indicator.

Table 4.2 — Regional economically vulnerable populations and endogenous energy-poverty indicators under national and regional conditioning

	n_N	n_R	Π_3^N	Π_4^R	$\widehat{\Pi}_3^N$	$\widehat{\Pi}_4^R$
Abruzzo	107,788	97,171	0.0253	0.0253	0.0248	0.0511
Basilicata	73,322	42,546	0.0463	0.0298	0.0399	0.0709
Calabria	304,737	174,754	0.0403	0.0220	0.0459	0.0755
Campania	577,067	399,705	0.0270	0.0178	0.0269	0.0513
Emilia-Romagna	265,333	359,615	0.0180	0.0243	0.0200	0.0452
Friuli-Venezia Giulia	72,117	107,235	0.0186	0.0271	0.0224	0.0495
Lazio	341,561	516,514	0.0191	0.0247	0.0195	0.0424
Liguria	130,552	130,552	0.0314	0.0314	0.0304	0.0664
Lombardia	629,934	863,425	0.0197	0.0269	0.0215	0.0454
Marche	134,251	94,436	0.0191	0.0144	0.0224	0.0490
Molise	42,952	32,127	0.0421	0.0276	0.0324	0.0519
Piemonte	324,617	306,489	0.0240	0.0234	0.0255	0.0563
Puglia	540,227	248,893	0.0320	0.0126	0.0313	0.0561
Sardegna	192,015	117,797	0.0408	0.0195	0.0402	0.0733
Sicilia	543,158	364,161	0.0310	0.0216	0.0332	0.0633
Toscana	196,083	289,737	0.0250	0.0361	0.0260	0.0657
Trentino-Alto Adige/Südtirol	54,907	91,875	0.0265	0.0428	0.0259	0.0548
Umbria	60,456	65,241	0.0202	0.0237	0.0224	0.0507
Valle d'Aosta/Vallée d'Aoste	7,337	10,572	0.0136	0.0220	0.0155	0.0366
Veneto	278,928	348,640	0.0173	0.0256	0.0217	0.0526

Note: n_N and n_R denote the survey-weighted expanded numbers of households satisfying the national ($S < S_N$) and regional ($S < S_R$) economic-vulnerability conditions, respectively. Π_3^N and Π_4^R report the empirical weighted joint incidence, while $\widehat{\Pi}_3^N$ and $\widehat{\Pi}_4^R$ report the corresponding Beta-based fitted probabilities. Indicator values are expressed as proportions.

The correspondence between the empirical joint indicators and the probabilities obtained from the fitted Beta specification is uneven across regions, with particularly large discrepancies under some fully regional estimates. In Calabria, the reported fitted probability is approximately 7.55% compared with an empirical joint incidence of 2.20%, while Sardegna records approximately 7.33% against 1.95%.

These discrepancies should be interpreted cautiously. They indicate that the parametric representation and the empirical weighted joint incidence are not numerically interchangeable, but their precise interpretation depends on the construction of the fitted probability reported in the underlying implementation. For this reason, they are treated here as an empirical diagnostic rather than as immediate evidence either for or against the validity of the endogenous threshold. Their implications are reconsidered in the discussion of robustness and limitations in Section 4.7.

The four-indicator comparison shows that measured energy-poverty incidence is sensitive to both dimensions of the framework: the economic-vulnerability benchmark determines the population entering the joint condition, while the energy-burden threshold determines where high burden is identified within that population. Regional classifications therefore reflect the interaction between these methodological choices rather than either component in isolation.

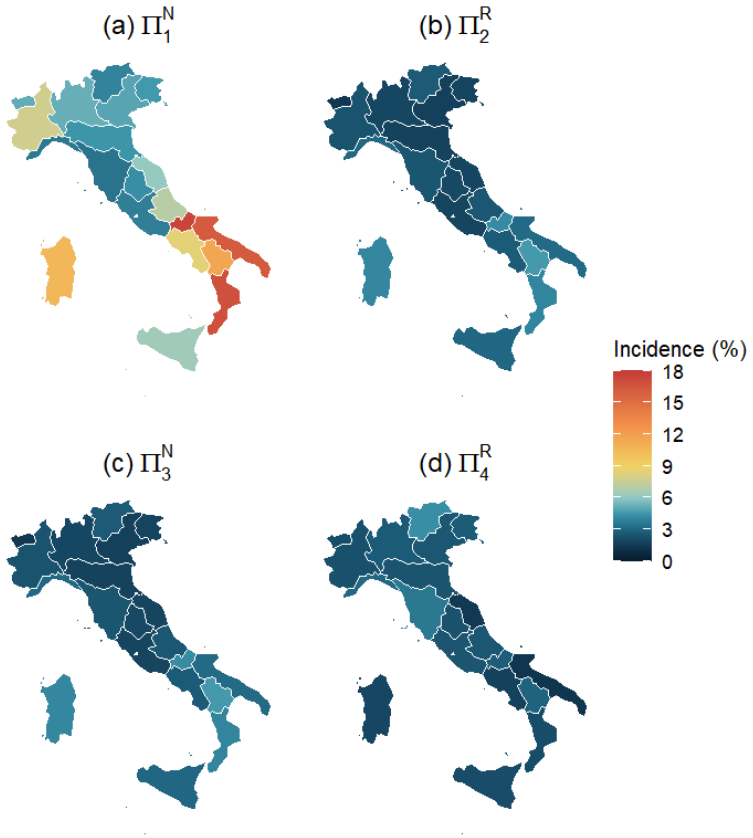
The geographical consequences of this numerical reclassification are examined in the following section.

4.5 The changing geography of Italian energy poverty

Examining the four indicators geographically makes it possible to assess whether alternative combinations of economic conditioning and energy-burden thresholding preserve the same territorial pattern or generate different representations of energy poverty across Italian regions.

The maps are therefore interpreted comparatively. Moving from Π_1^N to Π_2^R isolates the geographical consequences of regionalising economic vulnerability while retaining the fixed 10% threshold; moving from Π_1^N to Π_3^N instead preserves national conditioning while introducing the candidate endogenous threshold. The fully regional specification Π_4^R incorporates regional differentiation in both dimensions.

Figure 4.2 — Regional distribution of the four energy-poverty indicators under fixed/ endogenous energy-burden thresholds and national/regional economic conditioning, 2023



Note: Panels (a) and (b) report the regional incidence obtained using the fixed 10% energy-expenditure-share threshold under national and regional economic conditioning, respectively. Panels (c) and (d) report the corresponding incidence obtained using the candidate endogenous regional threshold $\tau_{\text{endo},r}$. All panels use a common colour scale, expressed in percentage terms, to ensure direct comparability across indicators

The fixed-threshold national specification largely reproduces the conventional territorial pattern of measured vulnerability in Italy, with greater exposure in several Southern regions because households are evaluated against a common national expenditure benchmark.

Regionalising the economic-vulnerability benchmark changes this pattern even while the 10% energy threshold remains fixed. Because Π_2^R evaluates households relative to their regional expenditure distribution, the resulting geography places greater emphasis on within-region relative vulnerability and is less closely aligned with the traditional North–South pattern generated by a common national benchmark.

The comparison between Π_1^N and Π_3^N instead holds national economic conditioning constant, so the geographical reclassification is associated with replacing the uniform 10% criterion by region-

specific candidate thresholds. The endogenous specification therefore allows the high-burden boundary to respond to the fitted regional energy-share distribution.

The largest conceptual departure from the fixed national framework occurs under Π_4^R, where economic vulnerability is assessed relative to the regional expenditure distribution and high energy burden relative to the candidate boundary derived from the regional conditional Beta density. Neither dimension is therefore imposed uniformly across Italy.

Greater contextualisation should not be interpreted as automatic methodological superiority. A common national criterion and a regional criterion answer different measurement questions. The former emphasises uniform comparability across territories, whereas the latter emphasises a household's position within its regional economic and energy-burden environment.

Taken together, the four geographical representations show that the conventional North–South divide is sensitive to measurement design. It remains more visible under specifications retaining a common national economic benchmark, whereas regional conditioning and endogenous thresholding produce vulnerability profiles that are less closely aligned with the same territorial gradient. The higher-incidence position of Trentino-Alto Adige/Südtirol, Toscana and Liguria under the fully regional specification illustrates this reordering and is consistent with the numerical reclassification reported in Section 4.4.

These geographical changes do not imply that underlying regional socioeconomic conditions change with the indicator; they reflect differences in the measurement lens. National and regional economic benchmarks emphasise disadvantage relative to common and local expenditure standards, respectively, while fixed and endogenous energy-burden criteria identify high burden through uniform and distribution-sensitive boundaries.

The geographical comparison therefore shows that measurement design affects not only estimated prevalence but also the territorial diagnosis of energy poverty. Indicators with similar average incidence can direct attention toward different regions and household populations, with potentially different implications for geographically targeted intervention.

From a policy perspective, national and region-sensitive indicators may serve complementary analytical purposes: uniform criteria favour transparency and cross-territorial comparability, whereas region-sensitive measures provide information on vulnerability relative to local expenditure and energy-burden distributions. The results do not establish which criterion should determine policy eligibility, but show that relying exclusively on one geographical reference system may conceal dimensions highlighted by the other.

The geographical patterns should also be distinguished from their underlying determinants. The maps identify where measured vulnerability is concentrated under each specification, but not why regional energy-burden distributions differ. Climatic conditions, dwelling characteristics, heating technologies, energy infrastructure, household composition and broader socioeconomic conditions may contribute to the observed heterogeneity, but their individual effects cannot be identified from the geographical comparison alone.

The maps therefore establish that alternative measurement specifications produce different geographical configurations of measured energy poverty, but visual differentiation does not by itself establish spatial statistical dependence. Section 4.6 consequently examines whether the four indicators are associated with different spatial structures once regional covariates and neighbouring relationships are taken into account.

4.6 Spatial evidence and empirical assessment

The geographical differences identified in the previous section raise a further question: whether the four energy-poverty indicators are associated with different spatial statistical structures across Italian regions. Because visual concentration does not itself establish spatial dependence, the descriptive mapping exercise is complemented by a spatial econometric assessment.

Spatial relationships are represented through a row-standardised Queen-contiguity matrix, with regions sharing a geographical boundary treated as neighbours. Nearest-neighbour connections are added for Sicilia and Sardegna to maintain a connected twenty-region system, after which row standardisation expresses each region's spatial lag as a weighted combination of neighbouring values.

For each indicator, OLS provides the initial benchmark, after which Moran's *I* on the residuals and Rao's Score diagnostics assess potential spatial dependence. Where appropriate, OLS is compared with spatial autoregressive (SAR) and spatial error (SEM) specifications, whose relative empirical adequacy is evaluated jointly through the diagnostic evidence, estimated spatial parameters and Akaike Information Criterion (AIC).

The spatial analysis relates the 2023 energy-poverty indicators to the available regional covariates, which refer to 2022. The covariates included in the spatial specifications capture selected dimensions of energy use, housing conditions, demographic structure, education, prices and the regional electricity-generation mix. Specifically, ELC denotes total domestic electricity consumption, measured in GWh; HDR denotes the percentage of households reporting damaged dwelling structures; OVR is the overcrowding index, measured as household members per square metre; AGE denotes average age; EDU is the percentage of graduates; PRI denotes the FOI consumer-price index;

and PVS measures photovoltaic electricity production as a percentage of total electricity production. These variables are included as regional covariates for examining statistical associations with the alternative energy-poverty indicators; their estimated coefficients are therefore interpreted as conditional associations rather than causal effectsThe SAR and SEM specifications represent different forms of spatial dependence. In the SAR model, the spatial parameter captures statistical association between the dependent variable in one region and corresponding values in neighbouring regions, whereas in the SEM model it captures spatial structure in the unexplained component. A significant spatial parameter therefore identifies a statistical spatial pattern within the corresponding specification, but does not by itself establish a causal spillover between regions**.**

Table 4.3 — Spatial diagnostics and model comparison for the four energy-poverty indicators, 2023

Indicator	Moran's I	p-value	Robust RS lag p	Robust RS error p	AIC OLS	AIC SAR	AIC SEM	Preferred specification
Π_1^N	−0.416	0.023	0.171	0.010	−75.25	−73.87	−90.01	SEM
Π_2^R	−0.210	0.305	0.915	0.522	−89.66	−88.94	−91.53	OLS adequate
Π_3^N	−0.044	0.959	0.021	0.044	−132.92	−132.66	−131.14	OLS
Π_4^R	−0.266	0.202	0.473	0.684	−148.62	−149.90	−153.13	SEM

Note: Moran's *I* refers to the residuals of the OLS specification. Robust RS lag and Robust RS error report the p-values of the corresponding robust Rao's Score diagnostics. AIC values compare the OLS, spatial autoregressive (SAR) and spatial error (SEM) specifications; lower values indicate better relative fit. The preferred specification is determined from the overall diagnostic evidence rather than from AIC alone.

The fixed-threshold national indicator Π_1^N provides the clearest initial evidence of residual spatial structure. Moran's $I = -0.416$ with $p = 0.023$ indicates statistically significant global residual spatial autocorrelation, with the negative sign implying spatial contrast rather than positive clustering: neighbouring residuals tend, on average, to be dissimilar.

The diagnostic evidence favours the spatial-error specification. The robust Rao's Score error test is significant while the robust lag test is not; consistently, the SEM has a substantially lower AIC (-90.01) than OLS (-75.25) and SAR (-73.87), and its spatial-error parameter is statistically significant. Taken together, these results support the SEM as the preferred specification for Π_1^N.

The preference for the SEM suggests that residual variation in the fixed-threshold national indicator contains a spatially structured component not fully captured by the included covariates. This is

compatible with omitted or imperfectly measured regional characteristics that themselves display spatial structure, but does not identify which factors generate the pattern.

One possible contextual interpretation of this spatial contrast concerns the heterogeneity of regional energy systems and households' access to distributed generation. GSE data for 2023 document substantial territorial differences in photovoltaic production and self-consumption across Italy, indicating that exposure to purchased electricity is embedded in region-specific energy structures rather than necessarily following a smooth geographical gradient. From the structural perspective introduced by Boardman and developed in Chapter 2, access to residential self-generation may affect household energy expenditure by allowing part of electricity needs to be satisfied without an equivalent purchase from the retail market. Photovoltaic diffusion may therefore represent one among several structural characteristics potentially contributing to territorial heterogeneity in observed energy burdens. Photovoltaic generation is also included in the subsequent spatial specification through PVS, measured as the regional share of electricity production generated from photovoltaic sources. This regional measure does not directly identify household ownership of photovoltaic systems or household self-consumption and should therefore not be interpreted as a household-level measure of access to distributed generation. Its spatial-regression coefficient is used instead to assess whether differences in the regional photovoltaic generation mix are statistically associated with the alternative measures of energy vulnerability, conditional on the other included covariates. Any such association remains non-causal and cannot, on the basis of this specification alone, be attributed to the effects of a particular photovoltaic policy or to household self-consumption [43].

A different picture emerges for Π_2^R. Moran's $I = -0.210$ is not statistically significant ($p = 0.305$), and neither the standard nor robust Rao's Score diagnostics provide significant evidence of spatial-lag or spatial-error dependence. The model fits are also relatively close, with AIC values of -89.66 for OLS, -88.94 for SAR and -91.53 for SEM.

Although the SEM reports a statistically significant spatial-error parameter and a slightly lower AIC than OLS, the broader diagnostic evidence does not provide a comparably strong case for spatial dependence. OLS is therefore treated as an adequate specification for Π_2^R, while recognising that the SEM representation suggests some residual spatial structure may remain.

The endogenous-national indicator Π_3^N provides particularly limited evidence of global residual spatial autocorrelation. Moran's $I = -0.044$ is close to zero and statistically insignificant ($p = 0.959$); OLS also records the lowest AIC (-132.92), compared with -132.66 for SAR and -131.14 for SEM, while neither estimated spatial parameter is statistically significant.

These results favour OLS and indicate that replacing the uniform 10% rule with region-specific candidate thresholds under national conditioning does not mechanically generate residual spatial dependence; the empirical contribution of the endogenous approach should therefore not be evaluated according to whether it produces stronger spatial dependence.

Some diagnostic ambiguity remains because the robust Rao's Score statistics are significant for both the lag and error alternatives, despite the absence of global residual autocorrelation in Moran's I and the lack of improvement in the reported spatial-model fit. This reinforces the need to evaluate the complete diagnostic pattern rather than relying on an individual test in isolation.

The fully regional endogenous specification Π_4^R presents a different configuration. Moran's $I = -0.266$is not statistically significant ($p = 0.202$), but model comparison favours the SEM, whose AIC (-153.13) is lower than those of OLS (-148.62) and SAR (-149.90), with a statistically significant spatial-error parameter.

These findings are not necessarily contradictory. Moran's I is a global diagnostic of residual spatial autocorrelation in the OLS specification, whereas the SEM estimates a specific form of spatial dependence jointly with the remaining model parameters. A non-significant Moran statistic therefore does not preclude a spatial model from providing a better fit, and in this case the combined model-comparison evidence supports the SEM representation.

Considered jointly, the four indicators do not exhibit a common spatial structure: SEM is preferred for the fixed-national Π_1^N and fully regional endogenous Π_4^R specifications, OLS remains adequate for the fixed-regional Π_2^R, and OLS is preferred for the endogenous-national Π_3^N. No single econometric specification therefore dominates across the four indicators, indicating that the spatial structure of measured energy poverty is specification-dependent rather than uniformly associated with either methodological component.

Beyond the spatial diagnostics, the estimated covariate coefficients provide additional evidence on how regional characteristics are associated with the alternative measurement specifications. The following comparison focuses on $\Pi_1^N$and Π_4^R, for which the spatial-error specification is preferred, and therefore compares the estimated coefficients from the corresponding SEM models. Statistical significance is denoted by " $***$ " for $p < 0.001$, " $**$ " for $p < 0.01$, " $*$ " for $p < 0.05$, and "." for $p < 0.10$.

ELC displays opposite associations across the two specifications. For Π_1^N, total domestic electricity consumption is positively and statistically significantly associated with measured energy poverty at the 1% level ($\hat{\beta} = 6.4606 \times 10^{-6}$, $p < 0.01$). For Π_4^R, the association becomes negative while

remaining statistically significant at the 1% level ($\hat{\beta} = -1.4728 \times 10^{-6}$, $p < 0.01$). This sign reversal suggests that, under the fully regional specification, higher electricity consumption does not necessarily correspond to greater measured vulnerability and may instead reflect differences in regional consumption patterns and access to energy services.

HDR exhibits a comparable sign reversal. Under Π_1^N, the share of households reporting damaged dwelling structures is positively associated with measured energy poverty and is statistically significant at the 1% level ($\hat{\beta} = 2.6542 \times 10^{-3}$, $p < 0.01$). Under Π_4^R, the coefficient becomes negative and is significant at the 0.1% level ($\hat{\beta} = -1.5134 \times 10^{-3}$, $p < 0.001$). Rather than indicating that housing deprivation becomes protective, the negative conditional association suggests that the regional endogenous specification captures vulnerability relative to locally calibrated expenditure and energy-burden distributions, thereby altering the relationship observed under the fixed-national benchmark.

OVR is positively and statistically significantly associated with Π_1^N at the 5% level ($\hat{\beta} = 3.6429 \times 10^{-2}$, $p < 0.05$), consistent with greater measured vulnerability in regions characterised by higher overcrowding. For Π_4^R, however, the coefficient is much smaller ($\hat{\beta} = 1.2843 \times 10^{-3}$) and is not statistically significant at conventional levels. The evidence therefore does not support a robust conditional association between overcrowding and the fully regional endogenous indicator.

AGE shows the opposite significance pattern. Its coefficient for $\Pi_1^N$is positive ($\hat{\beta} = 2.0033 \times 10^{-3}$) but not statistically significant at conventional levels. Under Π_4^R, AGE becomes negatively associated with measured energy poverty and statistically significant at the 5% level ($\hat{\beta} = -1.7473 \times 10^{-3}$, $p < 0.05$). The latter association may reflect differences in consumption behaviour, housing tenure and other characteristics of older regional populations, but the aggregate specification does not permit these mechanisms to be identified separately.

EDU is strongly negatively associated with Π_1^N, with a coefficient statistically significant at the 0.1% level ($\hat{\beta} = -1.7078, p < 0.001$). For Π_4^R, the coefficient becomes positive ($\hat{\beta} = 5.9300 \times 10^{-2}$) but is only marginally significant at the 10% level ($p < 0.10$). The contrast indicates that the strong negative association observed under the fixed-national benchmark is not preserved once both vulnerability and the energy-burden boundary are regionally calibrated.

PRI is negatively and statistically significantly associated with Π_1^N at the 0.1% level ($\hat{\beta} = -2.0429 \times 10^{-2}$, $p < 0.001$). Under Π_4^R, the estimated coefficient remains negative but is close to zero ($\hat{\beta} = -9.6504 \times 10^{-5}$) and is not statistically significant at conventional levels. Consequently,

the regional endogenous specification provides no robust evidence of an independent conditional association between PRI and measured energy poverty.

Finally, PVS exhibits a marked reversal across the two specifications. The regional photovoltaic-production share is positively and statistically significantly associated with Π_1^N at the 0.1% level ($\hat{\beta} = 2.6639 \times 10^{-1}$, $p < 0.001$), whereas its association with Π_4^R is negative and statistically significant at the 5% level ($\hat{\beta} = -2.6276 \times 10^{-2}$, $p < 0.05$). The positive coefficient under the fixed-national specification indicates a positive conditional association between the regional photovoltaic generation share and measured vulnerability. Given the aggregate regional nature of PVS, however, this result should not be interpreted as evidence that photovoltaic generation itself increases household energy poverty. Conversely, the negative coefficient under the fully regional specification is consistent with the possibility that a greater regional photovoltaic contribution is associated with lower energy vulnerability once the measurement framework is adapted to regional conditions. However, PVS measures the regional photovoltaic share of electricity production rather than household photovoltaic ownership or self-consumption; the estimated relationship therefore cannot establish that photovoltaic deployment or a specific photovoltaic policy causally reduces household energy poverty.

Overall, the changes in sign and statistical significance across Π_1^N and Π_4^R reinforce the conclusion that the observed relationships between regional characteristics and measured energy poverty are sensitive to the underlying measurement architecture. They should therefore be interpreted as specification-dependent conditional associations rather than as structural or causal effects.

Crucially, stronger spatial dependence should not be interpreted as evidence of a superior energy-poverty indicator. The strongest significant global Moran statistic occurs for the conventional fixed-national specification, whereas Π_3^N exhibits virtually no global residual spatial autocorrelation; the empirical value of endogenous thresholding therefore lies in its distribution-sensitive measurement properties, not in generating stronger spatial dependence.

The spatial evidence should therefore be interpreted as an assessment of the empirical consequences of alternative measurement choices rather than as a validation test for the rightmost solution of $f'''(s) = 0$. Spatial dependence cannot establish that the stationary-curvature point is the uniquely appropriate substantive boundary; it shows only that changing indicator construction can also alter the spatial statistical structure associated with measured vulnerability.

Overall, the spatial analysis shows that measurement design affects not only incidence and regional ranking but also the associated spatial statistical structure, while the absence of a uniform pattern

across the four indicators cautions against treating any single econometric outcome as decisive evidence in favour of one specification.

The combined empirical evidence therefore provides the basis for the broader discussion of strengths, robustness and limitations developed in the following section.

4.7 Discussion, robustness and limitations

The empirical evidence provides a nuanced assessment of the endogenous-threshold approach. The procedure generates region-specific candidate boundaries that respond to conditional energy-burden distributions and can materially alter territorial classifications, but the results do not establish the endogenous boundary as an empirically definitive or uniquely valid poverty threshold; its contribution lies instead in providing a distribution-sensitive alternative through which the consequences of uniform measurement rules can be examined.

A first strength is sensitivity to regional distributional heterogeneity. Unlike a fixed threshold, which applies the same energy-expenditure share across territories, the endogenous procedure derives the candidate boundary separately from each fitted regional conditional density. The observed variation in the resulting thresholds therefore confirms that the procedure responds to region-specific distributional structure rather than reproducing a common alternative to the 10% rule.

A second contribution concerns the distinction between aggregate prevalence and territorial allocation. The results show that modest differences in cross-regional average incidence can coexist with substantial regional reclassification, making the geographical allocation of measured vulnerability an important empirical outcome when indicators inform territorially differentiated analysis or intervention.

The four-indicator framework further clarifies that regional reclassification cannot be attributed to the energy threshold alone, since measured incidence is sensitive to both economic conditioning and the criterion used to identify high energy burden. The 2×2 design helps separate these mechanisms, while also showing that regional conditioning changes the population on which the conditional Beta distribution and resulting candidate threshold are estimated.

These advantages are accompanied by a fundamental trade-off between uniform comparability and contextual sensitivity. A common national benchmark provides a transparent reference for direct cross-regional comparison, whereas region-specific criteria recognise territorial differences in expenditure conditions and energy-burden distributions but no longer apply an identical numerical standard across regions. The choice therefore reflects different measurement objectives rather than a purely technical distinction between a correct and an incorrect indicator.

A first limitation concerns the interpretation of observed energy expenditure itself. The energy-burden ratio captures realised expenditure rather than the energy services required to maintain adequate living conditions. A low energy share may therefore reflect genuinely limited energy needs or, alternatively, involuntary consumption restriction caused by financial constraints, in which case an expenditure-based indicator may fail to identify households experiencing inadequate heating or other forms of energy deprivation.

Consequently, neither the fixed nor the endogenous expenditure-share threshold fully resolves the problem of hidden energy poverty. The endogenous procedure changes the way high observed burdens are identified, but households suppressing energy consumption may remain outside the upper tail altogether. This limitation concerns the underlying expenditure-based measurement framework rather than the Beta specification alone.

A related limitation concerns the economic-vulnerability component. Total household expenditure provides an operational representation of material resources but cannot capture dimensions such as wealth, access to credit, housing tenure, accumulated savings or temporary expenditure adjustments; the national and regional low-expenditure conditions should therefore not be interpreted as complete measures of household deprivation.

The endogenous procedure additionally depends on the adequacy of the Beta distribution as a parametric representation of the conditional energy-share data. Its bounded support provides a natural framework for modelling the energy-expenditure share, and the estimated parameters reproduce the broad asymmetric structure observed in the application; nevertheless, regional data may contain local features, multimodality or tail behaviour that a two-parameter Beta density does not fully represent.

Since the candidate threshold is obtained from derivatives of the fitted density, model misspecification can propagate directly into the estimated location of $\tau_{\mathrm{endo},r}$. The interpretation of the endogenous boundary therefore depends not only on the geometric criterion itself but also on the quality of the underlying distributional approximation.

The comparison between empirical and fitted probabilities provides an additional reason for caution. As reported in Section 4.4, their correspondence is uneven across regions, indicating that the fitted parametric quantities should not be treated as numerically interchangeable with the observed weighted incidence.

The available evidence does not, by itself, identify a unique source of these discrepancies. They may reflect differences between the empirical joint construction and the corresponding fitted probability, sensitivity of the parametric approximation in the relevant tail, or features of the implementation that

require further diagnostic examination. Accordingly, the discrepancy is best treated as a robustness issue requiring additional investigation rather than being assigned a definitive interpretation from the present results alone.

Several robustness exercises could strengthen the empirical assessment. Threshold stability could be examined through resampling or alternative sample specifications; the Beta-based boundary could be compared with alternative flexible distributional representations; sensitivity to economic vulnerability could be assessed using alternative expenditure cut-offs; and repeated regional applications across multiple years could assess the temporal stability of both thresholds and classifications.

The regional results must also be interpreted within their temporal scope. Although the data-processing framework harmonises HBS information for 2014–2023, the regional Beta-threshold and spatial analysis focuses on the 2023 cross-section, so the estimated configuration should not be treated as a time-invariant regional characteristic; changes in energy prices, expenditure patterns, climatic conditions or policy interventions may alter both the conditional distributions and the resulting candidate boundaries.

The spatial analysis is additionally constrained by the small number of territorial units. With only twenty Italian regions, the econometric estimates and diagnostic tests rely on a limited cross-sectional sample, reducing the information available to distinguish among competing spatial specifications; the results should therefore be treated as complementary evidence on indicator behaviour rather than as definitive identification of regional energy-poverty mechanisms.

Spatial inference also depends on the regional neighbourhood structure. The Queen-contiguity matrix supplemented by nearest-neighbour connections for the islands provides a transparent representation of geographical proximity, but alternative distance-based, economic or energy-market connectivity structures could produce different estimates of spatial dependence. The reported results should therefore be interpreted conditional on the adopted spatial-weighting scheme.

More generally, the empirical analysis is diagnostic rather than causal. Regional indicator differences may be associated with climatic, housing, demographic, infrastructural and socioeconomic characteristics, but the present design does not establish causal effects; similarly, significant spatial parameters identify statistical dependence rather than causal transmission between neighbouring regions.

The central methodological question concerns the interpretation of the rightmost stationary-curvature point itself. The empirical application shows that the criterion produces admissible regional

boundaries, responds to differences in fitted distributions and generates classifications that differ materially from those obtained under a uniform 10% rule, supporting its investigation as a data-driven criterion for delimiting the upper tail of the conditional energy-burden distribution. These findings do not, however, demonstrate that the rightmost solution of $f'''(s) = 0$ constitutes a uniquely correct or normatively optimal energy-poverty threshold. The stationary-curvature point has a formal geometric interpretation within the fitted Beta density, but translating that property into a substantive poverty boundary requires an additional conceptual judgement. The evidence therefore supports its relevance as a candidate endogenous boundary while leaving broader substantive validation open to further research.

Stronger substantive validation would require evidence beyond the internal geometry of the expenditure-share distribution. For example, the candidate classification could be compared with independent measures of thermal deprivation, arrears, inability to maintain adequate indoor temperatures, dwelling energy performance or other externally observed dimensions of energy vulnerability. Such evidence would make it possible to assess whether households identified beyond the candidate boundary also exhibit forms of deprivation that are conceptually independent of the expenditure-share measure from which the threshold itself is derived.

Overall, the evidence supports a balanced interpretation of the endogenous-threshold approach. Its main empirical contribution is to make regional distributional heterogeneity explicit and reveal territorial reclassification that may remain hidden behind similar aggregate incidence, while its interpretation remains conditional on observed expenditure, the definition of economic vulnerability, the adequacy of the Beta approximation and the substantive meaning assigned to the stationary-curvature point. The spatial evidence adds information on specification-dependent statistical structure but does not provide an independent criterion for selecting the substantively correct poverty boundary.

The contribution of the proposed framework should therefore be understood not as replacing one universal threshold with another, but as providing a systematic way to investigate how energy-poverty measurement changes when the burden boundary is allowed to respond to the distributional context in which households are observed.

The concluding section now synthesises the principal empirical results and the contribution of the endogenous-threshold framework to energy-poverty measurement.

4.8 Conclusion

This chapter empirically assessed the endogenous-threshold framework developed in Chapter 3 by applying it to energy-poverty measurement across the Italian regions. The analysis examined whether allowing the energy-burden boundary to emerge from regional conditional expenditure-share distributions provides information not captured by a uniform threshold, considering regional Beta distributions, candidate thresholds, alternative indicators, geographical patterns and associated spatial statistical structures.

The threshold estimates provide clear evidence of regional distributional heterogeneity. Although the candidate boundaries remain close to 15% on average under both national and regional economic conditioning, individual thresholds vary substantially across territories and respond heterogeneously to the conditioning benchmark; moreover, all exceed the conventional 10% rule in the 2023 application. The endogenous procedure consequently generates region-specific, distribution-sensitive boundaries rather than replacing the conventional rule with a single alternative threshold.

This territorial sensitivity is also consistent with the structural perspective discussed in Chapters 1 and 2: observed household energy burdens emerge within heterogeneous regional contexts characterised by different housing, climatic, socioeconomic and energy-system conditions. The endogenous procedure does not identify the contribution of any individual factor, such as photovoltaic self-generation, but allows the expenditure-burden boundary itself to respond to the regional distribution generated within that broader context.

The comparison of the four indicators shows that measurement design affects both estimated prevalence and the territorial allocation of measured energy poverty. Changes in the economic-vulnerability benchmark and energy-burden threshold alter the population and criterion entering the joint classification, so relatively modest differences in cross-regional average incidence can coexist with substantial changes in regional rankings and geographical patterns. In particular, the fully regional specification produces vulnerability profiles that are less closely aligned with the conventional North–South representation obtained under nationally uniform criteria.

The spatial analysis further shows that the four measurement specifications are not associated with a common spatial statistical structure, with spatial-error dependence supported for some specifications while OLS remains adequate or preferable for others. The endogenous indicators do not systematically generate stronger spatial dependence than their fixed-threshold counterparts, so spatial autocorrelation should not be interpreted as a criterion of indicator quality or as validation of the endogenous threshold. Rather, the econometric evidence shows that alternative definitions of

energy poverty can be associated with different spatial statistical structures of measured vulnerability.

Overall, the empirical evidence supports the continued investigation of the endogenous threshold as a candidate distribution-sensitive boundary, while not establishing it as a uniquely valid or normatively optimal energy-poverty threshold. The rightmost stationary-curvature point of the fitted Beta density provides a systematic data-driven criterion for investigating the upper tail of regional energy-burden distributions, and its application identifies dimensions of territorial heterogeneity not fully represented by a uniform measurement rule. At the same time, its substantive interpretation remains conditional on the adequacy of the expenditure-based framework, the quality of the parametric approximation and the conceptual meaning assigned to the resulting boundary. The contribution of the approach therefore lies not in replacing the conventional 10% rule with another universal benchmark, but in showing how the diagnosis of energy poverty changes when the burden threshold is allowed to respond to the distributional context in which households are observed.

In this sense, the analysis reinforces a broader conclusion running throughout the thesis: the measurement of energy poverty is not a neutral technical exercise, since the methodological choices used to define vulnerability directly influence the households and territories that become visible through the indicator.

CONCLUSION

Energy poverty has progressively emerged as a policy and research problem that cannot be reduced to a single dimension of household deprivation. The analysis developed throughout this thesis has shown that difficulties in securing adequate domestic energy services arise from the interaction of household economic resources, energy expenditure, dwelling characteristics, market conditions and the institutional environment in which households operate. This complexity has important consequences not only for the design of public intervention, but also for the apparently preliminary question of how energy poverty should be identified and measured.

The historical reconstruction developed in Chapter 1 demonstrated how the concept evolved from the early observation of disproportionate household fuel expenditure toward increasingly multidimensional interpretations of energy deprivation. The contributions of Boardman and Hills progressively refined the relationship between energy requirements, expenditure and residual resources, while the Capability Approach and Energy Justice extended the analysis beyond monetary affordability to questions of effective access to adequate energy services, unequal needs, recognition and participation. Energy poverty consequently emerged not simply as a particular manifestation of low income, but as a condition in which economic, material and institutional constraints can prevent households from converting available resources into adequate domestic energy services.

This conceptual evolution has been accompanied by a substantial transformation of the policy framework. As examined in Chapter 2, European energy governance progressively moved from an approach centred predominantly on market integration and general consumer protection toward the explicit recognition of vulnerable consumers and energy poverty within energy and climate policy. The Clean Energy Package, the European Green Deal, Fit for 55 and the Social Climate Fund illustrate the growing integration of distributive considerations into the decarbonisation process. The Italian experience reflects the same transition. Instruments such as the Bonus Sociale and regulated retail protection have provided forms of compensatory support, while more recent measures directed toward renewable self-generation, energy communities and energy-efficiency investment indicate a gradual movement toward structural prevention. Nevertheless, the coexistence of compensatory and preventive instruments demonstrates that the transition remains incomplete and that the effectiveness of energy-poverty policy ultimately depends on the capacity to identify the households and territories that require protection.

Measurement therefore represents a central connection between the conceptual and policy dimensions of energy poverty. The methodological analysis conducted in Chapter 3 showed that established expenditure-based indicators do not provide interchangeable representations of a

uniquely observable condition. Measures based on high expenditure burdens, unusually low expenditure, residual resources or combined economic conditions capture different manifestations of vulnerability and depend on specific choices concerning variables, thresholds and reference populations. Indicator design consequently affects both the estimated incidence of energy poverty and the households classified as vulnerable.

Against this background, the thesis investigated an experimental distributional approach based on the household energy-expenditure share and the Beta distribution. Rather than imposing exclusively a predetermined expenditure-burden threshold, the proposed methodology examines whether the rightmost admissible stationary-curvature point of the fitted Beta density can provide a candidate endogenous boundary for delimiting the upper tail of the expenditure-share distribution. This criterion was combined with a 60%-of-median economic-vulnerability condition and incorporated into a four-indicator architecture contrasting fixed and endogenous energy-burden thresholds under national and regional economic reference structures. The purpose of this framework was not to replace established measures with another universal threshold, but to examine how measured energy vulnerability changes when both the burden boundary and the geographical reference structure are allowed to respond to the empirical distribution.

The application to Italian regional data in Chapter 4 provides several results relevant to this question. The candidate endogenous thresholds were admissible across the regional applications and remained close to 15% on average under both national and regional economic conditioning, while displaying meaningful variation across individual territories. In the 2023 application, all of the estimated candidate boundaries exceeded the conventional 10% expenditure threshold. The empirical exercise therefore shows that a uniform threshold and a distribution-responsive criterion can identify materially different portions of the expenditure-burden distribution.

The comparison of the four measurement specifications further demonstrates that similar aggregate incidence can coexist with substantial territorial reclassification. Changing the economic reference from a national to a regional benchmark, or replacing the fixed energy-burden boundary with the candidate endogenous threshold, alters the regional pattern of measured vulnerability. The geographical and spatial analyses reinforce this conclusion by showing that alternative specifications can generate different territorial structures even when their national aggregates appear comparatively similar. These findings are particularly relevant for policy analysis because geographically uniform measurement rules may conceal forms of heterogeneity that become visible when regional expenditure distributions and economic conditions are explicitly incorporated into the measurement process.

At the same time, the empirical results require a deliberately cautious interpretation. The fact that the rightmost stationary-curvature point can be identified within the fitted Beta distribution and produces empirically differentiated regional classifications does not establish that it represents a uniquely correct or normatively optimal energy-poverty threshold. Its mathematical interpretation is internal to the geometry of the fitted distribution, whereas the translation of that property into a substantive boundary of deprivation requires additional evidence. The empirical findings therefore support the endogenous criterion as a candidate data-driven instrument for investigating the upper tail of energy burdens, rather than validating it as a definitive replacement for existing energy-poverty measures.

This distinction also reflects the broader limitations of expenditure-based measurement. Realised household expenditure does not directly reveal whether energy services are adequate. A household may report a relatively low energy burden precisely because it restricts consumption below the level required for adequate heating, cooling or other essential domestic services. Conversely, high expenditure may result from several combinations of income, dwelling efficiency, climatic conditions and household needs. The Beta-based framework therefore remains an analysis of the expenditure dimension of energy poverty and cannot independently observe thermal deprivation, arrears, dwelling energy performance or subjective difficulties in maintaining adequate indoor conditions.

Further research could consequently strengthen the substantive assessment of the candidate endogenous boundary by comparing the resulting classifications with independent dimensions of energy deprivation. Evidence concerning inability to maintain adequate indoor temperatures, payment arrears, housing quality, energy performance or other direct indicators of insufficient energy services would make it possible to determine whether households located beyond the candidate distributional boundary also exhibit vulnerability that is observable independently of the expenditure share from which the threshold is derived. Repeating the analysis across different years and economic conditions would additionally help determine whether the regional candidate thresholds remain sufficiently stable when energy prices, household expenditure and broader macroeconomic circumstances change.

The results also have a broader implication for the relationship between measurement and public policy. As European and Italian strategies increasingly seek to combine decarbonisation with social protection, the identification of vulnerable households becomes part of the effectiveness and distributive fairness of the transition itself. Policies may mobilise substantial financial resources and technically appropriate interventions while still producing unequal outcomes if the indicators used to identify vulnerability fail to recognise relevant forms of deprivation or territorial heterogeneity.

Measurement should therefore be understood not merely as a statistical exercise preceding policy intervention, but as part of the institutional process through which social vulnerability becomes visible and resources are directed toward it.

The principal contribution of this thesis lies in connecting these different dimensions of the energy-poverty problem. The historical analysis shows how the concept expanded beyond a narrow affordability perspective; the institutional analysis demonstrates how this evolution entered European and Italian energy governance; the methodological analysis makes explicit the assumptions through which energy vulnerability is translated into measurable criteria; and the empirical application illustrates how those assumptions affect the regional patterns ultimately observed. The experimental endogenous-threshold framework contributes to this discussion by providing a systematic way to investigate the information contained in the distributional structure of household energy burdens while retaining established indicators as essential complementary benchmarks.

Energy poverty therefore remains a phenomenon for which no single statistical criterion can fully reproduce the complexity identified by its theoretical definition. Greater methodological flexibility can improve the capacity to detect heterogeneous patterns, but it cannot eliminate the conceptual judgement involved in defining vulnerability. The appropriate objective is consequently not to search mechanically for a universally valid numerical boundary, but to develop measurement frameworks whose assumptions are transparent, whose empirical behaviour can be evaluated and whose classifications can be compared with independent evidence of deprivation. In this perspective, the candidate endogenous threshold investigated in this thesis represents one possible contribution to a broader measurement architecture rather than its final solution.

Ultimately, the analysis developed throughout the thesis leads to a common conclusion across its conceptual, institutional, methodological and empirical dimensions. The effectiveness of energy-poverty governance depends not only on how much support is provided or which technologies are promoted, but also on how vulnerability itself is recognised. The households and territories identified as energy poor are partly shaped by the variables, thresholds, reference populations and geographical scales through which the phenomenon is measured. Making these choices explicit, testing their empirical consequences and combining complementary sources of evidence are therefore essential conditions for developing energy-poverty policies capable of supporting a transition that is not only environmentally sustainable, but also socially equitable.

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