UNIVERSITY OF RIJEKA
FACULTY OF ECONOMICS AND BUSINESS

Ivana Rogulj

The impact of the decarbonisation policies in energy sector on the vulnerable energy consumers

DOCTORAL THESIS

Rijeka, 2026

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Supervisor: dr. Pavle Jakovac, Associate Professor

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SVEUČILIŠTE U RIJECI
EKONOMSKI FAKULTET U RIJECI

Ivana Rogulj

Utjecaj dekarbonizacijskih politika u energetskom sektoru na ugrožene potrošače energije

DOKTORSKI RAD

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Rijeka, 2026.

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Doktorski rad obranjen je dana _____ _____ u/na _____ _____, pred povjerenstvom u sastavu:

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1. ZAHVALA

ACKNOWLEDGEMENTS

2. SAŽETAK

Disertacija istražuje utjecaj dekarbonizacije energetskog sektora na ranjive skupine potrošača, s posebnim naglaskom na mikro poduzeća, skupinu koja je unatoč svojoj gospodarskoj i društvenoj važnosti nedovoljno zastupljena u postojećim energetskim politikama, statistikama i analizama distribucijskih učinaka energetske tranzicije. Polazi se od hipoteze da dekarbonizacijske mjere, ako nisu odgovarajuće vremenski usklađene, ciljano oblikovane i utemeljene na dovoljno detaljnim i pouzdanim podacima, mogu povećati energetsku ranjivost i nerazmjerno opteretiti potrošače s najmanjom sposobnošću prilagodbe. Istodobno, dobro osmišljena dekarbonizacija može povećati energetsku sigurnost, otpornost i dugoročnu dostatnost energetskog sustava te pridonijeti društveno pravednijem razvoju.

Prva tri dijela disertacije uspostavljaju konceptualne i empirijske temelje istraživanja. U prvome se razvija višedimenzionalni okvir za definiranje i mjerenje energetske ranjivosti mikro poduzeća, uzimajući u obzir specifičnosti njihova poslovanja i ograničenja postojećih pokazatelja. Drugi i treći dio identificiraju ključne strukturne čimbenike koji određuju sposobnost mikro poduzeća za prilagodbu promjenama cijena energije i zahtjevima dekarbonizacije. Među njima se izdvajaju visok udio troškova energije u prometu ili ukupnim troškovima poslovanja, ograničeni investicijski i administrativni kapaciteti, slabiji pristup financiranju te česta povezanost i preklapanje financija poduzeća i kućanstva vlasnika.

Četvrti i peti dio predstavljaju središnji metodološki i empirijski doprinos disertacije. Razvija se integrirani model koji, u kombinaciji s mikrosimulacijskim pristupom, omogućuje procjenu distribucijskih učinaka dekarbonizacijskih politika na dobrobit kućanstava i poslovanje mikro poduzeća. Model uključuje strukturu potrošnje energije, promjene cijena, cjenovne elastičnosti i bihevioralne reakcije te omogućuje procjenu učinaka promjena troškova energije na potrošnju, dobrobit, profitabilnost, likvidnost i financijsku stabilnost. Učinci na kućanstva procjenjuju se metodom kompenzacijske varijacije, dok se učinci na mikro poduzeća analiziraju primjenom mikrosimulacije njihove financijske otpornosti.

Rezultati pokazuju da prilagodba na više cijene energije i druge učinke dekarbonizacijskih politika nije linearna niti ravnomjerno raspoređena među različitim skupinama potrošača. Kućanstva s nižim prihodima imaju ograničen prostor za prilagodbu te potrošnju energije često smanjuju na način koji može negativno utjecati na razinu komfora, kvalitetu života i zdravlje. Mikro poduzeća, s druge strane, mogu biti suočena s padom profitabilnosti, smanjenjem likvidnosti, odgodom ulaganja i povećanom poslovnom nestabilnošću. Rizici su posebno izraženi kod mikro poduzeća kod kojih postoji snažno preklapanje financija poduzeća i kućanstva.

Zaključno, rezultati potvrđuju da distribucijski ishodi dekarbonizacije u velikoj mjeri ovise o vremenskom usklađivanju politika, kvaliteti i razini detaljnosti dostupnih podataka te preciznom usmjeravanju mjera potpore. Pravodobne, diferencirane i ciljane intervencije mogu značajno ublažiti negativne učinke tranzicije, istodobno čuvajući njezine klimatske i energetske ciljeve. Disertacija stoga naglašava potrebu za sustavnim uključivanjem ranjivih kućanstava i mikro poduzeća u statističke, analitičke i političke okvire kako bi tranzicija prema klimatskoj neutralnosti bila učinkovita, društveno pravedna i usmjerena prema ostvarivanju pozitivnih učinaka na društvo u cjelini.

Ključne riječi: dekarbonizacija; distribucijski učinci; energetska ranjivost; mikro poduzeća; energetska tranzicija

3. SUMMARY

This dissertation examines the impact of energy sector decarbonisation on vulnerable consumer groups, with particular emphasis on micro-enterprises, a group that remains insufficiently represented in existing energy policies, statistical systems, and analyses of the distributional effects of the energy transition. The research is based on the hypothesis that decarbonisation measures, if not appropriately timed, carefully targeted, and grounded in sufficiently detailed and reliable data, may increase energy vulnerability and place a disproportionate burden on consumers with the least capacity to adapt. At the same time, well-designed decarbonisation policies can strengthen energy security, resilience, and long-term affordability, while contributing to a more socially just transition.

The first three parts of the dissertation establish the conceptual and empirical foundations of the research. The first develops a multidimensional framework for defining and measuring the energy vulnerability of micro-enterprises, considering the specific characteristics of their operations and the limitations of existing indicators. The second and third parts identify the key structural factors that determine the ability of micro-enterprises to adapt to changes in energy prices and the broader requirements of decarbonisation. These include a high share of energy costs in turnover or overall operating costs, limited investment and administrative capacity, restricted access to finance, and the frequent overlap between business finances and the household finances of the business owner.

The fourth and fifth parts represent the central methodological and empirical contribution of the dissertation. An integrated model is developed which, in combination with a microsimulation approach, enables the assessment of the distributional effects of decarbonisation policies on household welfare and the performance of micro-enterprises. The model incorporates energy consumption structures, price changes, price elasticities, and behavioural responses, and assesses the effects of changes in energy costs on consumption, welfare, profitability, liquidity, and financial stability. Impacts on households are estimated using compensating variation, while the impacts on micro-enterprises are analysed through microsimulation of their financial resilience and stability.

The results show that adjustment to higher energy prices and other effects of decarbonisation policies is neither linear nor evenly distributed across consumer groups. Low-income households have limited scope for adaptation and may reduce energy consumption at the expense of comfort, quality of life, and health. Micro-enterprises, in turn, may experience declining profitability, reduced liquidity, delayed investments, and increased business instability. These risks are particularly pronounced where household and business finances are closely interconnected.

In conclusion, the findings confirm that the distributional outcomes of decarbonisation depend largely on the timing of policy measures, the quality and granularity of available data, and the accurate targeting of support. Timely, differentiated, and targeted interventions can substantially mitigate the negative effects of the transition while preserving its climate and energy objectives. The dissertation therefore highlights the need to systematically incorporate vulnerable households and micro-enterprises into statistical, analytical, and policy frameworks to ensure that the transition towards climate neutrality is effective, socially just, and capable of delivering positive outcomes for society.

Keywords: decarbonisation; distributional impacts; energy vulnerability; micro-enterprises; energy transition

4. CONTENTS

1. Zahvala 6
2. Sažetak 8
3. Summary 10
4. Contents 12
5. Introduction 14
   5.1. Overview of the previous research 14
   5.2. Purpose and objectives of research 19
   5.3. Scientific methods used 20
   5.4. Structure of the dissertation 22
6. Composite index for the evaluation of energy vulnerability of micro-enterprises 23
   6.1. Abstract: 23
   6.2. Introduction 23
   6.3. Energy vulnerability of micro-enterprises 26
   6.4. Methodology 29
   6.5. Results 39
   6.6. Discussion, conclusion and implications 45
7. Determinants of energy vulnerability in micro-enterprises 48
   7.1. Abstract 48
   7.2. Introduction 48
   7.3. Conceptual framework 50
   7.4. Case study - Croatia 58
   7.5. Methodology 58
   7.6. Results 63
   7.7. Discussion 67
   7.8. Conclusions and policy implications 68
8. Influence of data deficiency on evaluating vulnerability 71
   8.1. Abstract 71
   8.2. Introduction 72
   8.3. Background 72

8.4. Methodology 74
8.5. Results 80
8.6. Discussion and contribution to literature 91
8.7. Conclusions 93
9. Impacts of decarbonisation policies on vulnerablity 95
9.1. Abstract 95
9.2. Introduction 96
9.3. Literature Review 97
9.4. Methodology 104
9.5. Results 109
9.6. Policy Implications 116
9.7. Summary and Conclusions 118
9.8. Recommendations for Future Research 119
10. Evaluating the effects of decarbonisation policy on micro-enterprises 121
10.1. Abstract 121
10.2. Introduction 121
10.3. Literature review and research context 123
10.4. Methodology 125
10.6. Results / impacts of ETS2 prices in M-Es in four countries 135
10.7. Discussion, conclusions and policy implications 138
11. Concluding remarks 141
12. Literature 144
13. List of figures and tables 160
14. Prošireni sažetak na hrvatskom jeziku 164
CURICCULUM VITAE 184
IZJAVA 187

5. INTRODUCTION

The energy transition is a central pillar of EU development policy through 2030, focusing on reducing GHG emissions, enhancing energy efficiency, and increasing the use of renewable energy sources. Over four decades of research have explored various dimensions of the energy transition, the micro-level effects on disposable income and productivity, as well as broader multi-country scenarios and technological innovations reshaping energy consumption patterns. Well-designed policy interventions and decarbonisation measures have consistently been shown to positively contribute to economic welfare. (Saunders, 2021)

Examining these objectives from different angles, energy transition and decarbonisation policies also alter import dependencies and global energy dynamics. (Yang & Qian, 2023) This became critically important in the past years, as the wars in Ukraine and Iran exposed vulnerabilities in energy supply security. Volatile energy prices and unstable import sources have imposed significant burdens on consumers, including those not directly engaged in energy-intensive activities, and have strained public funds aimed at stabilizing the economy (UN Global Crisis Response Group (GCRG), 2022). Certain countries are particularly vulnerable to these disruptions due to factors such as market structure (including limited access to alternative energy supplies), building ownership patterns (which influence the feasibility of energy efficiency interventions), reliance on energy imports, macroeconomic conditions, and the strength of social protection systems.

Some consumer groups in those countries are at risk of changes in energy prices. These consumer groups were until now mostly viewed as households vulnerable to energy poverty, and particular measures have been targeted towards them. The new European Social Climate Fund (SFC) and the reference to it in the Commission Recommendation on energy poverty, for the first time, mentions the vulnerability of the micro-enterprises in the same policy documents as the energy poverty of households, putting small vulnerable consumers together, as specific target group of the policies. (European Commission, 2023: b), (European Commission, 2023)

5.1. Overview of the previous research

In 2022, households represented 27% of final energy consumption in the EU-27 Eurostat. More recent data indicate that this share slightly declined to around 26% in 2023, alongside a reduction in total household energy consumption to 9.6 million TJ, continuing a downward trend observed since 2021. (EUROSTAT, 2025) In addition to being a significant consumer of energy, they are also relevant macroeconomic aggregate in most EU countries. Diagnosing vulnerable or energy poor groups involves measuring and monitoring their different characteristics and multiple impacts that affect them. As there is no uniform definition of vulnerable consumers, indicators are crucial, offering valuable insights into identifying and evaluating the vulnerability of those lacking access to adequate energy resources.

Table 5-1 Part of the recognised indicators of vulnerability to energy poverty

Indicator	Definition	Source
2M	Share of energy / transport in total expenditures / income is more than twice the national median	Household budget survey - statistics on consumption expenditure/HBS, Eurostat
M/2	(Equivalised) expenditures on energy are less than half the national median	
LIHC	Household is at risk of poverty, i.e. expenditures are less than 60% of the national median AFTER paying for energy / transport AND share of energy / transport in total expenditures / income is larger than national median	
10%	Household spends more than 10% of income / total expenditure on heating, hot water and other activities in the building using heating oil, natural gas (e.g. cooking) or coal	
Keep home warm	Households' answers "cannot keep home adequately warm"	EU statistics on income and living conditions /EU-SILC
Arrears	Household is "in arrears on paying utility bills "	
Efficiency of the building	Households living in buildings with low energy efficiency or worst-performing buildings (WPB).	National data
REPI	Rented Private Housing Energy Poverty Indicator - A composite energy poverty indicator (combining standard consensual measures of energy poverty, with a lower weighting for the share of people living in poor housing) and an indicator of the size of the PRS in a given area.	

According to European Commission data, approximately 35 million EU citizens (around 8% of the population) were unable to keep their homes adequately warm in 2020, a figure that increased to 9.2% in 2026. (EUROSTAT, 2026) There is even a more significant number of citizens in the risk of poverty and exclusion, to as much as 35% in some of the European countries, while for the first income quintile this number rises to 85% on the EU level.

Based on the later calculations in our case study using HBS data, low income and vulnerable households use 20-50% less energy, depending on the type of energy and Member State. However, to achieve adequate warmth of the household, one can argue that the poor household energy expenditure should be at least the same as average. (Champagne, et al., 2023) Otherwise, health and social consequences of inadequate living conditions contribute to the total costs to society. (Polimeni, et al., 2022) This means that we should evaluate energy expenditure of vulnerable and low-income households as a significant impact on the total household sector energy consumption. This has been recognised in specific policies targeting energy poor households, helping them get out of vulnerability. However, at the level of general energy transition policies, there has not been an adequate evaluation of effects on different socio-economic consumer groups, in particular vulnerable groups.

Looking into the business segment, the situation is even more complex for multiple reasons: current policies focus on larger consumers, barriers to implementing energy transition policies in all SMEs, and even more micro-enterprises, and the novelty and lack of definition of vulnerability of micro-enterprises. The importance of micro - SMEs is shown on Graph 2, developed by JRC from the Eurostat data, where it can be seen that most European industries' ecosystems and value chains rely on the work and productivity of micro-enterprises. (Di Bella et al., 2023)

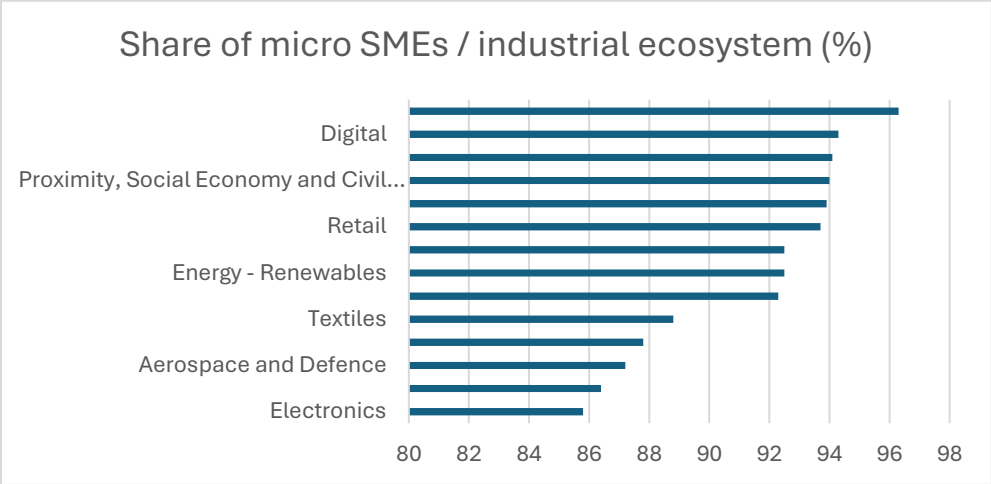


Figure 5-1 Share of micro-enterprises in EU industries' ecosystems, source Di Bella et al.,2023

According to the Eurostat Structural Business Statistic, share of total net turnover of micro-enterprises in Europe is also significant, almost 17% on the EU level. (Eurostat, 2024) From it, there are significant reasons to keep micro-enterprises strong and stable.

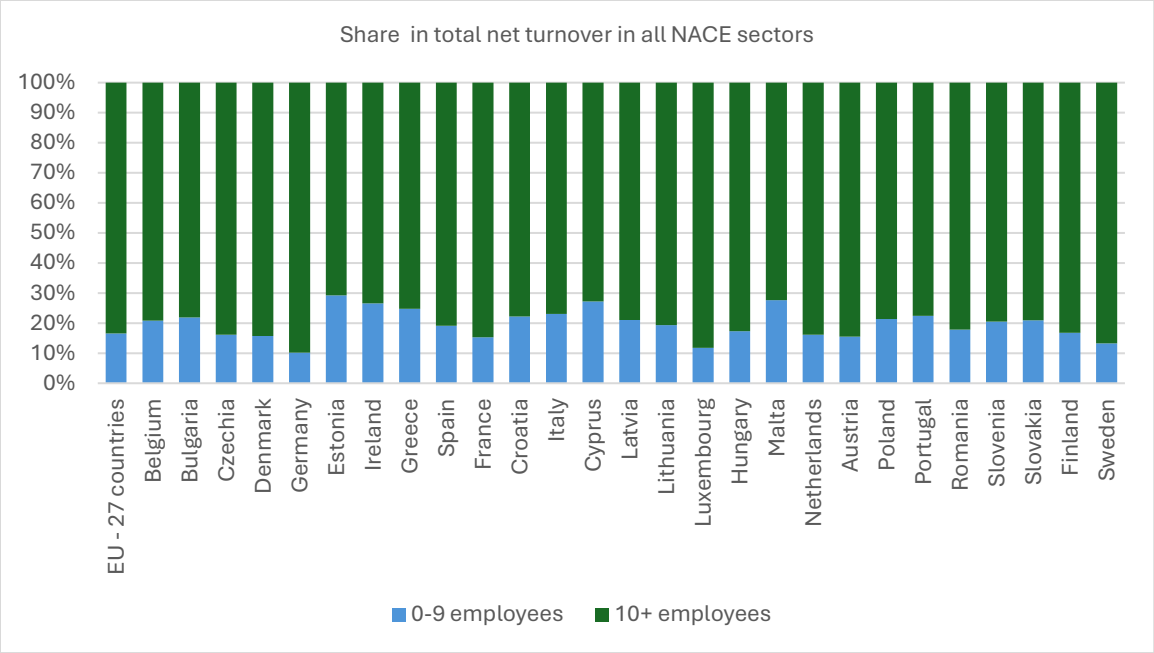


Figure 5-2 Share of small companies in total net turnover, source: EUROSTAT SBS, 2024

As there is no specific research on barriers to energy transition and in particular energy efficiency measures in micro-enterprises, they are in this part of review viewed at as a subgroup of SMEs, facing same but even more emphasized difficulties. They are confronted with numerous competing business priorities, other investments, such as internationalization, digitalization, "just-in time" organization, etc. At the EU level, there is a lack of specific quantitative objectives and mandatory requirements for SMEs, leading to being limited to voluntary involvement. At the national level, it remains unclear how policies can be aligned, and the assistance provided is primarily informative, lacking sufficient financial support. The review of the existing barriers has already been done in the paper by (Agrawal, et al., 2023):

Table 5-2 Barriers to implementation of energy efficiency projects in SMEs

Detailed barriers	References
LOW CAPITAL AND DIFFICULTY TO ACCESS FINANCING	
Large capital investment requirement for energy efficiency upgrades and small funds available to SMEs for investments; longer payback period for some of the potential energy saving investment opportunity; difficulties for securing loans from banks.	Catarino et al. (2015); Thiede et al. (2013); Prasad Painuly (2009); Nigohosyan et al. (2021); Viesi et al. (2017); Lee (2015); Meath et al. (2016)
LACK OF HUMAN RESOURCES, KNOWLEDGE and AWARENESS	
The absence of internal knowledge to recognize and execute energy-saving measures, insufficient information regarding (a) energy expenses, (b) the significance and advantages of energy efficiency, and (c) outreach by technology providers to SMEs, presents a notable deficiency.	Fuchs et al. (2020); Rohdin et al. (2007); O'Keeffe et al. (2016); Kostka et al. (2013)

Detailed barriers	References
Small businesses do not have the resources to designate energy management responsibilities to any team member, let alone create a dedicated department or office for this purpose.	Eurochambres (2010); Sorrell et al. (2000); Henriques and Catarino (2016)
A lack of knowledge and awareness prevents SMEs from accessing any available financial schemes that support investments in energy efficiency.	Prashar (2017a); Hrovatin et al. (2021); Trianni et al. (2013); Fresner et al. (2017)
A shortage of time or an excess of other responsibilities among SME employees diminishes the priority placed on energy efficiency.	Paramonova and Thollander (2016); Henriques and Catarino (2016); Rohdin et al. (2007); Johansson (2015)

Source: (Agrawal, et al., 2023)

There was a long-term focus on decarbonisation and there are more policies focused on energy-intensive large industries in comparison to SMEs, particularly micro-enterprises. The number of SMEs (and especially micro-companies) is disproportionate to their energy consumption, which is one of the reasons why they have not yet been a priority for energy transition measures (Reuter, et al., 2021). Therefore, the EU Commission has established or supported multiple networks, projects and programmes assisting SMEs, like Covenant of Companies (including advisory services for companies and intermediaries in energy transition; expertise and support materials; visibility, recognition and incentive schemes; effective monitoring, reporting and verification systems to verify company commitments; analysis of potential synergies between businesses and local authorities) or Enterprise Europe Network (world's largest support network for SMEs). However, even the developed and EC led initiatives have unpredictable or low success, some of them already being abandoned due to the fact the effort introduced, and resources involved did not result with expected outcome.

A significant existing discussion focuses on the correlation between changes in energy expenses and the company's profitability depending on its sector. Such changes can impact a company's expenditure due to the escalation of energy costs. Moreover, new expenses might constrain companies to maintain competitiveness, necessitating cost reductions, increased sales efforts, and/or price adjustments for their products. Holding all other factors constant, increased energy costs could lead to diminished profits for certain companies under specific conditions. If firms have not optimized the equilibrium between changes in revenue and production costs through price adjustments, they might need to explore alternative financing avenues to sustain their operations, such as seeking loans. Research shows that the size of the company affects these consequences, with smaller (and younger) companies being affected more significantly. (Herman, et al., 2023)

The major challenge in the assessment of influence of policies on vulnerable micro-enterprises is that their energy vulnerability is only recently recognized and hence not properly addressed. Research on energy poverty and/or general vulnerability of the business sector to energy, as it is mentioned in the newest EU regulation, is practically non-existent in literature. A review of the literature shows one very working paper from Greece, aiming to evaluate the extent of energy

poverty in SMEs according to research findings. (Vatikiotis, 2021) In this research, the author uses a past survey of small and very small businesses and interviews 19 energy experts in the business sector. The indicator used is the same as for the residential sector, “arrears on paying utility bills “, where around 15% of small companies have such issues. Energy data are collected and sorted in three different consumption groups, self-employed doing dispersed work (can be interpreted as mostly service crafts, for example plumbers), using commercial buildings, but having minor energy consumption (for example, hairdressers) and manufacturing. The analysis is not followed up by any scientific method but does open the question of the major diversity among target groups in sectors, sizes and energy dependence. This also opens a research precondition, constituting the main research questions: *Which indicators should be employed to measure and analyse the energy vulnerability of micro-enterprises?*

5.2. Purpose and objectives of research

Previous research shows that the socioeconomic status of the final consumer significantly affects the success of energy transition measures. It demonstrates that, for example, households in lower income brackets tend to evaluate discount rates subjectively, which significantly impacts measures due to the maturity of their repayment. For example, impoverished households use higher implicit discount rates compared to higher-income households, meaning they prefer investments with shorter repayment periods, estimating the subjective value of the implicit discount rate (IDR) for energy renovation at 45% compared to 26%, as estimated by individuals living in adequate conditions. This implies that low-income households might prefer (or are forced into) short-term solutions over investments, while deep measures in residential sector or small companies’ buildings require long-term investments. (Damigos, et al., 2021)

Additionally, the introduction of certain energy transition measures that have a positive impact on consumers with average socioeconomic status does not have a positive effect on those from other economic classes. Price elasticity of energy demand, which defines the change in the quantity demanded of, in this case, energy, due to a percentage change in the price of the observed product, is extremely difficult to analyse and information is lacking. (Labandeira, et al., 2017) provide data on average elasticities, but average elasticity does not necessarily indicate the success of implemented measures in the targeted group of households. (Charlier & Sondès, 2018) conducted research on citizens considered energy poor, and their results showed heterogeneity in households' response to changes in energy prices. They identified two groups of households that react differently and through group composition analysis demonstrated that some belong to the group of households with the highest price elasticity. These are households with high incomes, even though their share of energy costs is high. In the case of households with a high share of energy costs in their income but without high incomes, their price elasticity is low. They are unable to reduce energy consumption below a minimum comfort level, so some of the price-response policies are of unknown effect in vulnerable consumers.

If decarbonisation does not come from switching fuels (using on-site renewable energy) or enhancing energy efficiency, it must be a result from decreased energy usage. Given that the target demographic is vulnerable and low-income, while some energy savings may arise from behavioural efficiency measures, the majority would likely stem from simply using less energy, even at the expense of comfort, leading to economic and social strain. This could push more low-income households into vulnerability, affecting their ability to pay bills, reducing comfort levels (such as warmth), and ultimately impacting the health and social well-being of the household.

The primary obstacle to structural change (such as upgrading buildings or heating systems for energy efficiency) is the challenge low-income groups face in financing upfront costs without adequate compensation mechanisms in place.

As visible from the analysis, there is a need to research and evaluate the impacts of different energy decarbonization policies on the vulnerable consumers. Therefore, the hypotheses this research will be built upon is the following:

- *Research hypothesis:*

Decarbonisation measures reduce energy vulnerability when implemented under supportive structural conditions and accompanied by appropriately sequenced, data-informed mitigation.

To establish a meaningful evaluation of policy outcomes, it is essential first to undertake a comprehensive and systematic examination of the concept of energy vulnerability of micro-enterprises. The goal is to determine not only the defining characteristics of vulnerability within this group but also the extent to which their vulnerability mirrors or diverges from patterns already extensively documented in the household sector. Given that the vulnerability of households, particularly in the context of energy poverty and decarbonisation transitions, has been the subject of substantial research, resulting in a well-established set of indicators, measurement approaches, and theoretical frameworks, it becomes necessary to adopt a similarly rigorous approach in the case of micro-enterprises. Without first establishing whether comparable dimensions of vulnerability (such as exposure to energy price volatility, limited adaptive capacity, or structural barriers to efficiency upgrades) are present among micro-enterprises, any subsequent evaluation of the outcomes of decarbonisation policies would risk being incomplete.

- *Supporting research question 1:*

How effectively do composite multidimensional indicators identify and measure energy vulnerability among micro-enterprises across countries?

- *Supporting research question 2:*

How do socioeconomic characteristics shape the degree of energy vulnerability observed in micro-enterprises?

5.3. Scientific methods used

- *Design and application of a custom modelling tool for energy policy evaluation*

In this research, a custom static energy economics modelling tool was developed by the student to simulate the effects of policy-induced changes in energy prices, incorporating energy consumption structures and accounting for demand responsiveness. The model applies additional expense layers to baseline energy prices and adjusts energy consumption based on price elasticities, thus capturing consumer responses to price shifts. Consumption is disaggregated by energy carrier and sector, allowing differentiated impacts of price changes to be modelled across varied consumption profiles. When additional costs are applied, the model recalculates final energy demand through predefined price elasticity coefficients, reflecting the expected decrease in energy use in response to price movements. This methodology was developed and tested in two papers.

- *Use of the Compensating Variation as a Measure of Welfare Change (Chipman, 1992)*

The papers also employ Compensating Variation (CV) as the measure of welfare change. CV is the amount of income required to return a consumer to their initial level following a change in prices or policy. This method provides a consistent and theoretically grounded measure of welfare impacts.

- *Micro-simulation for determination of effects on vulnerable micro-enterprises*

To assess the economic impact of decarbonisation policies on vulnerable micro-enterprises, we employ a micro-simulation framework to estimate changes in firm-level profitability arising from increased operating costs induced by regulatory interventions. Profitability under policy implementation is computed by deducting the adjusted cost structure, reflecting additional expenditures such as elevated energy or compliance costs, from baseline revenue. The deviation from pre-policy profit levels serves as a quantitative indicator of the financial burden imposed by the policy. Beyond this direct assessment, we examine the broader effects, including its potential to constrain reinvestment capacity, reduce employment, and undermine long-term business sustainability.

- *Structured expert elicitation for weighting of indicators*

In one paper, a structured expert elicitation method was employed to determine the relative importance of selected indicators of energy vulnerability. Experts were selected based on their professional experience in the field, applying purposive sampling techniques. Through a structured questionnaire, experts evaluated and ranked the relevance of indicators, categorized into four thematic groups. The collected responses were used to assign weights to each indicator, ensuring that the final composite index integrated expert knowledge and context-specific insights. This weighting process constitutes a distinct methodological step.

- *Indicator development and composite index construction*

Following the expert elicitation process, a composite indicator was developed in the paper using a weighted linear ordering method with integrated normalization. Relevant indicators were normalized using a min-max normalization approach. Weighted sums of normalized indicators

were calculated within each thematic group, producing group-level synthetic indicators. These were then aggregated to form a final composite index representing the overall energy vulnerability of micro-enterprises across EU Member States. This composite index construction integrated both statistical processing and expert-derived weightings to ensure validity and relevance.

- *Primary data collection from micro-enterprises*

In two papers, primary data were collected through structured surveys targeting micro-enterprises. The survey gathered detailed information on business characteristics, energy consumption and fuel use patterns, operational challenges, and perceptions of energy-related risks and vulnerabilities. Data collection was conducted systematically to ensure internal consistency and comparability across responses, providing a solid empirical basis for subsequent descriptive, inferential, and regression analyses.

- *Descriptive statistical analysis*

In those papers, initial data analysis was conducted using descriptive statistical methods. This analysis provided an overview of the data structure and identified major patterns necessary for further inferential exploration.

- *Inferential statistical analysis and regression modelling*

Following descriptive analysis, inferential statistical methods were applied to explore relationships between variables. These methods allowed for a robust assessment of potential dependencies between key variables.

5.4. Structure of the dissertation

This doctoral dissertation follows the Scandinavian model and, in addition to the introductory and concluding chapters, comprises five papers. Four papers were published, while one is in the review and editing process by the journal. The introductory chapter presents the research topic and objectives, reviews the relevant literature, and sets out the research questions and hypotheses. The concluding chapter synthesises the main findings of the dissertation, emphasises its key contributions, and outlines directions for future research.

6. COMPOSITE INDEX FOR THE EVALUATION OF ENERGY VULNERABILITY OF MICRO-ENTERPRISES

Authors: Ivana Rogulj, Saša Žiković, Pavle Jakovac

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6.1. Abstract:

The goal of European energy policies is a just and sustainable energy transition. While extensive research has focused on energy transition and efficiency, micro-enterprises, a critical segment of the European economy, remain underexplored. Micro-enterprises account for 93.7% of EU companies and nearly 17% of total EU turnover. They are also a contributing factor to welfare, where entire families rely on the stability of a single micro-enterprise. Due to their size and supply chain positioning, they are disproportionately vulnerable to energy price fluctuations, supply disruptions and regulatory changes. We investigate the energy vulnerability of micro-enterprises in the EU, highlighting their unique challenges in energy transition policies, financial constraints, and market dynamics. A composite vulnerability index (MEVI) is developed, integrating factors like energy dependency, market access and business vulnerabilities, to rank EU Member States based on their micro-enterprise energy vulnerability. The findings suggest variations in vulnerability across countries, influenced by energy market structure, macroeconomic conditions or sector-specific energy needs. The research underscores the necessity for tailored policies and further data collection to better address the energy vulnerability of micro-enterprises, a sector often overlooked in energy policies.

Keywords: *composite index, energy efficiency, energy vulnerability, micro-enterprise*

6.2. Introduction

Given the growing issue of energy availability, security and price, combined with climate change and the resulting inequalities, the European Union through its European Green Deal (EGD), proposed a set of objectives, measures, and mechanisms to promote a just, efficient and competitive transition by 2050. (Schot & Kanger, 2018) Over four decades of research on energy transitions have explored various aspects of it, with a particular emphasis on energy efficiency. Studies have highlighted its micro-level impact on disposable income and productivity, as well as its role in shaping energy consumption patterns through multi-country analyses and

technological advancements. Thoughtfully designed policy interventions and measures have consistently demonstrated a positive contribution to economic welfare. (Saunders et al., 2021) Energy transition and decarbonisation policies change import dependencies and global energy relations. (Yang et al., 2023) This fact became of utter importance during the past years and the threat to supply security caused by the Ukrainian war. Volatile energy prices and unstable sources of imports influence even the non-energy intensive consumers, creating additional burden to public and private funds. (UN Global crisis response group, 2022) Some countries are especially vulnerable to these circumstances, depending on their market structure (the lack of access to energy supply alternatives on infrastructural and market level), real estate ownership (affecting the possibility for interventions in the private-owned buildings), energy import dependences, macroeconomic indicators and the capacity of the social protection system.

Some consumer groups in countries with more vulnerable energy systems are at specific risk of energy price changes and negative impacts of energy policies. These consumer groups were until now mostly viewed as households vulnerable to energy poverty, and particular measures have been designed for them. The new European Social Climate Fund (SCF) and the reference to it in the Commission Recommendation on energy poverty, for the first time, mentions the vulnerability of the micro-enterprises in the same regulation as energy poverty of households, putting small vulnerable consumers together, as a specific target group of the policy.(European Commission, 2023)

Micro-enterprise is defined as an enterprise that employs fewer than 10 persons and whose annual turnover or annual balance sheet does not exceed EUR 2 million, calculated in accordance with Articles 3 to 6 of Annex I to Commission Regulation (EU) No 651/2014 (27)). The importance of micro - enterprise is obvious from the fact most European industries' ecosystems and value chains rely on the work and productivity of micro-enterprises, 93.7% of EU companies are micro-enterprises. (Katsinis et al., 2024) According to the Eurostat Structural Business Statistic, the share of total net turnover of micro-enterprises in Europe is also significant, almost 17% on the EU level. (EUROSTAT, 2015) There are important reasons to keep micro-enterprises strong and stable.

6.2.1. Energy consumption and efficiency of micro-enterprises

In terms of energy consumption and efficiency, micro-enterprises are much more complex and under-researched target group in energy policies than households. The number of SMEs (and especially micro-companies) is disproportionate to their energy consumption, which is one of the reasons why they have not yet been a priority for energy transition measures. This is already a recognised issue by some authors. (Herce et al., 2024) They are also not separately accounted in energy statistics, so it is hard to find datasets for policy development. Given the absence of specific research on the barriers to energy transition, particularly regarding energy efficiency measures in micro-enterprises, it becomes evident that, as a subgroup of SMEs, they face similar

but often more pronounced challenges. These enterprises must navigate numerous competing business priorities, including investments in areas such as internationalisation or digitalization. At the EU level, the lack of concrete quantitative targets and mandatory requirements for SMEs leaves their participation largely voluntary. Meanwhile, at the national level, policy alignment remains unclear, and the support provided is predominantly informational, with insufficient financial backing.(Agrawal et al., 2023), (Directorate-General for Energy (European Commission) et al., 2024)

Research shows that volatility of energy prices can impact a company's expenditures, but also investment decisions. (Weller & Fields, 2011) Moreover, new expenses might constrain companies to maintain competitiveness, necessitating cost reductions, increased sales efforts, and/or price adjustments for their products. Holding all other factors constant, increased energy costs could lead to diminished profits for companies. If firms have not optimized the equilibrium between changes in revenue and production costs through price adjustments, they might need to explore alternative financing avenues to sustain their operations, such as seeking loans. Research shows that the size of the company has influence on these consequences, with smaller (and younger) companies being affected more significantly. (Herman et al., 2023)

The objective of our paper is to develop a comprehensive assessment framework for energy vulnerability specifically tailored to micro-enterprises. By developing a composite vulnerability index (Micro Enterprises Vulnerability Index, MEVI), this research evaluates the risk factors that contribute to energy vulnerability. The index is designed to provide a first step towards evaluation of how energy circumstances influence micro-enterprises' vulnerability The rationalisation of using this specific composite of indicators stems from the need for a comprehensive and standardised method to assess the energy vulnerability of micro-enterprises across very heterogeneous European Union Member States. Micro-enterprises are very diverse, with varying energy consumption, business models and vulnerabilities, making it extremely challenging to apply broad and all-encompassing policies. (Rajagopal, 2021)

The MEVI index tries to answer this challenge by using a methodology that addresses key factors like energy prices, access to energy, financial health and regulations, which impact company's ability to transition to energy-efficient and decarbonized practices. The MEVI index is intended as a macro-level screening tool that maps the national structural conditions influencing the vulnerability of micro-enterprises, rather than as a substitute for micro-level data. This exploratory approach highlights where further, detailed bottom-up research is needed once dedicated micro-enterprise datasets become available. Energy vulnerability varies across countries due to differences in markets, infrastructure, and socio-economic conditions. The index therefore uses normalization and expert weighting to ensure all indicators are comparable, preventing any single factor from dominating the final score and reflecting a balanced view of vulnerability.

With limited data on micro-enterprise energy needs, the MEVI index fills this gap by using available companies' datasets and expert input to assess broader macroeconomic, energy, and regulatory factors affecting vulnerability. Results could also be used for tracking energy vulnerability over time, allowing policymakers to monitor the effectiveness of interventions, as it enables comparison of micro-enterprise vulnerability across EU Member States, helping identify regions at greater risk, but also helping identify specific contributors in each country. The paper begins with a literature review and theoretical foundation *(Sections 1 and 2).* Next, the paper outlines the methodology devised for the research and identifies the corresponding data sources *(Section 3).* This is followed by a presentation of the general findings, including the composite index used to evaluate energy vulnerability *(Section 4).* The results are analysed *(Section 5),* concluding with a discussion and policy implications, key findings, and the need for further research.

6.3. Energy vulnerability of micro-enterprises

The major challenge in the assessment of influence of policies on micro-enterprises' vulnerability is that their energy vulnerability has only recently been recognized and hence not properly defined. Research on energy poverty and/or general vulnerability of the small business sector to energy – related circumstances, is practically non-existent in the literature. There are however some research dealing with energy price changes affecting SMEs. EIB (European Investment Bank, 2025) report highlights that smaller firms face stronger exposure to energy price volatility and greater vulnerability to energy shocks than large companies. An estimate from some non-EU countries is that 20% price change affects SME profit by 4%. (Greve et al., 2023) An affect on industry and households' impacts from price changes is also researched, and micro-enterprises are in between the two with their price responses. (Directorate-General for Energy (European Commission) et al., 2024)

A review of the literature shows a working paper from Greece, aiming to evaluate the extent of energy poverty in SMEs. (Vatikiotis, 2021) The author uses a past survey of small and very small businesses and interviews 19 energy experts in the business sector. The indicator used is the same as for the residential sector, "arrears on paying utility bills ", where around 15% of small companies have such issues. Energy data is collected and sorted in three different consumption groups, self-employed doing dispersed work (can be interpreted as mostly service crafts, e.g. plumbers), using commercial buildings, but having minor energy consumption (e.g. hairdressers) and manufacturing. The analysis is not followed up by method but opens the problem of the major diversity among target groups ranging from their sector, sizes, and energy dependence. It seems that two data issues stand out: sample heterogeneity issue and appropriate measurement instrument i.e. indicator. This leads to a research pre-condition, constituting the question: *Which indicators should be employed to measure and analyse the energy vulnerability of micro-enterprises?*

Previous work on microenterprise surveys highlights severe measurement problems in profits or revenues, including large recall errors and underreporting, which reinforces the argument that comparable micro-level data on energy vulnerability are not realistically available for now. (de Mel et al., 2009) We present the information across European countries based on publicly available datasets of the wider socio-economic and technical trends that influence vulnerability of companies to energy prices change. Although not related to energy, there are other vulnerability frameworks such as the ITC Fragility Exposure Index, that also assess structural exposure through macro-level proxies rather than direct firm-level data, which is a recognised method if micro-enterprise information is scarce or inconsistent. (World Trade Organization, 2025)

The important part of what influences micro-enterprises vulnerability is the infrastructure, access to different networks, energy dependency, market development and energy prices and tariffs. It is visible the prices of gas and electricity have risen around 50% relative to 2019, where there is a noticable reduction in 2020, due to COVID-19 crisis. Prices refer to the lowest consumption bandwidth, so presumably include most of the micro-enterprises.

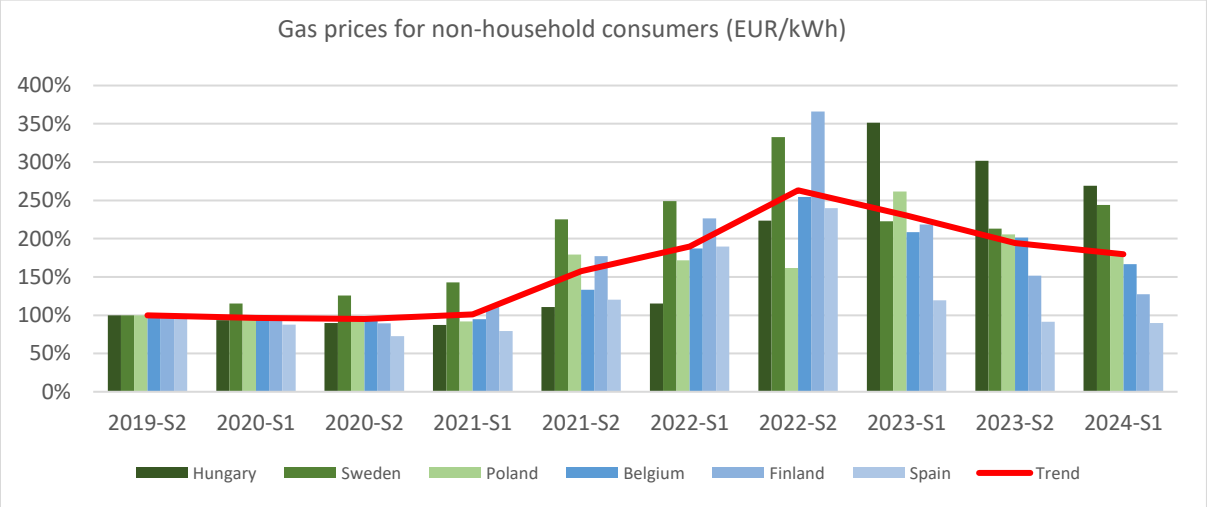


Figure 6-1 Gas prices for non-household consumers (relative to 2019-S2), countries with highest, medium and lowest prices in the EU, source: EUROSTAT, 2019S2-2024S1

Network charges and taxes compose a large part of the final electricity price. This is, as visible from **Pogreška! Izvor reference nije pronađen.**, particularly pronounced in Denmark, Poland and Italy.

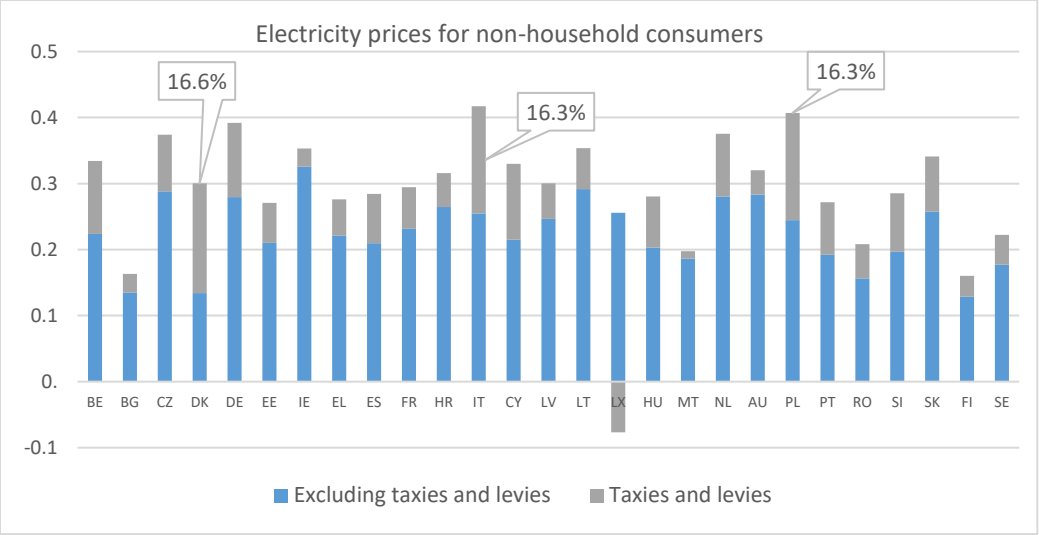


Figure 6-2 Electricity prices for non-household consumers in the EU, Consumption less than 20 MWh - band IA, with and without taxies and levies, EUROSTAT, 2024-S1

The addition of non-tariff (or any other) charges onto electricity prices has been shown as additional burden to the vulnerable consumers. Their demand elasticities are generally lower than those of average consumers, since the basic consumption is still needed to keep the business or household going. Therefore, the expenditure, when compared to the one without additional expenses, remains relatively higher in vulnerable in comparison to average consumers. (Jamissen et al., 2024) The structure of electricity and gas retail markets has also been shown to influence consumer choice, which in theory should bring down prices through supplier switching, and broader possibilities for low-carbon transitions.(Amenta et al., 2022) This of course is not as straightforward as the market theory would assume but could be used as one of the possible indicators, especially in highly dense markets. Import dependency is, along with the macroeconomic indicators, the primary indicator of possible price capping.

When looking more into external indicators contributing energy vulnerability, important aspect is the building sector in the country. Unlike residential buildings, where extensive data is available for evaluating building stock quality, U-values, energy efficiency, and refurbishment, information on commercial buildings is far less accessible. For instance, while the EU Building Stock Observatory offers data on building age and tenancy (ownership versus rental), both of which are relevant to our work, but it completely lacks information on fuel distribution. This gap necessitates additional literature review to address these areas.

Regarding access to finances and assistance from all the governance levels, there are multiple initiatives to assist micro-enterprises, like financial subsides (example grants for energy efficiency measures (BMWi)) or technical assistance, but the common challenge is the accessibility and lack of capacities to efficiently use the provided assistance(Rohdin & Thollander, 2006), (Agrawal et al., 2023).

Further analysis of indicators contributing to energy vulnerability of micro-enterprises is presented in the indicators' explanation section.

6.4. Methodology

Our aim is to develop a composite indicator that effectively reflects the level of vulnerability of micro-enterprises among European Union Member States, and enables their ranking based on selected indicators. We utilize the linear ordering method with expert-determined weighting and integrated normalization. This method is used as it has been proven effective in previous studies on determining energy vulnerability indicators. (Kashour & Jaber, 2024),(OECD et al., 2008), (Kryk & Guzowska, 2023) This approach enables us to rank Member States using a distance-based technique, comparing them by their proximity to an ideal reference point, which represents the "best possible" outcome across multiple indicators. Due to significant differences among indicators, we also use normalization. The choice of normalization method depended on the indicators applied, mainly using min-max normalization, as appropriate.

The data is collected from the sources outlined in the **Pogreška! Izvor reference nije pronađen.** and sorted in four indicator groups. Every variable in the dataset is normalized, based on the interval of a normalized variable given the equations:(Kacprzak, 2024)

$$I_{Nni} = \frac{I_{ni} - min\{I_n\}}{max\{I_n\} - min\{I_n\}}$$

l

$$I_{Nni} = \frac{max\{I_n\} - I_{ni}}{max\{I_n\} - min\{I_n\}}$$

$$I_N \in \lfloor 0,1 \rfloor$$

where I_{Nn1} is the normalised value of I_{n1}, and I_{n1} is the vulnerability indicator (EC1…BA4, as described in **Pogreška! Izvor reference nije pronađen.**) for country *1 (I=1)*. What type of normalisation will be used depends on the influence of the variable of the final vulnerability (positive, negative). In the context of min-max normalization for vulnerability indicators, the terms "positive" and "negative" refer to how specific factors contribute to the overall vulnerability score, based on their relationship with the scale. For example, higher energy prices could lead to greater vulnerability. When these factors are normalized, a higher value corresponds to a score closer to 1, indicating greater vulnerability, therefore, for this example, the normalisation used is the one shown in Equation *(1).*

6.4.1. Setting up the indicators:

The initial step of defining and establishing the relevant indicators involves researching the existing literature and insights from energy consumption and efficiency in micro-enterprises, vulnerability in commercial sector and household energy poverty to identify the most relevant variables indicative for energy vulnerability in micro-enterprises. These variables were categorized into four distinct groups, each detailed in **Pogreška! Izvor reference nije pronađen.**. The variables can be divided into those that have strong statistical datasets collected on yearly basis (like *EUROSTAT*) or more structural approaches to data collection (*like information on availability of financing*).

There are some datasets that were included in the first evaluation of possible indicators but later not used for final evaluation for different reasons. These include *Availability of financing and access to financing options (EF5),* as the results from Survey on the Access to Finance of Enterprises (SAFE) are not representative for this specific group of enterprises. This dataset would be much more relevant to evaluate general EU level or SMEs (not only micro-companies). Additional issues have been found with indicator *Ownership structure (private/public/family-owned – BV5), and Supply chain position (BV6),* which are relevant from the perspective of experts but shows uneven availability of data among EU Member States and scarce additional data sources.

However, it would be ideal that all these indicators could be considered when looking at the specific vulnerability per micro-enterprise.

Table 6-1 Indicators showing energy vulnerability of micro-enterprises, literature references and dataset sources

Indicator	CODE	Dataset description (as described in dedicated metadata website)	Literature references[1]	Dataset & link
External factors related to energy and climate				
Heating, cooling degree days	*EC1*	*Heating degree day (HDD) index is a weather-based technical index designed to describe the need for the heating energy requirements of buildings. Cooling degree day (CDD) index is a weather-based technical index designed to describe the need for the cooling (air-conditioning) requirements of buildings.* *Used dataset for indicator: Heating degree days*	(Sun et al., 2024),(Grigorescu et al., 2024)	EUROSTAT (nrg_chddr2_a)
Energy dependence and energy mix of the region (country)	*EC2*	*The energy balance is the most complete statistical accounting of energy products and their flow in the economy. The energy balance offers a complete view on the energy situation of a country in a compact format, such as on energy consumption of the whole economy and of individual sectors.* *Used dataset for indicator: Import ratio in energy consmuption of all energy carriers*	(Śmiech et al., 2025), (Carfora et al., 2022)	EUROSTAT (nrg_bal_s)
Final energy consumption in buildings and transport	*EC3*	*JRC-IDEES-2021 - Integrated Database of the European Energy System (Energy consumption in the service sector and the number of employees)*	(Li et al., 2021)	JRC IDEES 2021

[1] References confirm why certain indicators have been included in evaluation.

		Used dataset for indicator: energy consumption in toe per employee of micro-enterprises' sectors		
Quality of building environment (energy label of buildings)	*EC4*	*The BSO covers a broad range of energy-related topics and provides data on buildings-related areas: building stock, energy consumption, building elements and technical building systems, of which we use the energy aspects of service buildings.* *Used dataset: : EU BSO: W/m2/K (lower U value= more energy efficiency; less vulnerability; higher U-value = more vulnerability)*	(Fan & Fang, 2023), (Fabbri, 2024), (Aranda et al., 2017)	EU BSO – EU building stock observatory
National energy infrastructure	*EC5*	*Market share of District Heating and Cooling at EU level.* *Used dataset: : accessability of infrastructural networks to small final consumers*	(Bridge et al., 2018),(De Rosa et al., 2022)	Euroheat&Power
Status of regulatory framework for energy efficiency in industry and SMEs	*EC6*	*The European Energy Efficiency Scoreboard assesses the energy efficiency performance of EU Member States across sectors, based on the ODYSSEE-MURE databases. The scores are based on three main criteria for each country: energy efficiency level reached, energy efficiency progress, and the impacts of energy efficiency policies.* *Dataset: EU MORE score for industry and services*	(Drago & Gatto, 2022), (Agrawal et al., 2023)	Odysee-Mure 2023 EU Energy Efficiency scoreboard
External factors related to finances, market and development				
Degree of energy market liberalisation	*EF1*	*The Herfindahl-Hirschman Index (HHI) is a widely used metric for assessing market concentration globally.*	(Pepermans, 2019), (Nolden et	EUROSTAT (nrg_ind_market)

		Used datset for the purpuse: the numbers are percentage of largest retailer and total number of electricity retailers	al., 2022), (Cabeza, n.d.)	
Regional or/and national energy prices	*EF2*	*Dataset: Electricity and gas prices for non-residential consumers in the smallest band*	(Herman et al., 2023), (Tamasiga et al., 2024), (Bajo-Buenestado et al., 2025)	EUROSTAT (nrg_pc)
Economic development of the region	*EF3*	*Dataset: The ratio between more developed, transition and less developed regions in a specific country*	(Jové-LLopis & Trujillo-Baute, 2024), (McDowall et al., 2023)	IJG Categories of NUTS2 regions
Access to energy subsidies or EU level support	*EF4*	*Dataset: % of GDP and relative subsidies for energy vulnerability/employee during last energy crisis*	(Sovacool, 2017)	Buegel reports
Availability of financing and access to financing options	*EF5*	*Access to grants and subsidies, access to bank loans* *Dataset for the indicator: % of positive answers, dataset is vague due to sampling being unbalanced in EU countries*	(Parashar & Jaiswal, 2024)	Survey on the Access to Finance of Enterprises (SAFE)
Quality of transport network	*EF6*	*Dataset: Share of zero emission vehicles registred and share of electrified rail network, 2023*	(Dorantes & Murauskaite-Bull, 2023), (Science & Ijsrset, n.d.)	Statistical pocketbook 2024 - European Commission
Business determinants affecting vulnerability				

Enterprise size	*BV1*	*Dataset for indicator: Number of employees per micro-enterprise in every of the countries (average)*	(Darman & Andini Hilumalo, 2023), (Sánchez-Infante Hernández et al., 2020)	EUROSTAT SBS sbs_sc_ovw
Age of company	*BV2*	*Survival rate of companies (number of births and deaths in a period), a total age of survival*	(Bajo-Buenestado et al., 2025)	EUROSTAT BD bd_size
Annual revenue or turnover	*BV3*	*Net turnover/company in micro-enteprises, means a total net turnover in the group of companies divided by the number of micro-enterprises*	(Agrawal et al., 2023)	EUROSTAT SBS sbs_part_bscl
Location (urban/rural)	*BV4*	*Alignement of employment in the rural and urban area of the country (more aligned – lower vulnerability)*	(Jové-LLopis & Trujillo-Baute, 2024), (McDowall et al., 2023)	EUROSTAT lfst_r_ergau
Ownership structure (private/public/family-owned)	*BV5*	*The datasets on family – ownership and are scarce, and cover only part of the Member States. This trait will remain relevant for the evaluation of the vulnerability of a specific business.* *The sectoral evaluation of the position in the supply chain is overly complex for this analysis and will remain as useful for the per-company information.*		
Position in the supply chain	*BV6*			
Business determinants affecting adaptation				
Business confidence (expectations of growth)	*BA1*	*The EES Indexes are computed as the percentage of "Increase" minus the percentage of "Decrease", all divided by the percentage of "Constant". A positive/negative EES*	(Khan & Upadhayaya, 2020)	EUROCHAMBERS economic survey 2024

		Index implies that participants expect the trend to increase/decrease in comparison to the current year. *Data is missing for 4 MS included, and the approximation is used in those 4 cases.*		
Dwelling ownership	*BA2*	*Represents the possibility to switch fuel and invest in energy efficiency.* *Dataset: Ratio between owners and tenants in the service buildings in the countries, showing less vulnerability in countries where companies own their permises.*	(McAllister & Nase, 2023)	EU BSO – EU building stock observatory
Digitalisation of the company	*BA3*	*Digital Intensity, means a dataset on the number of enterprises with very low DI (%) (it cannot be done by size class as there is data inconsistency for micro-enterprises)*	(Chen et al., 2024), (Bastida et al., 2019)	EUROSTAT (isoc_e_dii)
Age and education of the owner(s) and employees	*BA4*	*General educational levels are used due to lack of statics for the micro-enterprises owners and employees. This dataset has to be further investigated since it does not perfectly represent micro-enterprises, but is not insignificant.*	(Le et al., 2024)	EUROSTAT (edat_lfs_9903) and EUROSTAT (lfsi_emp_a)

6.4.2. Importance of indicators defined trough weighting methodology

Weighing indicators of energy vulnerability using expert opinions involves a structured process of collecting and synthesizing insights from experienced professionals to determine the relative importance of each indicator. This approach ensures that the weighting reflects informed, context-specific perspectives and leverages the expertise of individuals well-experiences in either energy vulnerability or SME energy policies' issues. The expert consultation in this study is used solely to complement the available structural data and to inform indicator weighting, and it is not intended to substitute for future bottom-up empirical evidence.

Description of the expert' group included in the analysis

35 experts were included in the analysis, from 14 European countries, with the largest representation from Germany (6 experts), followed by Belgium and Croatia (4 each), and Bulgaria, Italy, and Netherlands (3 each). Other experts are from Poland, Austria, Greece, France, Portugal, UK, Hungary and Spain.

The experts are chosen using purposive sampling, due to their knowledge, practical or policy work in the area of energy poverty or SMEs energy efficiency.(Czernek-Marszałek & McCabe, 2024) Researchers included are the most cited energy-poverty researchers in Europe. NGO representatives are those with long-term experience with the target groups of vulnerable consumers. Associations included are EU – level representatives of consumer groups (mainly SMEs). The expert group represents leading specialists in energy poverty and SME vulnerability, yet we emphasise that detailed surveys, case studies, and direct micro-enterprise data will be essential in subsequent research. Initially, 40 experts have been invited based on these criteria. Out of the contacted experts, 35 have responded positively and filled the survey. To reduce the subjectivity inherent in expert-based weighting, we compared the expert-weighted MEVI results with an unweighted version and found the overall ranking patterns to be highly consistent. In addition, tests showed no significant differences across expert backgrounds, and this aligns the approach with established practices in composite indicator design.

General information about the experts is provided in the tables and graphs below.

Table 6-2 Experts' employment background, Source: Authors based on EU survey results

Experts employment background	
Research and/or educational institution (university, think tank, research institute)	18

Government or public body (ministry, energy agency, funding or support institution)	4
Independent professional (freelancer or consultant)	3
Non-profit organization (civil society organization, trade union, non-company association)	3
Private sector organization – small or medium enterprise (SME)	3
Private sector organization – large enterprise	2
Other	2

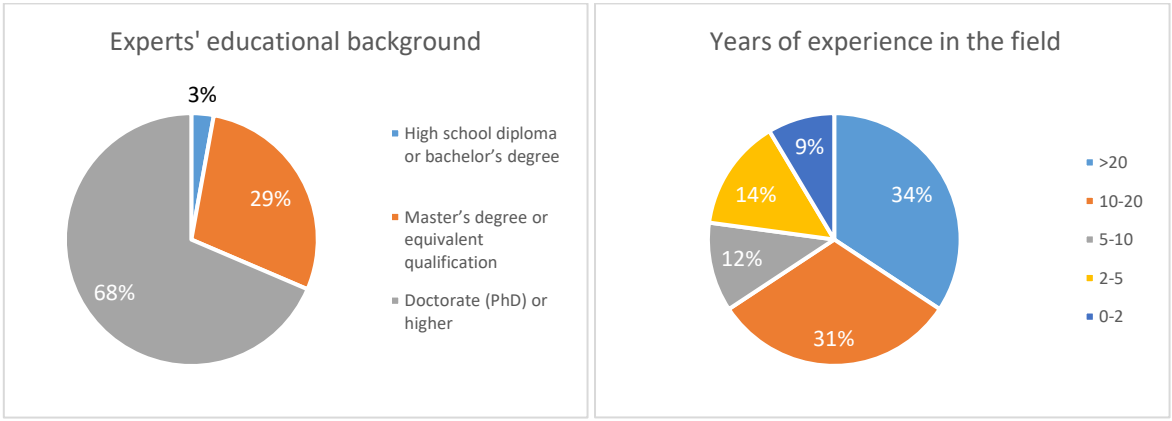


Figure 6-3 Experts educational background and experience, source: EU-survey, interpretation by authors

Experts were asked to self-evaluate their knowledge on the topics, the average familiarity of experts on the topic has already been calculated by converting the columns to numeric values and computing the mean.

- *Energy vulnerability, energy poverty, and related frameworks:* ***7.69***
- *Barriers and drivers of energy efficiency in SMEs/microenterprises:* ***6.23***

Ranking of the indicators based on cumulative score of experts' opinions

By assigning numbers to ranking, the weighting has been established for all the included groups of indicators.

Table 6-3 Experts' weighting of indicators by group

External factors related to energy and climate		Weight (%)

Energy dependence and energy mix of the region (country)	EC2	22
Final energy consumption in buildings and transport	EC3	18
Quality of building environment (energy label of buildings)	EC4	17
National energy infrastructure	EC5	16
Status of regulatory framework for energy efficiency in SMEs	EC6	14
Heating, cooling degree days	EC1	13
External factors related to finances, market and development		
Availability of financing and access to financing options	EF5	22
Regional or/and national energy prices	EF2	21
Access to energy subsidies or EU level support *(not used in MEVI)*	EF4	19
Economic development of the region	EF3	15
Degree of energy market liberalization	EF1	14
Quality of transport network	EF6	9
Business determinants affecting vulnerability		
Annual revenue or turnover	BV3	20
Location (urban/rural)	BV4	18
Enterprise size (number of employees)	BV1	18
Position in the supply chain *(not used in MEVI)*	BV6	17
Ownership structure (private/public/family-owned) *(not used in MEVI)*	BV5	16
Age of company	BV2	11
Business determinants affecting adaptation		
Dwelling ownership	BA2	28

Business confidence (expectations of growth)	BA1	26
Age and education of the owner(s) and employees	BA4	24
Digitalisation of the company (purchase of software)	BA3	22

Statistical analysis of the responses using H test, shows that expertise level does not significantly influence how experts rate the relevance of different business traits for energy vulnerability. There also seems to be consensus among different expert groups about the importance of factors in evaluating energy vulnerability in microenterprises.

Further on, a weighted sum of normalized values is calculated for every of the indicator groups *g* (EC, EF, BV, BA), and the joint normalised synthetised indicator.

$$S_{Igi} = \sum_{n=1}^{6} I_{Nngi} \times w_{ngi}$$

2

where S refers to the synthetised indicator per group (EC, EF, BV, BA) of normalised indicators, using assigned weighting by experts. From the four group synthetised indicators, we calculate the final result of the method. We name the "Composite index for the evaluation of energy vulnerability of micro-enterprises (MEVI)":

$$MEVI = \sum_{g=1}^{4} S_{NIgi}$$

3

MEVI can indicate which countries may be more susceptible to energy vulnerability in micro-enterprises and highlight the specific issues contributing to this vulnerability.

6.5. Results

In this chapter, we present the results of the calculations of the experimental values, along with the explanation of contributions of different groups of indicators.

The data gathering process involved, as shown previously, a wide range of both external and internal factors that could influence the energy vulnerability of microenterprises. External factors include macroeconomic data, energy prices, weather conditions, national energy policies, and infrastructure details e.g. energy access. Additionally, we use data on energy market trends and energy consumption patterns at the national level. With regards to internal factors we focus on microenterprise-specific characteristics such as financial health and business size. Data comes from various sources, but predominately from official

statistics. By analysing the broad array of data, we are able to assess the multifaceted nature of energy vulnerability across different micro- enterprises in different Member States.

The correlation between the groups of indicators has been examined to find out if two indicator groups show the same results. If such redundancy is found, it suggests that both indicators may be capturing the same underlying aspect of energy vulnerability, making one of them unnecessary for the analysis.

Table 6-4 Correlation between the groups of indictors, using R+

	EC	EF	BV	BA
EC	1	-0.43	-0.58	-0.17
EF	-0.43	1	0.50	0.49
BV	-0.58	0.50	1	0.34
BA	-0.17	0.49	0.34	1

There is a moderate negative correlation between EC (External factors related to energy and climate) and BV (Business determinants affecting vulnerability), but not significant in interpretation and more linked to the fact that the northern countries are less financially vulnerable. Other connections are moderate or weak- moderate, but none of them signalling that any of the indicators should be dismissed. This is also tested with developmental indicators and there is no statistically significant correlation between EF, BV, BA indicators and GDP or purchasing power parity of the country. This approach can be considered as a suitable initial step in assessing vulnerability conditions. However, with further research at the micro-enterprise level, the specific contribution of each indicator to the outcomes of energy vulnerability will become much clearer. Each group contains certain correlating indicators. For example, in the external indicators related to energy and climate (EC), higher heating/cooling degree days are correlated with higher final energy consumption (0.70), and a better energy mix is linked to a stronger national energy infrastructure (0.74), among other relationships. Interpretatively, these are expected correlations. The challenges posed by correlations within the indicator groups are partially addressed through expert weighting.

The countries differ in a way that certain aspects of vulnerability influence the results. Some countries are energy- intensive, like Luxemburg or have inefficient buildings like Belgium, or are in cold areas of Europe, leading to strong effect of consumption- related vulnerability.

In Hungary, Croatia, Slovakia, Lativa and Poland, the effects of market and external factors related to financies are strongly influencing the final result of the index. Vulnerability due to business circumstances is strongly affecting Bulgaria and Romania, among other countries with a bit smaller effect. Internal risks are pronounced in Slovenia; other countries are much more aligned in this aspect. This result is highly affected by the business pessimism (indicator BA1: Business confidence (expectations of growth)), coming from the survey conducted by EUROCHAMBER.

To show more clearly these aspects in the different countries, we choose the three exemplary countries with different contributors towards total MEVI indicator: Belgium, Bulgaria and Croatia:

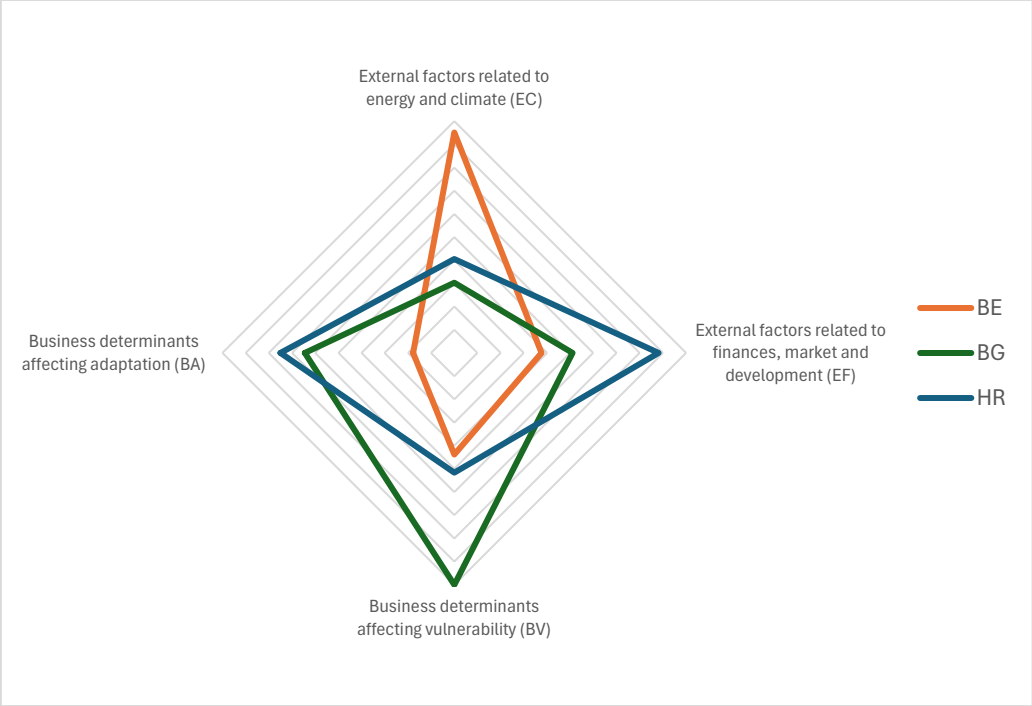


Figure 6-4 Contribution of different indicators to total MEVI (BE, BG, HR), authors

It is clear from this example, that the reasons why micro-companies in Belgium might be vulnerable is more linked to energy and climate, in Bulgaria to business vulnerabilities, while in Croatia it is a combination of business adapation and financial and energy market effects. Which effects exactly, is shown in the example of the compilation of graphs for the three countries:



Figure 6-5Every group of MEVI indicator - contribution for the three chosen countries, authors

A normalised combination of effects results with the MEVI indicator showing vulnerabilities based on all four groups.

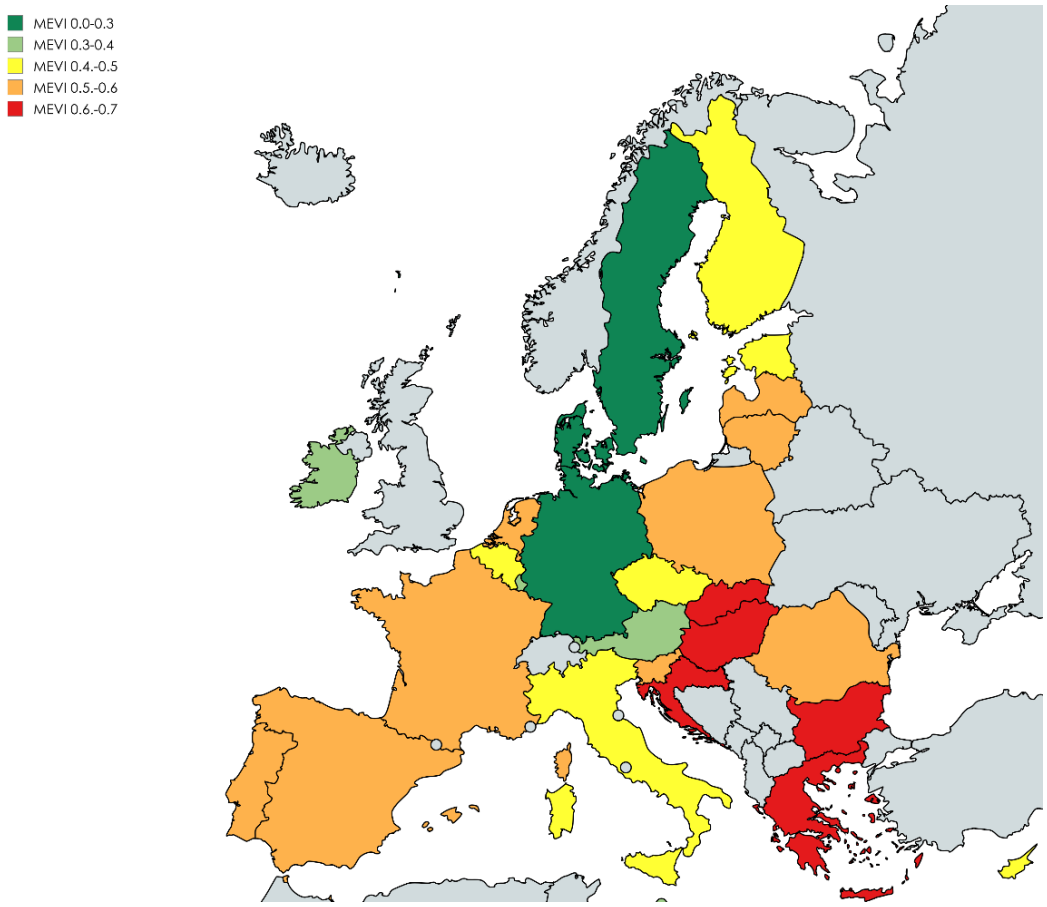


Figure 6-6 Calculated MEVI index for EU Member States, authors with MapCharts

The interpretation of the graph is that the vulnerability of micro-enterprises of a certain Member State is higher with higher MEVI, showing Hungarian and Slovakian companies probably most vulnerable when using selected indicators, followed by Croatia, Bulgaria and Greece. This is clear from the distribution of indicator – groups contribution in the Table 6-5.

Table 6-5 Contribution of normalized indicators to MEVI, Source: authors' calculation

Normalised weighted indicators sum	External factors related to energy and	External factors related to finances, market and development (EF)	Business determinants affecting vulnerability (BV)	Business determinants affecting adaptation (BA)	**Composite index-MEVI**

	climate (EC)				
Member State	EC	EF	BV	BA	
AT	0.59	0.00	0.59	0.41	**0.40**
BE	0.95	0.38	0.44	0.18	**0.49**
BG	0.30	0.51	1.00	0.64	**0.61**
HR	0.41	0.88	0.52	0.75	**0.64**
CY	0.49	0.73	0.46	0.30	**0.49**
CZ	0.30	0.64	0.56	0.47	**0.49**
DK	0.00	0.38	0.30	0.17	**0.21**
EE	0.24	0.54	0.48	0.48	**0.43**
FI	0.63	0.40	0.54	0.33	**0.48**
FR	0.50	0.56	0.41	0.63	**0.52**
DE	0.52	0.12	0.27	0.15	**0.27**
EL	0.66	0.72	0.38	0.78	**0.64**
HU	0.46	1.00	0.68	0.67	**0.70**
IE	0.76	0.39	0.03	0.15	**0.33**
IT	0.72	0.26	0.24	0.69	**0.48**
LV	0.27	0.79	0.52	0.63	**0.55**
LT	0.25	0.58	0.85	0.67	**0.59**
LU	1.00	0.06	0.00	0.39	**0.36**
MT	0.38	0.38	0.35	0.42	**0.38**
NL	0.54	0.39	0.49	0.65	**0.52**
PL	0.09	0.77	0.67	0.51	**0.51**
PT	0.48	0.74	0.53	0.48	**0.56**
RO	0.02	0.67	0.99	0.38	**0.52**
SK	0.35	0.84	0.87	0.80	**0.72**

SI	0.20	0.51	0.43	1.00	**0.54**
ES	0.70	0.42	0.39	0.50	**0.50**
SE	0.37	0.27	0.46	0.00	**0.27**

6.6. Discussion, conclusion and implications

Due to lack of specifically collected data, we used the available literature to find out what could be the indicators showing the levels of vulnerability of micro-enterprises per country. We follow the two assumptions, first one is on what is the indication of energy poverty of households, due to similarity of very small businesses to households. The second is the traits affecting the vulnerability of small enterprises, larger group than micro-businesses with overlapping issues. With the confirmation from experts, and the weighting from their side, statistical data available give us the ex-ante indication of what countries might face bigger issues related to micro-enterprise vulnerability. The dataset used are consistent across countries and in time, usually providing rather recent datasets, not affected anymore by the dramatic changes during COVID19 crisis. All the aspects of vulnerability are covered with indicators (affordability, accessibility, efficiency, market). The dataset does not rely still on the specific information linked to the micro-enterprise energy due to unavailability of such statistics.

The index provides the first systematic, EU-wide assessment of the structural conditions that shape the energy vulnerability of micro-enterprises. The results show clear differences across Member States and demonstrate that vulnerability is not uniform but driven by distinct combinations of factors. Countries such as Hungary and Slovakia score highest on MEVI due to the combined influence of financial market pressures and limited adaptive capacity, while Bulgaria and Romania are characterised primarily by strong business-related vulnerabilities. In contrast, Belgium, Luxembourg and several Western European countries exhibit higher exposure linked to energy- and climate-related factors, including inefficient building stock and higher energy consumption needs. These patterns confirm that micro-enterprise vulnerability emerges from the interaction of national energy systems, economic conditions, and business characteristics rather than from a single determinant.

The decomposition of the index into four indicator groups further highlights how different drivers dominate in different national contexts. For example, business adaptation indicators contribute significantly to vulnerability in Croatia and Slovenia, while financial and market-related indicators are most influential in Central and Eastern Europe. Northern countries, where building quality is higher and energy infrastructure more robust, generally exhibit

lower levels of structural vulnerability. This differentiation illustrates that micro-enterprises face diverse challenges depending on their local context and that no uniform policy response can be effective across the EU.

Overall, the MEVI results provide an evidence-based starting point for identifying where micro-enterprises are most structurally exposed and which factors deserve priority in national and EU policymaking. The analysis also underscores the substantial data gaps that currently prevent a more granular understanding of micro-enterprise energy use and resilience. As a first step, the index clarifies the structural landscape, but future research must integrate bottom-up data collection, surveys, and case studies to capture the lived experience of micro-enterprises and to validate these macro-level patterns.

Micro-enterprises are, due to their undoubted heterogeneity and complexity, often omitted in policy developments and programs related to energy efficiency or energy vulnerability. There are several reasons for this, many of which have already been discussed in the literature. (Trianni & Cagno, 2012) However, one of the primary factors is the complete absence of available datasets. Collecting statistically relevant data for micro-enterprises, for energy related purposes, is a truly complex task. Energy needs vary at the NACE class level (level 4), a classification for which none of the datasets are available. The premises and facilities used by micro-enterprises often overlap partially or entirely with those of the household, especially in family businesses. (Niehm et al., 2009) When they don't, it is frequently unclear which aspects of the work are conducted at the premises, and which are done elsewhere. Vehicle ownership and usage statistics are also unreliable, as they are not exclusively related to business activities. But this also leads to the conclusion household and transport poverty data might be influenced with the consumption of micro-businesses. Micro-enterprises occupy a space between households and companies and might be statistically assigned to either.

6.6.1. Future research

This research focused on how familiar information and available datasets can aid in assessing the potential energy vulnerabilities of micro-enterprises across Member States. Policies focusing on energy efficiency, energy poverty, and the energy transition typically either do not target micro-enterprises or treat them as part of the broader category of small and medium-sized enterprises (SMEs). This oversight occurs because micro-enterprises don't easily fit into any clearly defined statistical category. The main takeaway from this analysis is the need for a closer examination of how the specific characteristics can influence current policies. However, it does not provide an evaluation of the vulnerability of individual micro-enterprise.

To start such evaluations, we have already included in the survey of experts some denominators we found common in the vulnerability of micro-enterprises and households. The comprehensive analysis of the prioritization data from the survey reveals that "*Energy costs as a percentage of revenue (high share of energy expenditure in revenue)*" is the most critical factor in identifying a company as vulnerable. (Al Kez et al., 2024), (Campagna et al., 2024) This significant score highlights that experts consistently prioritise the burden of energy costs, particularly their impact on business revenue. The considerable gap between this factor and the second-ranked one emphasizes its importance in the assessment. The next level of concern is related to "*Companies facing issues with utility bills*," (Neacsa et al., 2020) indicating that while this is a notable challenge, it is considered less urgent than the energy cost-to-revenue ratio. Following this, "*Energy expenditure in comparison to median energy expenditure by sector*" ranks third. (Deller, 2018) The least emphasized factor is "*Dependence of households of owners and employees on micro-enterprise health*," (Lateh et al., 2017) suggesting that although social impacts are acknowledged, they are seen as less important to evaluate vulnerability, than the immediate financial and operational energy challenges. In the comment section, experts mentioned important aspects of micro-enterprises' vulnerability that were not targeted earlier, like internal capacities and administrative strenght. This alignes with the literature that finds internal capacities missalingement with expected administrative burdens as one of the major barrier for higher energy efficiency of micro-enterprises.(Agrawal et al., 2023)

7. DETERMINANTS OF ENERGY VULNERABILITY IN MICRO-ENTERPRISES

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7.1. Abstract

Micro-enterprises are vital to the European economy, including in Croatia, where they make over 88% of the total number of businesses. Despite their significance, they face substantial energy vulnerability due to factors like small size, limited financial resources, and high energy costs. This paper investigates the determinants of energy vulnerability among Croatian micro-enterprises, employing a survey of 470 micro-enterprises. Key findings reveal that enterprises with higher energy expenditures relative to revenue are most susceptible to energy vulnerability, which is aligned with our assumption. On the other hand, businesses that own their premises, have more employees, and have been operational longer are more likely to invest in energy efficiency measures, thereby reducing vulnerability. Notably, a significant pro-portion of micro-enterprises report that energy costs adversely affect their household finances, highlighting the nature of business and personal economic stability. The paper underscores the need for targeted policies and support mechanisms to enhance the energy- related resilience of micro-enterprises, considering their unique structural and financial constraints.

Keywords: Determinants, energy vulnerability, micro-enterprise, survey

7.2. Introduction

Micro-enterprises are a crucial part of economies worldwide, especially in Europe, where they play a significant role in fostering economic growth and creating employment opportunities. (Eggers, 2020) Eurostat's Structural Business Statistic shows that micro-enterprises make a substantial contribution to Europe's economy, generating nearly 17% of the EU's total net turnover. Within the broader SME sector, they are responsible for 29.8% of total employment. (Katsinis et al., 2024) When examining energy consumption, defining an average for micro-enterprises is virtually impossible due to the significant variation based on sector and business activity. Even at the broader SME level, most countries lack

dedicated datasets, and European energy statistics do not differentiate by company size. As a result, research findings vary widely depending on the methodologies used and the EU countries included in the sample. Estimates range from 9% to 18% of total gross inland consumption (GIC), with some outliers reporting figures as high as nearly 30%. (Herce et al. 2024) Obviously, among other factors, their stability is strongly influenced by energy-related aspects, particularly the impact of energy vulnerability. (Weller, Fields, 2011)

Energy vulnerability of micro-enterprises refers to the challenges and risks these small businesses face in terms of their access to affordable, reliable, and sustainable energy. This vulnerability can result from a variety of factors, including a mix of external influences and internal determinants. We have been exploring factors looking into available statistical datasets in our research, like external factors related to energy and climate; external factors related to finances, market and development; business determinants affecting vulnerability and those affecting adaptation, forming a composite index.

In this research, we aimed to identify specific determinants that contribute to the energy vulnerability of micro-enterprises. We analysed independent factors such as lo-cation, business position, sector size, company age, and energy characteristics, informed by existing literature and expert prioritization of vulnerability indicators. Previous findings show that energy costs as a percentage of revenue and higher energy expenditures compared to sector peers might be the most critical determinants of energy vulnerability in micro-enterprises. With further insights, we developed dependent determinants – identifiers of energy vulnerability in micro-enterprises. We utilised these insights to design a survey for micro-enterprises and received 503 (470 eligible) responses from various businesses across Croatia, collected through an EU-survey tool, distributed with the help of the national stakeholders.

The first section presents a conceptual framework with the literature review on the common characteristics of micro-enterprises that contribute to their energy vulnerability. This is followed by an introduction to the research concept and a description of the methodology used. The Results section provides the information on the statistically significant determinants of vulnerability. The paper concludes with a discussion that interprets the results, provides policy recommendations, and outlines potential ideas for future research.

7.3. Conceptual framework

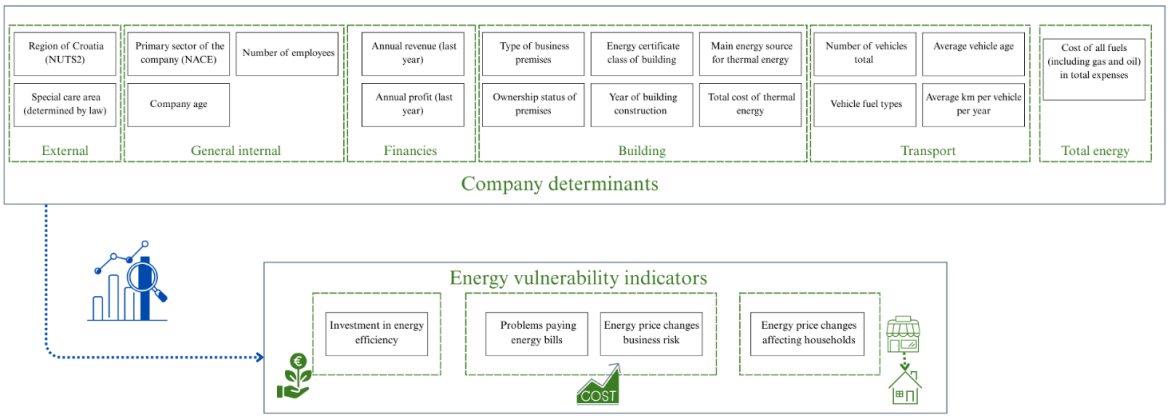


Figure 7-1 Presentation of the research concept, authors with Canva tool

A micro-enterprise is defined as a business employing fewer than 10 people and having an annual turnover or balance sheet not exceeding EUR 2 million, in accordance with Articles 3 to 6 of Annex I of Commission Regulation (EU) No 651/2014. (EUROSTAT, 2025) A key challenge in assessing the impact of policies on vulnerable micro-enterprises is that their energy vulnerability has only recently been acknowledged and is not yet clearly defined. Research on energy poverty and the broader vulnerability of the small business sector to energy, is virtually absent from the literature, no matter this recognition in the EU legislation.(European Parliament, 2023) Some empirical analyses focused on examining the level of involvement of micro and small enterprises in the energy transition and the impact this has on their market and financial performance.(Agrawal et. al, 2023) They found a clear link between the characteristics of micro and small enterprises and the energy efficiency measures they adopt. Therefore, we build our research on our previous findings, expert inputs and literature on energy poverty of households and energy-related challenges in SMEs. To identify indicators describing vulnerable micro-enterprise, we examined various potential factors such as location, sector size, company age, and energy characteristics, drawing insights from existing literature. The analysis also relies on the experts' prioritization of vulnerability indicators, which highlighted that Energy costs as a percentage of revenue (indicating a high share of energy expenditure relative to total revenue) is the most critical determinant of energy vulnerable micro-enterprises, followed by Higher energy expenditures com-pared to sector peers.

7.3.1. Independent variables of energy vulnerability in micro-enterprises

Location of the micro-enterprise

The location of the micro-enterprise affects multiple aspects of energy vulnerability:

- Heating, cooling degree days

Important social aspects of energy are accessibility, affordability and efficiency. (Singh, Ru, 2022) Affordability depends on the energy needs and price. There is a linear relationship between heating energy needs and heating degree-days. (Sun et al., 2024) A building's energy performance is influenced by the climate conditions, and to assess a building's energy performance and correlate energy demand with the climate context, it is essential to have access to weather data and the accurate HDD. (D'Amico et al., 2024)

- Energy dependence, transport network and infrastructure

Energy dependence can increase a region's vulnerability across multiple domains, the more dependent a region is on external or non-renewable energy sources, the more it faces risks from supply disruptions and price volatility. (Guarascio et al., 2025) However, this aspect is hard to use for specific purpose, due to the fact that the prices and imports are regulated on the national level. On the other hand, regions that rely on outdated or inefficient energy infrastructure (e.g., older coal-fired power plants, aging grids) may be more prone to energy disruptions and inefficiencies, influencing stable supply needed for business operations. (Cantoni, Brisbois, 2024) Transportation is more straightforward on a smaller scale, as it not only makes individuals vulnerable but also impacts micro-enterprises by limiting their access to es-essential services needed for business operations. (EPAH, 2025)

- Economic development

The economic development of a region can both increase and decrease its energy vulnerability. While development may increase energy demand and reliance on external sources, it can also provide the resources and technology needed to diversify energy sources, improve energy infrastructure, and invest in energy efficiency. It also ensures higher financial capacity of the individuals and micro-companies as adaptation factors for risks of energy related disruptions. However, in the case of significantly underdeveloped regions, there is undeniably higher risk for energy-related vulnerabilities. (Vrontisi et al., 2024; Jové-Llopis and Trujillo-Baute, 2024; McDowall et al., 2023)

In conclusion, the location of a micro-enterprise plays a critical role in determining its energy vulnerability through various interconnected factors.

<u>Company sector</u>

- Consumption per sector

Energy consumption intensity differs significantly across economic sectors, influencing the vulnerability of micro-enterprises. Enterprises in manufacturing, construction, and transport consume substantially more energy due to process-driven operations and heavy reliance on fossil fuel-based logistics or machinery. For example, textile micro-enterprises

often report energy expenditures exceeding 10% of their operating costs and food-processing industries display distinct energy consumption patterns, with in-dividual sectors exhibiting significant variations during production processes. Conversely, sectors like professional services and information technology tend to have lower energy consumption profiles. This variation underscores the importance of sector-specific strategies when addressing energy efficiency and vulnerability in micro-enterprises. (Corigliano and Algieri, 2024)

- Sectoral position in the supply chain

The position of a micro-enterprise within the supply chain can influence its exposure to energy-related risks. Enterprises operating upstream, such as raw material suppliers, may face different energy challenges compared to those downstream, like retailers or service providers. For instance, upstream enterprises might be more affected by fluctuations in energy prices due to their reliance on energy-intensive production processes, while downstream enterprises could be more sensitive to disruptions in energy supply that affect their ability to meet customer demands. Understanding these dynamics is crucial for developing targeted interventions to enhance energy resilience across the supply chain. Studies emphasise the need for multi-level supply chain management strategies to support micro and small enterprises in achieving sustainability. (Silva et al., 2021)

- Company size (number of employees)

The age and size of a micro-enterprise are critical factors influencing its energy vulnerability. Younger enterprises may lack the financial resources and experience to invest in energy-efficient technologies, making them more susceptible to energy price volatility. Similarly, smaller enterprises, often characterized by limited staff and capital, may find it challenging to implement energy-saving measures or negotiate favourable energy contracts. These constraints can exacerbate their exposure to energy-related risks, highlighting the need for supportive policies that facilitate access to energy efficiency resources for newer and smaller micro-enterprises. Research indicates that enhancing energy resilience in manufacturing enterprises is vital for operational stability, especially for smaller firms. (Lebepe, Mathaba, 2025)

Understanding the average number of employees in micro-enterprises across European countries provides essential insights into structural business dynamics, human resource limitations, and firm-level resilience. Micro-enterprises, defined by the Euro-pean Commission as those employing fewer than ten individuals, constitute the vast majority of enterprises in Europe (particularly in Southern economies such as Spain and Croatia), and their internal human capital configuration plays a pivotal role in shaping their economic viability, energy management capacity, and capacity to absorb exogenous shocks. The

average number of employees in micro-enterprises varies across countries, reflecting differences in economic structures and business practices. For example, in the European Union, micro and small enterprises employed approximately 77.5 million people in 2022, accounting for nearly half (48%) of the total employment in enterprises. (Margaritis, Psillaki, 2021)

In Spain, micro-enterprises constitute 94.4% of all firms, with the vast majority employing between 1 to 2 workers. (Sánchez-Infante Hernández et al., 2020) highlight that the average firm size for Spanish MSMEs leans heavily toward the micro category, often operating with minimal staff, which limits their ability to implement strategic measures such as energy management systems, sustainability frameworks, or Corporate Social Responsibility (CSR) programmes.

A similar structural profile exists in Croatia, where Financial Agency (FINA) data show that the average number of employees per micro-enterprise is 1.98. These firms, often sole proprietorships or family-run businesses, operate with severely constrained administrative and technical capacity, thereby facing inherent barriers to participation in formal sustainability schemes or accessing energy transition financing instruments.

The scholarly literature further confirms that the limited size of micro-enterprises is not merely a descriptive statistic but a critical determinant of firm behaviour and strategic performance. Firm size significantly moderates the relationship between CSR implementation and economic performance: enterprises with more employees demonstrate higher adoption rates of structured sustainability practices and perform better across economic indicators. Conversely, smaller micro-enterprises exhibit "silent social responsibility" practices that, while morally aligned with CSR principles, remain undocumented and non-strategic due to resource and reporting constraints.

- Survival rate of companies (age)

The average lifespan of micro-enterprises offers additional perspective on their stability and resilience. Enterprises with longer operational histories may have established customer bases and more robust financial structures, potentially enabling them to better absorb energy cost increases. In contrast, newer enterprises might lack such buffers, making them more susceptible to energy-related disruptions. Therefore, strategies aimed at enhancing energy resilience should consider the age distribution of micro-enterprises to ensure that support mechanisms are appropriately targeted.

<u>Turnover and profit of a company</u>

- Total / compared to peers

Turnover and profit are fundamental indicators of a micro-enterprise's financial health, directly influencing its capacity to manage operational costs, absorb external shocks, and invest in strategic areas such as energy efficiency. These metrics reflect not only the enterprise's current financial performance but also its resilience and adaptive capacity relative to its sectoral peers.

A commonly used indicator in this context is net turnover per company, calculated by dividing the total net turnover of a group of micro-enterprises by the number of firms in that group. This average value provides a useful benchmark for comparing financial performance across regions and sectors. A lower net turnover per micro-enterprise typically reflects limited income-generation capacity and may suggest higher exposure to energy-related costs due to constrained investment capabilities.

Recent evidence from both institutional reports and academic literature underscores growing pressures on SMEs, including micro-enterprises, in the post-pandemic and en-ergy crisis context. According to the European Central Bank's Survey on the Access to Finance of Enterprises, euro area firms have reported deteriorating profitability and muted turnover growth.(ECB, 2025) While only a minority of firms experienced an increase in turnover, a significantly larger share signalled declining profits amid mounting cost pressures, including those linked to energy, wages, and raw materials.

The SMEunited Barometer for the first half of 2025 corroborates these trends. It reveals that SMEs across Europe are operating in a challenging macroeconomic environment, marked by inflationary pressures and weakened demand. As a result, many firms, particularly micro-enterprises with limited financial buffers, reported reduced profitability and increasing difficulty in maintaining stable turnover levels. This situation has further constrained their capacity to reinvest in productivity-enhancing areas, including decarbonisation and energy efficiency upgrades. (SME United, 2025)

Academic literature reinforces these insights by showing a clear relationship be-tween energy prices and firm-level profitability. A recent study examined the impact of rising electricity prices on business margins across the European Union and found that sustained increases in energy costs significantly erode profit margins, particularly for smaller firms with less capacity to hedge against price volatility or invest in alternative energy solutions. (Herman et al., 2023) The authors also observed that sectors with high energy intensity, such as manufacturing, construction, and transport - face more acute profitability risks.

Similarly, the OECD's 2023 report on SME policy responses to the energy crisis identifies profitability deterioration as one of the most immediate consequences of the energy price spike triggered by geopolitical instability. (OECD, 2023) The report warns that without targeted policy support and affordable financing instruments, many SMEs may struggle to

maintain financial stability, undermining national recovery and climate transition goals. The OECD calls for proactive investment in energy efficiency as both a cost-containment measure and a resilience strategy.

In summary, turnover and profit provide important insight into the financial situation of micro-enterprises and are closely linked to their energy-related challenges. Businesses with lower profits are often less able to handle increases in energy costs or to invest in measures that would reduce those costs over time, such as improving energy efficiency. This can lead to ongoing financial strain. Monitoring these indicators, especially in relation to sectoral norms, is thus critical for designing effective support policies for micro-enterprises navigating the energy transition.

- Energy in turnover

The proportion of energy costs within a company's turnover is a crucial indicator of its financial resilience, especially for micro and small enterprises. When energy expenses constitute a significant share of turnover, even minor fluctuations in energy prices can substantially impact profitability.

This relationship becomes even more relevant when considered alongside net turnover per company. Micro-enterprises with relatively low net turnover are more likely to experience disproportionate financial stress when energy prices rise, as energy costs represent a larger slice of their revenue base. In such cases, businesses may struggle to maintain operational efficiency or to make the necessary investments in energy-saving technologies.

A study analysing micro and small enterprises in Mexico found that a 1% increase in fuel prices could lead to a profit reduction exceeding 1% for firms with low profit margins and high energy cost shares. (Greve et al., 2023) This effect was particularly pronounced in the transport sector, where fuel costs represent a substantial portion of operating expenses.

In the European context, the energy crisis has similarly affected small businesses. A survey by Business at OECD (BIAC) reported that SMEs experienced an average energy cost increase of 159%, with some facing hikes exceeding 600%. (BIAC, 2022) These surging costs have compelled many SMEs to raise product prices, delay investments, or reduce operations to manage expenses. Such financial pressures underscore the importance of energy efficiency measures. By investing in energy-saving technologies and practices, SMEs can reduce the proportion of energy costs in their turnover, enhancing profitability and resilience against future energy price volatility.

Urban development and energy vulnerability

The distribution of employment opportunities between rural and urban areas is an important structural factor influencing the energy vulnerability of micro-enterprises. In

regions where employment is concentrated in urban centres, rural businesses often encounter operational challenges, including longer travel distances, reduced access to qualified labour, and limited proximity to support services. These factors can contribute to higher transport and logistics costs, increasing overall energy expenditure.

Conversely, a more even distribution of employment across the rural-urban spectrum, more aligned – lower vulnerability, can reduce these burdens. Enterprises located in areas with better employment alignment tend to benefit from shorter commuting distances, stronger local labour markets, and improved access to infrastructure. Research has shown that spatial employment balance contributes to more stable economic conditions and lowers dependency on energy-intensive mobility. (Hartal et al., 2023) The European Commission, with the EU rural vision, similarly recognises the importance of employment alignment in its rural development strategy, noting its relevance to local economic resilience and energy efficiency. (EC, ENRD, 2021)

Building (dwelling) and energy

The energy efficiency of buildings occupied by micro-enterprises significantly in-fluences their operational costs and overall energy vulnerability. Many micro-enterprises operate in older structures that often lack modern insulation, efficient heating and cooling systems, and up-to-date energy management technologies. These deficiencies can lead to increased energy consumption, higher utility bills, and reduced comfort for occupants.

A comprehensive analysis examined challenges and opportunities for improving energy efficiency in small and medium enterprises (SMEs) across Europe. (Agrawal et al., 2023) The findings highlighted that barriers such as limited access to information, financial constraints, and lack of technical expertise hinder SMEs from adopting energy-efficient practices. Conversely, drivers like staff training, facilitation of energy audits, development of corporate policy measures, and collaboration among SMEs within the same supply chain were identified as key mechanisms to improve energy efficiency uptake.

Car and other vehicles and fuels

Transport-related energy consumption is a significant contributor to the operational costs of many micro-enterprises, particularly those active in services, logistics, delivery, repair, and construction. The reliance on vehicles, whether for transporting goods, ac-cessing customers, or carrying out mobile services, makes these businesses highly sensitive to fuel costs and energy market fluctuations.

The type of vehicle, age of the fleet, and fuel used are key variables in understanding this dimension of energy vulnerability. Micro-enterprises that own older or poorly maintained vehicles often face higher fuel consumption rates, increased maintenance expenses, and

elevated exposure to emissions-related regulations. Petrol and diesel vehicles, still dominant in many rural and semi-urban areas, are especially prone to cost volatility due to global oil price fluctuations. Firms located in remote areas, where alternatives such as public transport or electric charging infrastructure are limited, tend to depend even more heavily on such vehicles. The research emphasizes that electric vehicles (EVs) can offer significant reductions in greenhouse gas emissions compared to conventional internal combustion engine vehicles, especially when the electricity used is generated from low-carbon sources. This underscores the potential benefits of adopting EVs for micro-enterprises aiming to enhance energy efficiency and sustainability.

However, the transition to energy-efficient or alternative-fuel vehicles often requires upfront investment that many micro-enterprises cannot afford without public support. While national and EU-level funding schemes (e.g. green mobility grants, tax incentives, scrappage programmes) aim to address these gaps, awareness and access remain limited, especially among the smallest businesses.

Furthermore, the lack of suitable infrastructure (such as electric vehicle charging stations) in non-urban locations adds to the hesitancy. This is particularly relevant in rural or economically lagging regions, where vehicle dependency is high but fleet renewal is slow due to capital constraints. Support mechanisms should therefore not only promote cleaner fleets but also target local accessibility to supporting infrastructure and financial instruments tailored to micro-enterprise capacities.

7.3.2. Energy vulnerability of micro-enterprise

We also sought to answer the question of how we can determine if these factors result in energy vulnerability, by first understanding what exactly constitutes this vulnerability. We grounded our dependent variables on research related to household energy poverty and validated them with experts to identify key indicators of a micro-enterprise's vulnerability. These indicators include Challenges with bill payments (direct effect on the micro-company). We use this indicator in two ways, asking about current and prospective challenges, showing companies in absolute and future risk. Another one is Risks to households associated with micro-enterprises (indirect welfare effect), which literature finds inevitable for micro-enterprises and family companies. (Al Kez et al., 2024; Scheier and Kittner, 2022; Niehm et al., 2009) We also ask about the energy efficiency paradox (inability or missing resources to invest in energy efficiency by those who need it the most). (Koetse et al., 2008; Moreno-Mondéjar, Cuerva, 2020) insights contribute to a comprehensive understanding of the variables that define the energy vulnerability of micro-enterprises and help shape the relevant assessment.

7.4. Case study - Croatia

In 2023, there were 156,145 entrepreneurs in Croatia, of which the majority were micro-entrepreneurs, a total of 137,950 (accounting for 88.3%). With 273,474 employees (26.6%), they generated total revenues and expenses of about 11.5% of all companies. (FINA, 2024) These shares are a bit lower than the European average, where micro-enterprises account for 93.6% companies' share. However, EUROSTAT methodology is limited to size (not including the aspect of turnover), therefore if both are using the same methodology, results would be more in line with the EU. (Vizek, 2021)

Moody`s, Bureau van Dijk ORBIS database contains information on 84,663 Croatian micro-enterprises, which means the information about 61% of micro-companies and could be considered representative sample to show the overall financial status of micro-enterprises. After filtering out outliers using the 1.5 X IQR rule, the average net profit/loss account (net income) is approximately 6,745.99 EUR and the median is around 2,954.91 EUR. The spread, as shown by the summary, suggests that most companies have P/L values between approximately 110 EUR (25th percentile) and 12,640 EUR (75th percentile). This shows relatively low level of profit.

In 2021, the average energy expenditure of micro-enterprises in Croatia was 21,166 HRK (equivalent to €2,806.61). (Croatian Bureau of Statistics, 2025) According to the Croatian Bureau of Statistics, the energy price index rose from 105.3% in 2021 to 123.5% in 2024 (with 2015 as the base year at 100%), reflecting a 17% increase. (Mazhar et al., 2022) This suggests that, under current conditions, a median-profit level micro-enterprise may struggle to afford energy costs. This makes Croatian case study highly relevant for the topic.

7.5. Methodology

7.5.1. Data collection

To identify the determinants of vulnerability among micro-enterprises, we developed a survey that evaluates both independent and dependent variables. We have investigated what could affect the vulnerability of micro-enterprises, considering a range of internal and external determinants. The independent variables represent the structural characteristics of businesses, such as sector, size, location, energy use, and infrastructure, that may influence their exposure or sensitivity to external shocks, as described in the conceptual framework. The dependent variables assess actual or perceived vulnerability, focusing on areas such as past investments in energy efficiency, resilience to energy price fluctuations, or inability to cover energy costs. The questionnaire has been distributed using EU survey.

7.5.2. Sample

The sample consists of 503 responses, out of which 470 are valid and correspond to micro-enterprises. The sample offers strong geographic coverage across Croatia. This regional distribution reflects a well-balanced representation of micro-enterprises nationwide, as shown in Figure 7-2. The majority of companies (78.8%) do not fall into country's special care category areas (regions of particular state concern, supported regions, islands, mountain regions).

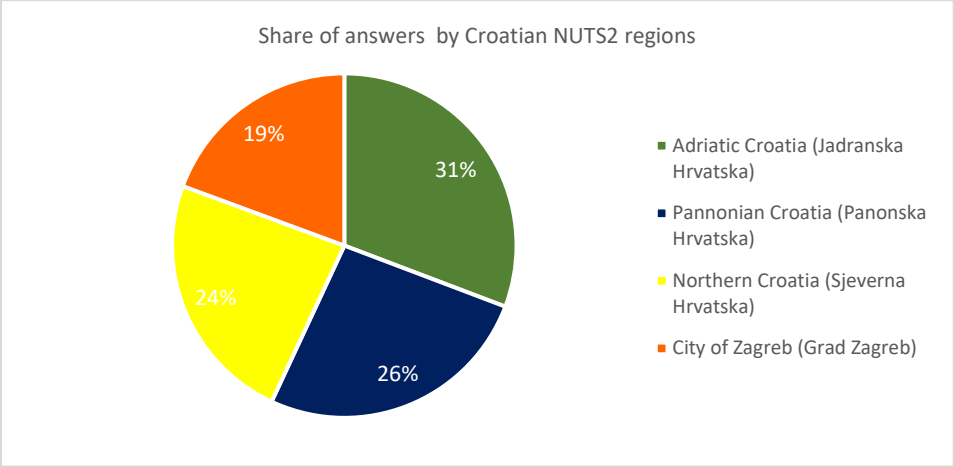


Figure 7-2 Share of micro-enterprises answering the survey by NUTS2, authors from survey

The sample reflects a diverse sectoral distribution across various industries. The services sector, including consulting, represents the largest portion at 36.5% of respondents. Other sectors—such as culture and creative industries, the digital sector, construction, and tourism—each account for approximately 7% of the sample. Transport-related businesses, encompassing both passenger and freight services, collectively make up around 10%. They also have highest energy (transport fuel included) expenditure in total expenditure as shown in Figure 7-3. Additionally, manufacturing and specialised industries, including textiles, electronics, and energy, are present in smaller yet notable proportions.

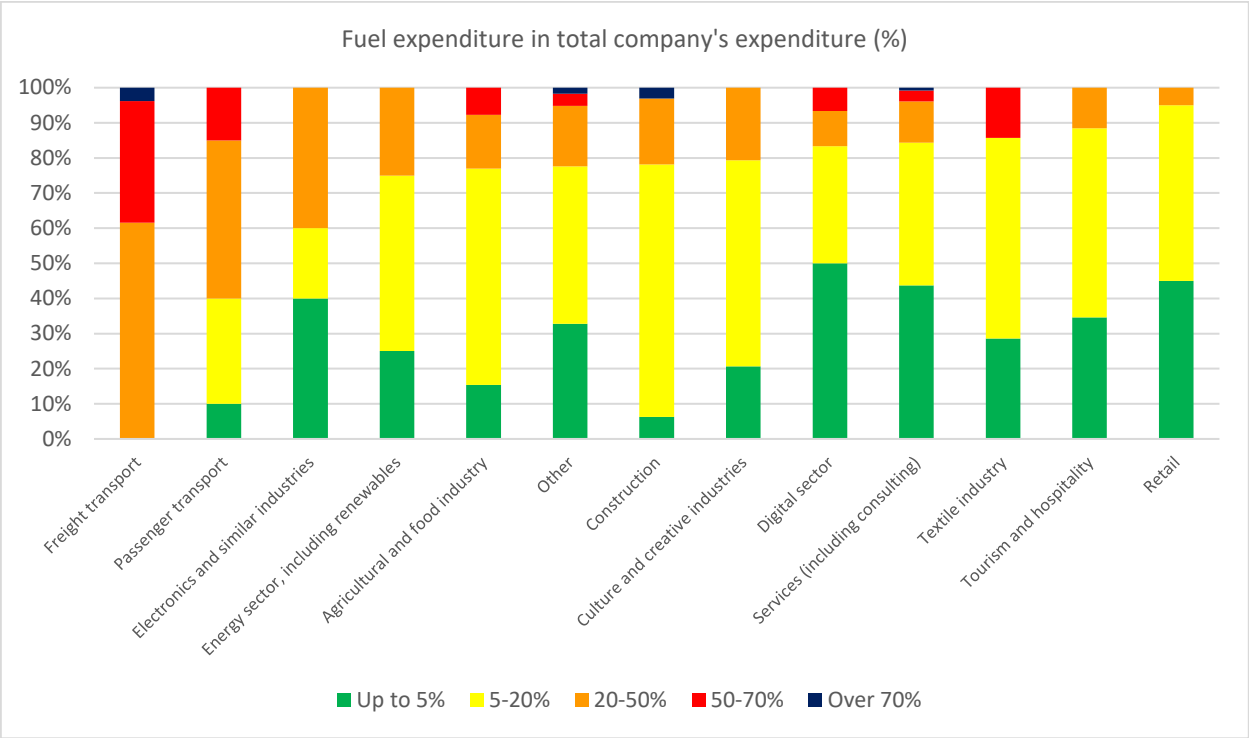


Figure 7-3 Fuel expenditure in total expenditure (%), authors from survey

Most companies have 1 employee, followed by a decreasing number as the employee count increases. The average number of employees is 1.93 (including the owner), and the median number is 1. Based on the dataset from Croatian Financial Agency (FINA), average number of employees in micro- enterprises is 1.98 in 2023, while median is also 1, therefore we can consider the dataset representative from the perspective of size.

The distribution of annual turnover indicates a predominance of companies with small annual revenue. The majority of companies, totalling 331 or 71.3%, report a turnover ranging from 0 to 100 thousand EUR. A significant proportion of these companies (over 70%) report profits below EUR 20,000. We can say this aligns perfectly with the description of the case study, stating low average profit of Croatian micro-enterprises.

Most companies operate from premises designated for residential use or situated in predominantly residential buildings. 124 companies (26.4%) possess an energy certificate, with the majority classified in energy classes B or C. Given the limited data set, we also inquired about the age of the company premises. Most of these buildings are relatively old and likely require energy renovation (if they have not implemented it already).

Companies utilising natural gas for heating and domestic hot water represent 34.3% of the total, around 33% use electricity, 22% wood, and around 6.2% district heating. Other energy carriers are minor. Most companies incur energy expenses ranging from 500 to 1000 EUR

or exceeding 1000 EUR annually. Most vehicles operate on diesel fuel, a lesser number use petrol, while a minority use alternative fuels. As anticipated, the findings indicate that companies within the transport (freight and passenger) and service sectors incur higher fuel cost shares (exceeding 20% of total expenses).

7.5.3. Analysis of variables

The dataset is structured to examine the determinants of energy vulnerability among micro-enterprises. It includes a comprehensive set of independent variables that describe various business characteristics, operational conditions, and contextual factors.

Table 7-1 Independent variables for statistical analysis of vulnerability, authors

No	Variable	Type
1	Region of Croatia (NUTS2)	Categorical
2	Special care area (determined by law)	Categorical
3	Primary sector of the company (NACE)	Categorical
4	Company age	Continuous
5	Number of employees (including owner)	Continuous
6	Annual revenue (last year)	Continuous
7	Annual profit (last year)	Continuous
8	Type of business premises	Categorical
9	Ownership status of premises	Categorical
10	Energy certificate class of building	Ordinal
11	Year of building construction (if no certificate)	Continuous
12	Main energy source for heating/hot water	Categorical
13	Total cost of heating and hot water	Continuous
14	Number of vehicles total (including all types)	Continuous
	Number of vans/minibuses, buses	*Continuous*
	Number of light duty vehicles (up to 3.5t)	*Continuous*
	Number of heavy-duty vehicles	*Continuous*
	Number of work machinery	*Continuous*
15	Vehicle fuel types	Categorical
16	Cost of all fuels (including gas and oil) in total expenses	Continuous
17	Average vehicle age	Continuous

18	Average km per vehicle per year	Continuous

The dependent variables in this dataset represent key indicators of energy vulnerability among micro-enterprises. They are used to assess how various business characteristics influence a company's exposure to energy-related challenges, financial strain, and capacity to adapt. We have explained in the conceptual framework why these indicators are used.

Table 7-2 Dependant variables detecting vulnerability, authors

	Variable	**Type**
1	Investment in energy efficiency (buildings/vehicles)	Binary
2	Problems paying energy bills last year	Binary
3	Energy price changes as business risk	Binary/Ordinal
4	Energy price changes affecting household	Binary

7.5.4. Methods for statistical analysis

Since our dataset includes 18 independent variables and 4 binary dependent variables, our first step was to assess whether there is a significant correlation among the dependent variables. This would help determine the most appropriate statistical analysis approach. To begin, we cleaned and prepared the dependent variables. For the variables related to investment, we recoded responses to reflect their impact on vulnerability: all positive answers (indicating investment) were coded as 0, as they suggest lower vulnerability, while negative answers were coded as 1, indicating higher vulnerability. For the other three dependent variables, such as those related to payment difficulties, we applied the opposite logic, coding positive responses (e.g., experiencing payment issues) as 1, to reflect higher vulnerability. We apply chi-square test on this dataset, using appropriate formulas.

When this test is performed for the first variable (investment in energy efficiency), there is no expected correlation with other variables, so it can be seen separately. However, there is a statistically significant relationship between having payment problems and perceiving energy price changes as a business risk. Companies with payment problems are much more likely to see energy price changes as a risk, as visible from Table 7-3.

Table 7-3 Relation between dependent variables, authors with Python

DV1	DV2	Chi-square	p-value

Payment problems	Business risk	36.861	2.186e-07

In “effect on household”, we have three types of answers, with many companies answering with “I don’t know”.

Table 7-4 Answers related to dependent variables, authors from survey

DV1 Payment problems	DV4 Answers about risks on households		
	I don’t know (2)	No (0)	Yes (1)
0	64	37	242
1	12	2	111

Most companies experiencing payment problems responded with "yes" or "don’t know," while only two answered "no." Among companies without payment issues, the majority also responded "yes," but there was a greater variety of responses, including "don’t know" and "no effect on the household." Although a correlation exists between the two variables, its statistical significance is notably lower compared to the relationship between payment issues and business risks. Based on this, we decided to proceed with separate analyses: for DV1 and DV4, with an intention to apply individual logistic regression models using the independent variables; for DV2 and DV3, which showed stronger interdependence, we used a multivariate model.

7.6. Results

7.6.1. Which companies invest in energy efficiency?

The analysis shows that companies are more likely to invest in energy efficiency or vehicles if they own their premises, have been around longer, or employ more people. On the other hand, having older vehicles or lacking an energy certificate is linked to lower investment in these areas. The age of the building also seems to play a small negative role. However, while these links are statistically significant, each factor by itself explains only a small part of the overall picture, the relationships are there, but they’re not very strong. All significant relationships have low R-squared values, indicating that while the relationships are statistically significant, each variable alone explains only a small portion of the variance in the dependent variable.

- r- corelation coefficient
- b- regression estimate

- R^2 - coefficient of determination
- p - value– statistical significance

Table 7-5 Independent variables with statistical significance to investment in energy efficiency, authors, R+

Independent variable		***r***	***b***	***R²***	***p-value***	**Interpretation of results**
4	Company age	0.123	0.044	0.015	0.0079	Older companies are more likely to have invested in energy efficiency or vehicles, possibly due to greater resources, experience, or established business practices.
5	Number of employees	0.111	0.033	0.015	0.016	Companies with more employees are more likely to have invested in energy efficiency or vehicles, reflecting greater capacity and need.
9	Ownership status	0.168	0.138	0.027	0.00025	**This is the most significant IV.** Businesses that own their premises are more likely to have invested in EE measures or vehicles (the dependent variable). **Ownership provides more control and incentive for long-term investments.**
10	Energy certificate class of building	-0.124	-0.023	0.016	0.0075	These relations respond to simple logic, companies with newer vehicles, better energy certificates are more likely to have invested in energy efficiency or vehicles. It is a consequence more than a determinant.
17	Average vehicle age	-0.143	-0.011	0.020	0.0043	

The analysis shows that companies with more employees, longer operational history, and ownership of their premises are significantly more likely to invest in energy efficiency or vehicle upgrades. These characteristics reflect greater financial capacity, stability, and autonomy, which reduce energy vulnerability.

7.6.2. Companies with problems paying the bills and expected risks of future price changes

As visible from the distribution in Table 7-6, there is obviously no significant difference in payment issues or risks based on location of the company, therefore no need to evaluate statistical significance. Regarding special areas, the highest rates of payment issues and risk perception are observed in mountainous and special state concern areas. However, none of the special care area categories have p-values below 0.05, meaning there is no statistically significant difference in the odds of payment issues between the reference group and any special care area group.

Table 7-6 Payment issues and perceived risk based on location, authors from survey

NUTS 2 region	Payment issues (proportion of businesses reporting payment problems)	Risk perception (proportion of businesses perceiving energy price risks)
City of Zagreb	33.0%	86.8%
Pannonian Croatia	29.3%	80.6%
Adriatic Croatia	23.6%	79.3%
Northern Croatia	23.4%	78.9%

As for the sector differences, both dependent variables p-values are well above the significance threshold of 0.05 (payment issues: p-value = 0.3962, risk perception: p-value = 0.6878), indicating no statistically significant association between sector and either payment issues or risk perception. The highest rates of risk perception are observed in transport of both freight and passengers, but these differences are not statistically significant.

For payment issues, none of the company age groups show a statistically significant difference compared to the reference group, although newly opened companies had most payment issues. For risk, companies older than 10 years have higher odds of perceiving risk related to energy prices (p – value = 0.016). This is likely due to perception of risk, not so much the reality of the issues.

The analysis shown in Table 7-7 clarifies that profit is a sensitive indicator of vulnerability. Regarding the energy and fuel costs, there is a strong link between expenses and vulnerabilities.

Table 7-7 Relation between significant independent variables (IVs) with payment issues and risk perception (DV), authors, Python

IV	DV	Chi^2	p-value
6. Annual revenue (last year)	Payment issues	13.1830	0.10569913
6. Annual revenue (last year)	Risk perception	8.9150	0.71015888
7. Annual profit (last year)	Payment issues	15.7500	**0.00441240**
7. Annual profit (last year)	Risk perception	18.3283	0.00546198
13. Total cost of heating and hot water	Payment issues	15.7869	**0.04553277**
13. Total cost of heating and hot water	Risk perception	46.2662	**0.00000625**
16. Cost of all fuel in total expenses	Payment issues	11.9028	0.15559380
16. Cost of all fuel in total expenses	Risk perception	40.3935	**0.00006186**

The results clearly demonstrate that both energy and fuel costs are strongly associated with how businesses perceive energy-related risks. The relationship between energy costs and risk perception is the strongest in the dataset, with an exceptionally high chi-square value and a p-value near zero, indicating an almost certain link. Fuel costs are also significantly related to risk perception. Additionally, energy costs are significantly associated with reported payment difficulties, although this relationship is not as strong as those related to risk perception. In contrast, fuel costs do not show a statistically significant link to payment issues.

Of all the other variables, which we assume have lower significance in the context of energy – related vulnerabilities, companies with more heavy- duty vehicles are more likely to experience payment problems, possibly due to higher operational costs. Businesses with older vehicle fleets show greater concern about energy price risks, likely due to lower fuel efficiency. Other variables (building type, energy certificates, etc.) don't show statistically significant relationships with payment problems or energy price risks. However, the number of companies included with ownership over heavy duty vehicles is small and therefore results might be biased.

7.6.3. Energy vulnerability of micro-enterprise affecting household

For the effect on household, we wanted to only consider relevant variables, including companies' location, age, size, financial situation, total costs and ownership of dwellings and vehicles. A total of 353 respondents (75.1%) answered "Yes" to the dependent variable, indicating strong agreement. 77 respondents (16.4%) selected "I don't know", while 40 respondents (8.5%) answered "No". This means that most participants confirmed the statement, while a notable minority, roughly one in six, expressed uncertainty, and a smaller portion disagreed. A clear majority of respondents confirmed that rising energy costs in their business have a direct impact on their household, highlighting the financial vulnerability of micro-enterprise owners and the blurred lines between business and personal budgets. Meanwhile, obviously 16.4% expressed uncertainty, indicating a lack of clarity or awareness about how business expenses influence their home life, a gap that may point to the need for better support. Only a small share reported no link between business energy costs and household finances, suggesting that full separation of business and household economics is rare in this group. This determinant cannot be used for evaluation of statistical relevance due to minimum number of negative answers. However, it can help us with conclusions in explaining importance of energy vulnerability of micro-enterprises

7.7. Discussion

The findings of the analysis reveal several key determinants that contribute to the energy vulnerability of micro-enterprises. Companies that own their premises are significantly more likely to invest in energy efficiency or vehicle upgrades, likely due to their ability to make long-term infrastructure decisions. Company size (number of employees) and company age show a positive relation with energy-related investments, suggesting that more established and larger businesses possess greater financial stability or operational capacity (or both) to manage energy investments. These characteristics collectively reflect a lower level of vulnerability. In contrast, companies that lack energy certificates, have older vehicle fleets, or do not own their properties are less likely to invest, pointing to greater exposure to energy-related financial stress. This might be an area where education could prove beneficial and provide assistance.

Profit levels were found to be significantly related to both payment difficulties and perceived risk, making it a more sensitive indicator of financial vulnerability than turnover/revenue alone. Additionally, total energy costs, especially for heating and hot water, emerged as the strongest predictor of both perceived risk and payment issues, while fuel costs were strongly linked to risk perception but not to actual payment difficulties. Sector, region, and company location did not show statistically significant effects, though certain groups (e.g., businesses in special concern areas or the transport sector) had higher observed levels of vulnerability. Some operational characteristics, such as the number of heavy vehicles, showed a possible link to higher payment issues, but the sample size was too small for reliable inference.

Finally, responses to whether energy price changes in micro-enterprises affect households underscore the deep personal impact of energy vulnerability of companies. With 75% of respondents affirming that energy costs influence their household finances, it's clear that energy vulnerability in micro-enterprises often transcends the business sphere and directly affects wellbeing, so this aspect should also be considered.

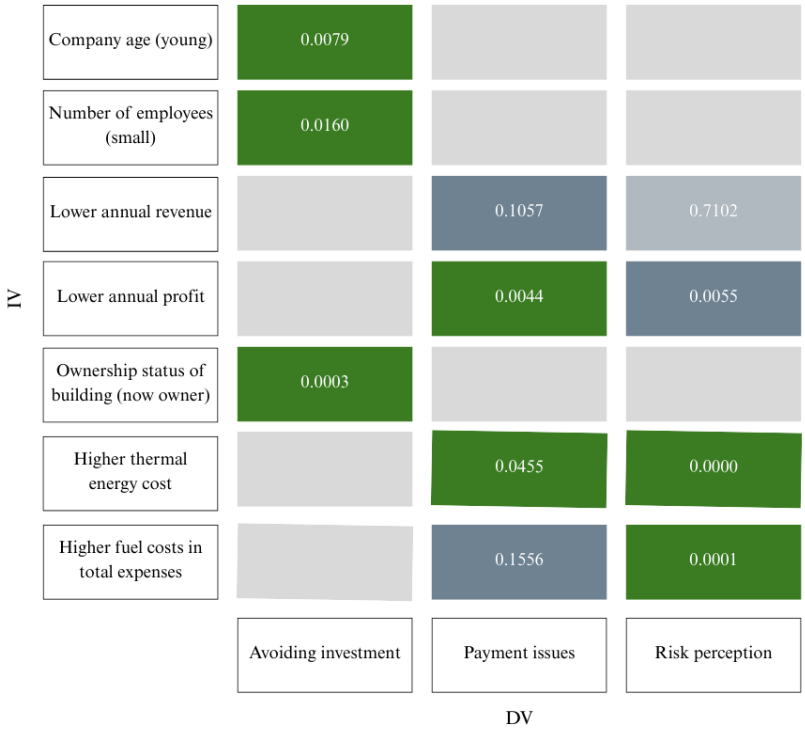


Figure 7-4 Most relevant determinants of vulnerability (p-values), results from analysis, authors with Canva tool

7.8. Conclusions and policy implications

In conclusion, energy vulnerability among micro-enterprises is primarily driven by structural and financial factors: ownership, size, profit, and energy expenses, with energy costs playing a central role. These findings highlight the need for targeted support policies that recognise the specific vulnerabilities of smaller, younger, and financially constrained enterprises. Results also show that energy price increases are not only a challenge for business operations but also pose a real threat to household wellbeing, especially for the most financially exposed small business owners. This brings several important conclusions:

7.8.1. Need for data collection for informing policies

The sample we evaluated is representative, but small and further data collection is essential. Effective data collection is important for understanding and mitigating energy vulnerability among micro-enterprises. By gathering data on energy consumption patterns, financial health, and operational practices, countries can identify specific vulnerabilities and tailor interventions accordingly. For instance, data can reveal which enterprises lack energy-efficient equipment or are burdened by high energy costs relative to their revenue. Moreover, data collection facilitates the monitoring of intervention outcomes, ensuring

that support measures are effective, and resources are allocated efficiently. It also contributes to broader policy development by highlighting systemic issues affecting micro-enterprises across regions or sectors. Such insights enable the development of targeted support programs, such as subsidies for energy-efficient upgrades or training on energy management (and we see the link between companies that, for example, do not have energy certificate and do have higher vulnerabilities).

7.8.2. Need for promoting energy literacy as an enabling tool

Beyond financial and structural constraints, the study highlights a notable awareness gap among many micro-enterprise owners, particularly in understanding the direct and indirect effects of energy costs on business and household finances. This lack of awareness limits their ability to assess risks, make informed energy-related decisions, and access available support schemes. To address this, energy literacy must be promoted as a core enabling pillar of policy frameworks targeting micro-enterprises.

Developing accessible educational resources, offering basic energy management training, and integrating advisory services into support structures (e.g. chambers of commerce, SME helpdesks) can significantly enhance decision-making capacity. Sector-specific guidance, simplified information on return-on-investment for energy efficiency upgrades, and awareness of public funding options can empower micro-enterprises to act. These efforts are particularly critical for addressing the energy efficiency paradox, whereby those most in need of energy-saving investments are least likely to pursue them due to lack of information or perceived complexity. Incorporating energy literacy into national and EU-level SME strategies will strengthen long-term resilience and improve the uptake of efficiency measures.

7.8.3. Further research

Building upon this understanding of energy vulnerability in micro-enterprises, several avenues for further research could be interesting. Sector-specific analyses could uncover unique vulnerabilities in different industries, enabling the development of tailored strategies to address sectoral needs. Investigating behavioural aspects, such as decision-making processes and risk perceptions related to energy use, would offer valuable insights into the adoption of energy-efficient practices. Developing energy vulnerability composite indicators that include indicators like energy cost threshold and financial health, could facilitate the identification of at-risk enterprises and the allocation of resources. Evaluating the effectiveness of existing policies and programs aimed at mitigating energy vulnerability would help in refining strategies and ensuring that support reaches those most in need. Exploring the intersection between business operations and household energy use is crucial, especially for micro-enterprises where personal and professional often overlap. This

could reveal compounded vulnerabilities and inform integrated support mechanisms (joint energy poverty/ energy efficiency measures).

8. INFLUENCE OF DATA DEFICIENCY ON EVALUATING VULNERABILITY

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8.1. Abstract

Micro-enterprises represent major share of EU firms and account for almost 19.8% of EU value added, yet they remain invisible in energy statistics and energy efficiency policy evaluation. This invisibility is not only a matter of missing data but also a classification problem, since energy use is commonly allocated to household, commercial, or industrial sectors based on metering and contract arrangements rather than enterprise characteristics. As a result, micro-enterprise energy consumption is embedded in sectoral aggregates and cannot be consistently observed as a distinct analytical category.

This paper examines how this statistical invisibility might affect the observability of micro-enterprises in energy efficiency policy design and evaluation. It combines a cross-country assessment of data availability across ten EU Member States with a Croatian case study based on a structured survey of 470 micro-enterprises. The survey investigates household-business overlap in workspace use, energy bills, and vehicle ownership.

The cross-country review shows that core indicators needed for policy evaluation, including energy consumption, workspace or building use, transport activity, and size specific sectoral classification, are largely unavailable or only observable at aggregated levels. Financial information is available in some countries but remains weakly harmonised. Complementary sources can improve firm level coverage for economic variables but do not resolve the absence of micro-enterprise specific energy consumption data.

The Croatian case study provides empirical evidence of extensive household and business overlap. 43% percent of respondents reported on shared household and business energy bills, and 64% report on shared vehicle use. These overlaps indicate that household energy statistics may overstate residential demand while business statistics may underestimate enterprises' energy needs, with the strongest overlap among the smallest firms.

The findings highlight the need to improve the statistical visibility of micro-enterprises and to explicitly account for mixed household and business energy use in both policy design and

evaluation. This is particularly relevant for instruments targeting distributional impacts and vulnerability, including measures linked to the Social Climate Fund.

Keywords: energy efficiency, households, micro-enterprises, industry, policy design, statistics

8.2. Introduction

Micro-enterprises, defined by the European Commission as enterprises employing fewer than ten persons and with an annual turnover or balance sheet total not exceeding €2 million, constitute the largest subgroup of small and medium-sized enterprises (SMEs), representing approximately 93.3% of all companies in the European Union in 2023. Although individually small, based on the data from the same year, micro-enterprises collectively account for almost 19.8% of EU value added and 30 % of employment, highlighting their considerable economic importance (Katsinis et al., 2024). Throughout this paper, the term SME refers to the broader enterprise category, whereas the analysis focuses exclusively on micro-enterprises unless explicitly stated otherwise. SMEs are a vital component of many economies around the world and even more in Europe, playing a key role in driving economic growth and providing employment (Eggers, 2020). A large portion of households depend on micro-enterprises for their income, making their viability an important concern for the EU.

Despite their importance, micro-enterprises have received limited attention in energy transition policies. On the EU level, there are no specific quantitative targets or mandatory energy efficiency requirements, hence their involvement in energy transition remains largely voluntary as with other SMEs (Agrawal et al., 2023). At the national level, policy coherence is weak, and most public support remains informational. One reason is that, compared to their numbers, individual energy consumption of micro-enterprises is relatively low and highly differentiated. Yet, aggregated across sectors, their consumption and costs are far from negligible. A key challenge is the absence of dedicated datasets (including energy consumption) and in the way micro-enterprises are represented in existing energy statistics.

The consequences of the data gaps extend beyond statistical precision. When micro-enterprises are embedded within household, commercial, or industrial energy categories based on contract type, their actual contribution to each sector remains unclear. If they are not represented in energy efficiency monitoring frameworks, policies might be poorly designed, inadequately targeted, or carry unintended effects. For instance, financial policies designed with medium-sized firms in mind, could impose disproportionate costs on micro-enterprises, requiring compensatory measures such as additional subsidies. Similarly, overlaps between household and business energy use, common among micro-enterprises operating from home, blur the boundaries between business and household energy statistics. This may distort indicators of both household energy demand and energy poverty.

This paper investigates how these deficiencies influence the design and evaluation of energy efficiency policies for micro-enterprises. We address the following research questions:

- How are micro-enterprises currently represented in energy statistics used for energy efficiency policy design, and what data assumptions does this representation imply?
- To what extent do existing datasets across EU Member States allow micro-enterprise energy use to be distinguished from household, commercial, and industrial consumption?
- To what extent can complementary data sources mitigate these limitations, and where do structural constraints remain to correct such data sources?
- How does household and business energy overlap among micro-enterprises affect the attribution of energy consumption in official statistics and the adequacy of energy efficiency and vulnerability policies, as illustrated by a Croatian case study?

To address this, the paper combines a cross-country assessment of data availability and traceability across ten EU Member States with a bottom-up case study survey of 470 micro-enterprises in Croatia. Croatia was selected as the empirical case study because it provided the comprehensive dataset available for this research, comprising 470 completed questionnaires from micro-enterprises. The availability of detailed firm-level information on household-business overlap enabled an empirical assessment that could not be conducted using existing statistical datasets. Section 2 provides background and conceptual framing. Section 3 describes the methodology used to assess data observability and household and business overlap. Section 4 presents the results from the cross- country data assessment and the Croatian case study. Section 5 discusses the implications of the findings for policy and future research, and Section 6 concludes.

8.3. Background

Looking into energy consumption, it is practically impossible to determine what average energy consumption means for a micro-enterprise, as it depends strongly on the company's sector and business activity. Even at the level of all SMEs, rather than specifically micro-enterprises, most countries do not maintain dedicated energy datasets, and European energy statistics do not distinguish enterprises by company size. Instead, energy consumption is generally allocated according to the type of energy meter. Existing estimates therefore vary considerably, methodologies across EU countries suggesting that SMEs account for between 9% and 18% of gross inland energy consumption, while some estimates approach 30%, as noted (Herce, Martini et al., 2024; Herce, Biele et al., 2024). For micro-enterprises, there is not even such assumption. Case studies further demonstrate substantial heterogeneity between sectors. For example, Greve et al. (2023) show that transport micro-enterprises allocate almost 60% of their total costs to fuel, whereas fuel and electricity account for only around 5% of costs in retail and wholesale trade.

These data limitations have important implications for policy evaluation. Bhardwaj (2022) notes that information gaps in micro-and small- enterprises extend beyond energy to financial and operational indicators, limiting the ability to evaluate policy impacts. Similarly, Hitsch and Misra (2018) argue that ignoring heterogeneity can lead to misleading policy conclusions, while Labandeira et al. (2020) demonstrate that distributional analysis is essential for identifying winners and losers of energy efficiency policies. This is particularly relevant for micro-enterprises, whose small size and limited financial capacity make them more vulnerable to energy price increases than larger firms. This issue has become obvious with the introduction of the EU Emissions Trading System for buildings, road transport and additional sectors (ETS2) under the revised EU ETS Directive (European Commission, 2023). ETS2 introduces carbon pricing for fuel suppliers in these sectors, which is expected to increase energy costs for end users, households and businesses included. To mitigate these social and economic impacts, the European Union established the Social Climate Fund (SCF), a financial instrument designed to support vulnerable households, vulnerable micro-enterprises and transport users through targeted investments and temporary income support (European Commission, 2023). Effective design, targeting and evaluation of these measures require reliable information on the energy consumption and characteristics of micro-enterprises, which is currently lacking.

However, without reliable and disaggregated data on micro-enterprises, the design and targeting of such measures remain challenging. Additional challenge, which has received comparatively little attention in literature, is the overlap between household and business energy consumption. Many micro-enterprises operate from homes, share energy bills with

households, or use privately owned vehicles for business purposes. Nevertheless, household energy demand studies generally analyse households as purely residential units. Reviews by Chen et al. (2023), Taneja and Mandys (2022), and Wu et al. (2024) identify climate, building characteristics, household composition, income, and behavioural factors as the main determinants of household energy consumption, but they do not explicitly consider productive business activities taking place within the dwelling.

Research on working from home provides partial insights into this issue. Hampton (2017) argues that home working remains an under-researched dimension of energy demand, while Battisti et al. (2022) estimate that home working increases household electricity and gas bills by approximately €20–25 per month. Shi et al. (2023) report increases in domestic energy demand ranging from 16% to 117% among teleworkers. The European Foundation for the Improvement of Living and Working Conditions (2020) distinguishes between remote employees, freelancers, and home-based family businesses according to their working arrangements. These classifications are useful for labour market analysis but cannot be directly translated into energy statistics, where energy consumption is allocated according to contracts, as previously noted.

Pogreška! Izvor reference nije pronađen. summarises the main forms of home-based work discussed in the literature, distinguishing between individual employment arrangements and home-based business activities. This distinction is important because only the latter are likely to create substantial household-business overlap in energy consumption, which is the focus of this study.

Table 8-1 Typology of home-based work and potential household-business energy overlap (adapted from European Foundation for the Improvement of Living and Working Conditions, 2020, and extended by the authors).

Category	Description	Example	Household-business overlap
Remote employee	Employee working from home for an employer located elsewhere	Analyst, programmer, accountant	Low–moderate
Freelancer	Self-employed person providing services from home	Designer, consultant	High
Entrepreneur	Own business operated from home	Craft maker, online seller	Very high
Home-based family business	Family members operating a business from the family home	Catering, crafts, online store	Very high

Family business with employees	Family-operated business sharing the dwelling but employing additional staff	Restaurant, local shop, small manufacturing	Moderate–high

There are many interesting aspects of this setting in relation to policies targeting energy efficiency and energy poverty. The ILO (2020) (*based on Delphi questionnaire data*) claims that 12-13% of workers from home are probably low income. These findings refer primarily to employees and do not explicitly capture micro-enterprises or family-run businesses, which are by default more exposed to income and cost vulnerabilities. Taken together, the literature shows: while household energy demand and teleworking impacts are studied, there is almost no systematic evidence on how micro-enterprises' energy use overlaps with household consumption. Addressing these knowledge gaps constitutes one of the principal objectives of this study.

Overall, literature demonstrates two important gaps. First, existing energy statistics do not allow the energy consumption of micro-enterprises to be identified as a distinct analytical category. Second, little evidence exists to the extent to which household and business energy use overlap among micro-enterprises. This study addresses both gaps by assessing the observability of policy-relevant indicators across ten EU Member States and by providing empirical evidence on household-business overlap using a Croatian case study.

8.4. Methodology

8.4.1. Analytical framework: policy evaluation requirements and statistical allocation

This part of the study examines the feasibility of evaluating energy efficiency policies for micro-enterprises under current statistical practices. We first establish the types of indicators typically required for policy evaluation by drawing on established evaluation frameworks used for households, services, and industry (e.g. ODYSSEE-MURE). Rather than applying these frameworks directly to micro-enterprises, we use them as an analytical reference to identify the implicit data assumptions underlying policy evaluation. These frameworks assume that energy consumption can be clearly attributed to a specific sector or economic unit. In the case of micro-enterprises, however, energy use is frequently allocated to household, commercial, or industrial categories based on metering or contractual arrangements rather than economic activity. This creates a structural limitation in observing micro-enterprise energy use as a distinct category. To assess which data would be required to design and evaluate energy efficiency policies for micro-enterprises, we draw on the evaluation framework developed within the ODYSSEE-MURE project, which is widely used to monitor energy efficiency policies across households, services, and industry. Rather than applying this framework directly to micro-enterprises, we use it as a reference to identify the types of indicators typically required for policy evaluation and to assess whether such indicators can be constructed for M-Es under current statistical practices.

This approach makes it possible to examine where and why existing evaluation frameworks break down for micro-enterprises. While ODYSSEE-MURE relies on sector-specific indicators based on clearly assigned energy consumption, the energy use of micro-enterprises is allocated across household, commercial, and industrial categories. As a result, the indicators required for policy evaluation cannot be consistently observed for M-Es. **Pogreška! Izvor reference nije pronađen.** presents the set of indicators commonly used in energy efficiency policy evaluation and examines their applicability and data availability for micro-enterprises, given their current treatment in energy statistics.

Table 8-2 List of indicators for micro-enterprises energy efficiency, adjusted from indicators in (ODYSEE-MURE, 2020)

Type	Indicator	Unit
Total company	Energy expenditure per employee (and/or users)	EUR/employee
	Energy expenditure per revenue (or in all expenditure or profit)	%
	Energy consumption per unit or value added	EUR/unit
Building and process energy	Energy consumption per office space	toe/office
	Energy consumption per m^2	toe/m^2

Building energy – *supportive indicators*	Unit consumption with climatic corrections Unit consumption of electricity for cooling Unit cons. per office for space and water heating Unit cons. per office for cooking Unit cons. per office for lighting and other	toe/office kWh/office kWh/office toe/office kWh/office
Transport	Unit consumption of a vehicle	toe/vehicle
	Consumption of all vehicles (cars/buses/freight/light duty vehicles) in micro-enterprise	toe/company

From the above indicators' list in Table 8-2, we evaluate the needed dataset:

- *Company location:* The location of a micro-enterprise impacts its energy consumption through factors like climate conditions and energy dependence. Heating and cooling needs are linked to heating degree-days, as D'Amico et al. (2019) argue, so they are needed to evaluate baseline consumption. However, location-specific effects cannot be isolated for micro-enterprises when their energy use is embedded within household or aggregated service-sector consumption.
- *Building characteristics and dwelling (including ownership):* The buildings sector includes various typologies with differing physical (age, size, construction) and operational (activities, internal loads, ventilation, schedules) characteristics, which affect energy demand, as González-Torres et al. (2022) describe. Besides these inputs, important information would be the square meters of the dwelling or part of the dwelling use and the purpose (office or industrial facility).
- *Ownership and/or use of vehicles* including number and type of vehicles, vehicle fuel and efficiency and average kilometres per year. In practice, business and private vehicle use are often inseparable for micro-enterprises, leading to systematic underestimation of transport-related business energy use.
- *Size of the micro-enterprise (number of employees):* Raggio et al. (2020) argue that for cross-sector comparison, the most relevant indicator of energy efficiency should be energy productivity. However, the most used indicators of energy efficiency are rather straightforward and link energy consumption to an economic activity in physical terms (Kotsopoulos et al., 2023; Ricardo Energy & Environment, 2019). In the case of micro-enterprise, the simplest indicator can be energy consumption per employee, due to differences among micro-enterprises.
- *Sector classification of micro-enterprises, along with sectoral activity indicators:* The energy consumption of micro-enterprises differs not only between NACE divisions (e.g. H49: Land transport and transport via pipelines) but also between NACE classes within the same division, such as H49.32 (Taxi operation) and H49.41 (Freight transport by road). Previous studies demonstrate that these two NACE classes exhibit substantially different energy consumption patterns (du Plessis et al., 2023; Weng et al., 2017). This illustrates why detailed sectoral classification is important for evaluating energy efficiency policies.
- *Financial information (revenue, expenses) and value added:* Financial information

of the micro-enterprises can help evaluate other direct indicators of energy efficiency, like energy efficiency in the units of produced outputs, ability to invest, turnover, revenue or profit.

- *Energy consumption:* Most important information to obtain is the energy consumption of micro- enterprise in terms of building and process energy and transport fuel consumption, shortly energy consumption per energy carrier.
- *Energy price:* Energy price is highly dependent on where (what kind of premises) micro-enterprise does their primary activity. A study by PWC (2018) shows significant differences in prices among households and commercial sector. In general, the assumption is that prices referring to micro-enterprises are those referring to the consumption of less than 1 000 GJ non-household consumers, all expenses included. Similar also applies to electricity, while other prices highly differentiate among countries. However, in all the calculations, there are still some implications of price regulation and capping (Kuzemko et al., 2022). For micro-enterprises, applicable prices are often unclear due to mixed-use contracts and regulatory interventions.
- *Number of offices or work premises:* Although this indicator is difficult to obtain, it provides a necessary proxy for space-related consumption (heating, lighting, cooking). Without it, building energy demand cannot be linked to business activity.

8.4.2. Assessment of data observability across EU Member States

Building on this framework, we assess whether the indicators required for policy evaluation can be empirically observed for micro-enterprises using existing data infrastructures. To this end, we apply a pedigree matrix approach, which is commonly used to assess data availability and quality across dimensions such as completeness, reliability, temporal coverage, geographical coverage, and technological representativeness (May & Brennan, 2003; Ciroth et al., 2016; X. Chen & Lee, 2021). Given the research focus, completeness is prioritised, as the absence or partial availability of data fundamentally constrains policy evaluation regardless of other quality dimensions. We recognise that indicators which are not observable cannot be meaningfully evaluated or approximated. The assessment relies exclusively on publicly available data sources, including Eurostat datasets (Structural Business Statistics, energy price statistics, and energy balances), national statistical offices and registries, the ORBIS database (Moody's Bureau van Dijk, 2026), and open-access governmental sources. ORBIS is a commercial firm-level database containing financial and structural information on companies worldwide, including variables such as company size, employment, turnover, sector classification (NACE), and ownership. In this study, the database was used because it provides firm-level structural and financial information relevant to energy policy analysis.However, it does not contain direct information on enterprise energy consumption.

Each dataset is classified according to a three-level scoring scheme indicating whether the indicator is not observable, partially observable at an aggregate level, or observable with sufficient granularity at the micro-enterprise level. The assessment covers ten EU Member States (*Belgium, Czechia, Denmark, Greece, Finland, Croatia, Lithuania, Latvia, Romania, and Slovakia*). These countries were selected because they participated in the project within which this research was conducted and had designated national experts responsible for assessing the availability of relevant datasets. The aim was therefore not to produce a statistically representative sample of all EU Member States, but to identify common challenges and differences in the availability of data relevant to the evaluation of energy efficiency policies for micro-enterprises across participating countries. This step establishes where micro-enterprise energy use can and cannot be statistically observed under existing data infrastructures. Given the limited observability of policy evaluation indicators for micro-enterprises identified, this subsection examines whether complementary datasets and analytical approaches can meaningfully address these gaps. The objective is not to reconstruct missing data or to develop a substitute evaluation framework, but to assess the extent to which alternative sources can support policy analysis and where their limitations remain. Commercial and research databases provide firm-level financial and structural information that allows micro-enterprises to be characterised by sector, size, and economic activity. These sources offer greater granularity than official statistics, particularly with respect to economic variables. However, they rely on samples rather than full population coverage and do not contain direct information on energy consumption or expenditure.

In the absence of direct measurements, approximation methods estimate micro-enterprise energy consumption using proxy variables such as the number of employees, floor area, turnover, value added, or production output, combined with sector-specific energy intensity benchmarks. Top-down approaches allocate aggregated sectoral energy consumption to enterprises using economic or structural indicators, whereas bottom-up approaches estimate energy demand from firm characteristics and representative energy-use profiles. Although these methods provide indicative estimates where direct observations are unavailable, they rely on strong assumptions regarding the relationship between proxy variables and actual energy consumption. Furthermore, they cannot resolve the underlying classification problem, as they do not distinguish whether observed energy use is attributed to households or businesses.

8.4.3. Empirical analysis of household–business energy overlap

Given the limitations identified above, the core empirical contribution of this study is a bottom-up analysis of household - business energy overlap among micro-enterprises. A structured survey was administered to micro-enterprises in Croatia as part of a broader data

collection exercise supported by the national Ministry of Environmental Protection and Green Transition in the context of Social Climate Fund - related research. The final sample consists of 470 micro-enterprises with complete responses. The survey captures the extent to which micro-enterprises operate from household premises, share energy bills with households, and use vehicles for both business and private purposes. Hybrid arrangements, such as partially shared energy contracts or mixed vehicle use, are explicitly accounted for.

Following data collection, the analysis focuses on quantifying the prevalence and patterns of household-business overlap and examining how these overlaps vary by firm size and sector. This empirical evidence is used to assess how household-business overlap affects the attribution of energy consumption in official statistics and the interpretation of energy efficiency indicators.

To examine whether the degree of household–business overlap is associated with firm size, we applied a chi-square (χ^2) test of independence. A contingency table was constructed from the Croatian survey dataset, where the rows represent firm-size categories based on the number of employees and the columns represent the three energy-bill overlap categories (no overlap, full overlap, and partial overlap). The expected frequency for each cell was calculated assuming that firm size and household–business overlap are independent:

$$E = \frac{Row\ total\ (\ Employee\ category\ ) \times Column\ total\ (overlap\ category\ )}{Total\ relevant\ answers}$$

$$x^2 = \sum_{i=1}^{n} \frac{(O_i - E_i)^2}{E_i}$$

where the observed frequency is the actual number of micro-enterprises in each cell of the table and the expected frequency is the value that would be expected if firm size and household–business overlap were statistically independent.

Scenario-based sensitivity analysis

To estimate the potential magnitude of household - business energy misattribution, we define O as the estimated share of household energy consumption attributable to business activities among micro-enterprises reporting energy bill overlap. Let *s(full)* denote the proportion of surveyed micro-enterprises reporting complete household - business overlap in energy bills, and *s(part)* the proportion reporting partial overlap. Both variables are expressed as proportions of the total survey sample. The parameters α and β represent attribution coefficients, corresponding to the assumed proportion of recorded household

energy consumption that is related to business activities under complete and partial overlap, respectively.

$$O = s(full) \times \alpha + s(part) \times \beta$$

The values of *s(full)* and *s(part)* are obtained directly from the survey results. The attribution coefficients (α and β) are not estimated from the data but are scenario assumptions used in the sensitivity analysis. Two scenarios are considered: a conservative scenario (α = 0.20; β = 0.10) and an upper-bound scenario (α = 0.60; β = 0.40). These values were selected to represent plausible lower and upper bounds of business-related energy use within shared household energy consumption and are intended to illustrate the potential magnitude of misattribution rather than estimate actual business energy consumption.

8.5. Results

Section 4 presents results in three steps that mirror the paper's core claim: micro-enterprises are statistically invisible not only because data are missing, but because energy use is allocated to sectors in ways that prevent attribution to the enterprise. First (4.1), we test whether the indicators required for policy evaluation can be observed for micro-enterprises across ten Member States and show they largely cannot. Second (4.2), we examine whether complementary sources and modelling approaches can compensate for these gaps and show they improve economic characterisation but not energy observability. Third (4.3), we use Croatian survey evidence to demonstrate the principal mechanism behind misattribution, systematic household - business overlap, thereby explaining why sectoral determinants and policy targeting become biased.

8.5.1. Data requirements for M-Es and completeness assessment across 10 EU Member States

We assess whether micro-enterprise energy use and the indicators required for policy evaluation are observable under current statistical infrastructures. Building on the analytical framework introduced in Section 2, this section examines whether the data required to evaluate energy efficiency policies for micro-enterprises can be observed in practice under current statistical systems. Using the indicator framework presented in Table 2, adapted from ODYSSEE-MURE (2020), we first confirm the types of data elements that policy evaluation implicitly requires and then assess their empirical observability across EU Member States.

Eurostat Structural Business Statistics (SBS) provide basic information on micro-enterprises, such as enterprise counts and employment. The indicators outlined illustrate a structural limitation of current energy statistics. Although relevant information exists in Eurostat datasets (such as Structural Business Statistics, Household Budget Surveys, and energy balances) and in national statistics, energy consumption is not allocated as expected. As a result, micro-enterprises are not observable as a distinct analytical category. Within this context, some variables required for policy evaluation, such as number of employees or sector classification at NACE level 2, are available, but lack the granularity needed to reflect the heterogeneity of micro-enterprises. Other key indicators, including vehicle use, characteristics of work premises, and energy consumption by company size, are largely absent or fragmented across datasets. Consequently, it remains unclear which parts of observed household, commercial, or industrial energy consumption can be attributed to micro-enterprises. This motivates the subsequent cross-country completeness analysis.

The assessment was carried out by the authors using the predefined scoring criteria presented below. To ensure the accuracy of the assessment, the availability of data and the

identified data sources for each country were verified by the national country experts participating in the project. The completed assessments were subsequently reviewed by the authors to ensure the consistent application of the scoring criteria across countries. To assess the extent of this limitation empirically, we evaluated the observability of the required indicators across ten EU Member States using a simplified pedigree matrix focused on data completeness, with the scoring:

0 - Not observable: No dataset exists that allows the indicator to be identified for micro-enterprises, either directly or indirectly. The indicator is entirely absent or only available for households or firms in aggregate, with no size disaggregation.

1 - Partially observable: Data exist at an aggregated level (SME, sectoral, household, or legal entity level) or through fragmented sources but require strong assumptions to approximate micro-enterprise values. The indicator cannot be consistently linked to micro-enterprise characteristics.

2 - Observable: Data are available with sufficient granularity to identify the indicator specifically for micro-enterprises (disaggregation by firm size or legal status) and are consistently reported across time.

Table 8-3 summarises the results of this assessment, showing that the highest result is 56% of the maximum

Table 8-3 Simplified pedigree matrix of data availability, authors with experts' inputs

Data completeness	BE	CZ	DK	EL	FI	HR	LT	LV	RO	SK
Number of M-E.	1	2	2	1	1	2	2	1	1	1
Number of employees	1	2	2	1	1	2	2	1	1	1
Energy price	2	2	2	2	2	2	2	2	2	2
Sectoral classification	1	1	1	1	1	1	1	1	1	1
Financial information	0	1	1	0	0	1	0	1	0	0
Vehicles	1	0	1	0	1	1	1	1	0	1
Dwelling	0	0	0	0	0	0	0	0	0	0
Energy consumption	0	0	0	0	0	0	0	0	0	0
Average completeness	0.75	1.00	1.13	0.63	0.75	1.13	1.00	0.88	0.63	0.75

It shows substantial variation in the availability of micro-enterprise-relevant data across countries but also highlights common structural gaps. Notably, several countries do not maintain national statistics on the total number of micro-enterprises and rely instead on Eurostat-derived estimates, which cannot be consistently linked to financial or energy-

related variables. Energy price data are available across all countries through harmonised sources (Eurostat energy prices and GlobalPetrolPrices.com), but these data are not disaggregated by enterprise size. As a result, assigning energy prices to micro-enterprises requires assumptions about applicable tariff categories. Sectoral classification data are generally available, but typically only at aggregate levels and without consistent disaggregation by enterprise size. Financial information is available in only a subset of countries, often through national sources, and even there it lacks harmonisation.

Data on vehicle ownership and use are available in several Member States through national registries, but these sources generally distinguish only between private and legal ownership and do not identify micro-enterprises specifically. Information on work premises and building characteristics used by micro-enterprises is entirely absent across all countries examined. Most critically, no country provides systematic statistics on energy consumption specific to micro-enterprises. Energy use remains embedded within household, commercial, or industrial categories, depending on metering and contractual arrangements. As a result, it is not possible to determine which shares of observed sectoral energy consumption can be attributed to micro-enterprises. Denmark stands out as an exception in terms of overall data availability, reflecting more advanced national data infrastructures. Nevertheless, even in this case, micro-enterprise energy consumption is not observable as a distinct category.

8.5.2. Limits of alternative data sources

We test whether alternative datasets and modelling approaches can restore observability or whether the allocation problem remains binding. Commercial databases such as ORBIS provide firm-level financial and structural information and enable an assessment of micro-enterprise coverage relative to national totals (**Pogreška! Izvor reference nije pronađen.**). These datasets play an important role in enabling bottom-up modelling and exploratory analysis of energy consumption patterns. However, coverage varies significantly across countries, and the absence of direct energy consumption data necessitates extrapolation and strong assumptions. Similarly, modelling approaches based on the JRC IDEES database allow estimation of average useful energy consumption per employee and per building, which can be converted to final energy using efficiency assumptions. While these estimates produce plausible orders of magnitude, they rely on aggregated sectoral data and do not resolve the underlying issue of misclassification. National sources, such as vehicle registries or building energy certificates, can add depth in individual Member States but lack harmonisation and cross-country comparability.

Overall, these alternative sources provide partial improvements but do not close the fundamental gap identified in the methodology: the absence of systematic, micro-enterprise-specific energy consumption data at EU level and the inability to separate micro-enterprise energy use from household and sectoral aggregates.

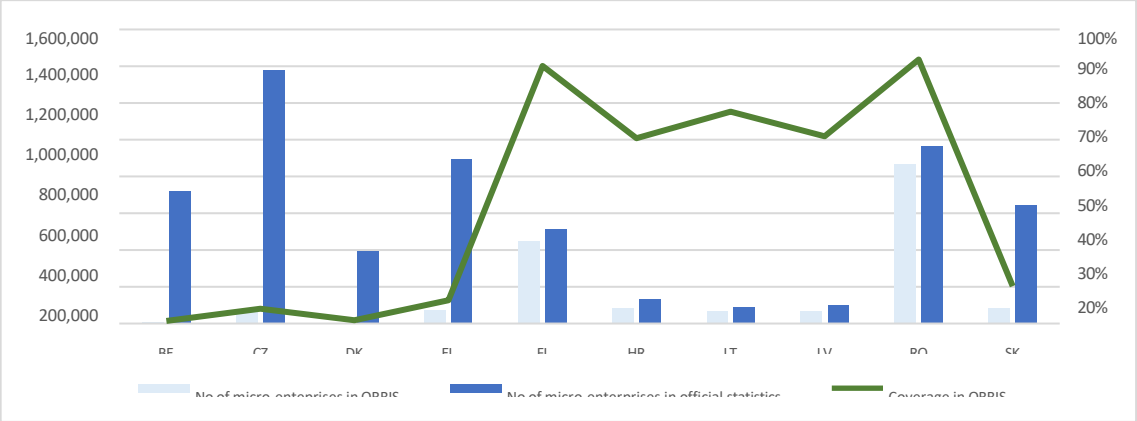


Figure 8-1 Coverage of M-Es in ORBIS, sources: national statistics, EUROSTAT SBS, ORBIS Moody's (BvD)

Recent work in energy efficiency research demonstrates that integrating multiple administrative data sources with calibrated statistical models can significantly improve the estimation of energy performance where standard proxies are incomplete (combining energy labels with microdata for housing efficiency). By analogy, we used similar integrative modelling approaches to estimate micro-enterprise energy consumption from available structural, financial, and overlap data, using surveys as calibration data, although the absence of population-level micro-enterprise energy measurements limits direct application and this level of results quality. (Geijtenbeek et al., 2026)

8.5.3. Empirical evidence on household-business energy overlap

Finally, we provide bottom-up evidence on household - business overlap as a structural mechanism that explains why micro-enterprise energy use is systematically misattributed in official statistics.

The empirical analysis is based on a structured online questionnaire administered using the European Commission's EU Survey platform. The survey was conducted as part of the preparation of the Croatian Social Climate Plan in cooperation with the Ministry of Environmental Protection and Green Transition and Ecorys Croatia. The questionnaire was disseminated to micro-enterprises through relevant stakeholder networks and business organisations. It comprised questions on enterprise characteristics (sector, number of employees, premises), energy use, workspace characteristics, vehicle ownership and use, and the extent of household-business overlap in energy bills and transport. The final sample covered micro-enterprises from a broad range of economic sectors, with services

representing the largest share, followed by construction, transport, trade, manufacturing, and other activities. After data cleaning and completeness checks, 470 valid responses from Croatian micro-enterprises were retained for analysis.

Figure 8-2 presents the share of micro-enterprises operating from household premises, showing that 53% of the surveyed micro-enterprises use household space for business activities. The category "Other" includes premises such as temporary workspaces, shared co-working spaces, mobile workplaces, and other locations that did not fit the predefined response categories.

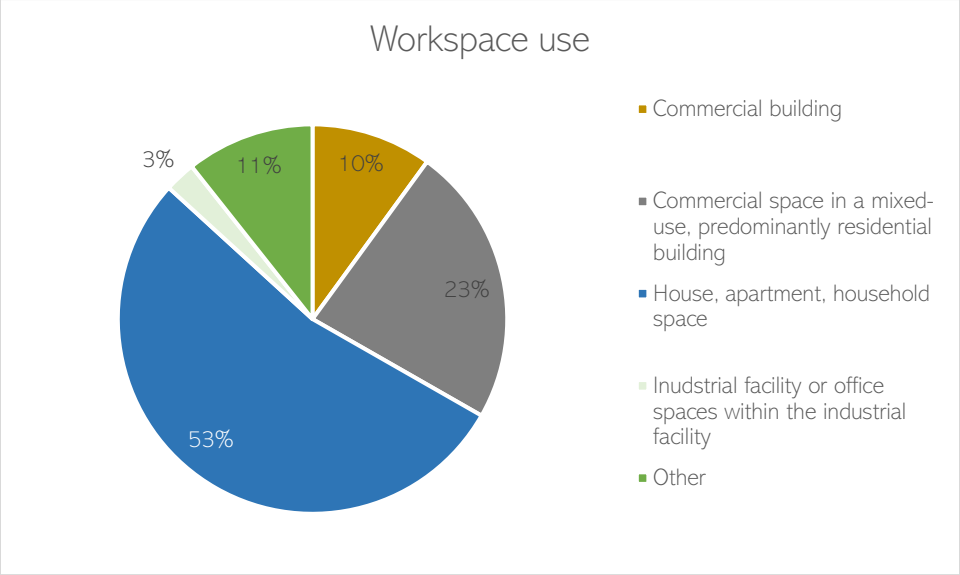


Figure 8-2 Distribution of workspace types, EU-survey with own analysis

Further analysis on the potential overlap of energy bills for business and households shows that 43% of businesses completely share bills between business and household expenses, 18% have partial overlap in their billing. Only 39% keep their business and household bills separate. Regarding the use of private vehicles for work purposes, 64% of respondents report having a vehicle in private ownership that is also used for business activities, as shown in Figure 3.

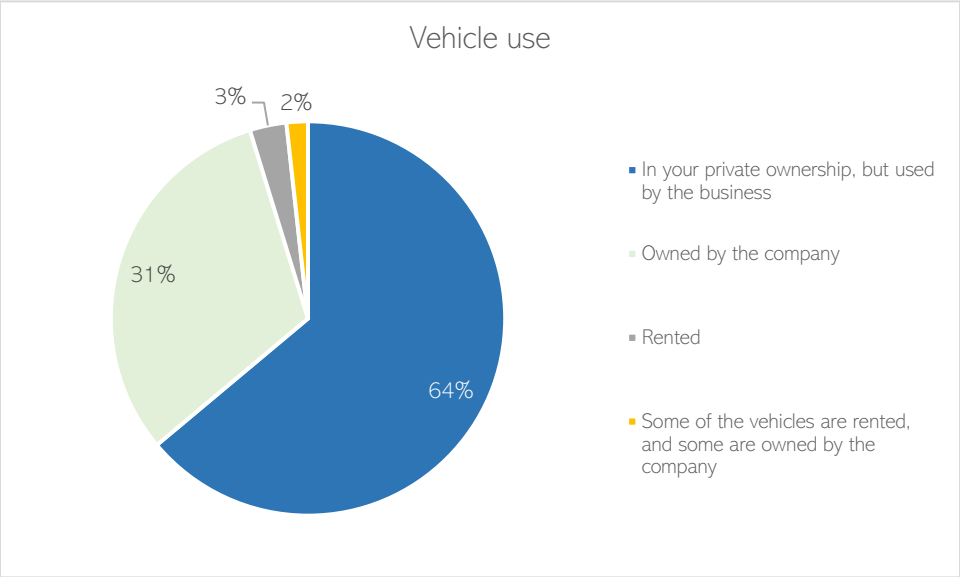


Figure 8-3 Distribution of vehicle ownership, source: EU-survey with own analysis

Taken together with findings on workspace use, the results demonstrate a substantial overlap between business and household activities among micro-enterprises. This overlap complicates the distinction between business and household energy consumption and poses challenges for energy modelling and policy design targeting either group. We further examine whether firm characteristics are associated with the degree of overlap. Statistical testing reveals a significant relationship between the number of employees and both forms of overlap (vehicle use and energy bills). For vehicle use, micro-enterprises reporting partial overlap have the highest average number of employees (mean = 3.0), followed by firms with no overlap (mean = 2.1), while those with complete overlap have the lowest average number of employees (mean = 1.6). This pattern is consistent with firm size dynamics, where very small businesses rely primarily on private vehicles, while larger micro-enterprises combine private and dedicated business vehicles.

A different pattern emerges for shared energy bills. Firms with no overlap tend to employ more workers, while those with complete overlap have the smallest number of employees. This suggests that the separation of business and household energy use increases with firm size, though hybrid arrangements remain common even among larger micro-enterprises.

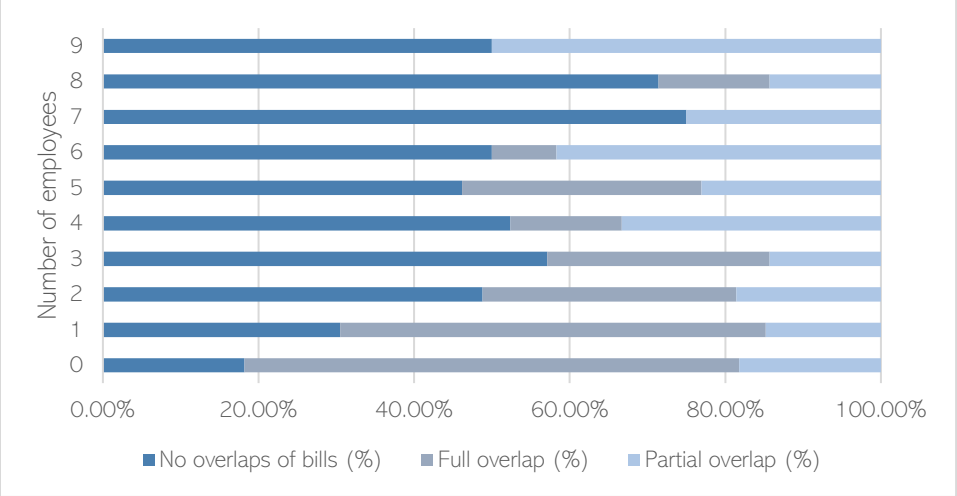


Figure 8-4 Energy bills overlap by number of employees in M-E, authors' analysis of the survey

Data are available also in the table below:

Table 8-4 Energy bills overlap by number of employees in M-E, authors' analysis of the survey

Employees (including owner)	Number of M-E	No Overlap	No (%)	Full Overlap	Full (%)	Partial Overlap	Partial (%)	Full+Partial (%)
0	22	4	18.20%	14	63.60%	4	18.20%	81.80%
1	256	78	30.50%	140	54.70%	38	14.80%	69.50%
2	86	42	48.80%	28	32.60%	16	18.60%	51.20%
3	42	24	57.10%	12	28.60%	6	14.30%	42.90%
4	21	11	52.38%	3	14.29%	7	33.33%	45.40%
5	13	6	46.15%	4	30.77%	3	23.08%	50.00%
6	12	6	50.00%	1	8.30%	5	41.70%	50.00%
7	4	3	75.00%	0	0.00%	1	25.00%	25.00%
8	7	5	71.40%	1	14.30%	1	14.30%	28.60%
9	4	2	50.00%	0	0.00%	2	50.00%	50.00%
n/a	1	1	100.00%	0	0.00%	0	0.00%	0.00%
Total	470	182	38.70%	203	43.20%	83	17.70%	60.90%

overlap (shared vehicles and shared energy bills). The χ^2 statistic equals 55.657, with a p-value below 0.001, allowing us to reject the null hypothesis of independence. This confirms that the extent of household–business overlap among micro-enterprises is significantly related to firm size, and this relationship is therefore relevant for interpreting the results. In addition to firm size, overlap patterns vary substantially across sectors. The construction sector exhibits particularly high levels of overlap, with 76% of firms sharing energy bills and 97% sharing vehicles between business and household use. Digital services also show a high prevalence of shared energy bills (89%). Similarly, the passenger transport sector demonstrates consistently high overlap in both categories, with 75% for shared bills and 90% for shared vehicles, a pattern also observed in the culture and creative sector.

Sensitivity scenarios' results

Applying the scenario analysis to the Croatian survey results demonstrates that household–business overlap may lead to meaningful distortions in sectoral energy statistics. The survey found that 43.2% of micro-enterprises reported full household–business overlap in their energy bills, while 17.7% reported partial overlap. Under the conservative scenario (α = 0.20; β = 0.10), the estimated share of household energy consumption attributable to business activities is:

$O = (0.432 \times 0.20) + (0.177 \times 0.10) = 0.104 \approx 10.4\%$. Under the upper-bound scenario (α = 0.60; β = 0.40), the estimated share increases to: $O = (0.432 \times 0.60) + (0.177 \times 0.40) = 0.330 \approx 33.0\%$.

These scenarios do not estimate the actual share of business-related energy consumption within households. Rather, they illustrate how different assumptions regarding the attribution of shared household energy consumption affect the estimated magnitude of household -business energy misattribution. Even under conservative assumptions, approximately one-tenth of energy recorded on overlapping household energy bills may be attributable to micro-enterprise activities, while the upper-bound scenario suggests that the proportion could reach approximately one-third. These findings demonstrate that the observed prevalence of household-business overlap has the potential to introduce non-negligible distortions into residential and business energy statistics, which may consequently affect energy efficiency indicators, distributional analyses, and the targeting of policy measures.

8.6. Discussion and contribution to literature

This paper contributes to the literature on SMEs and energy efficiency by demonstrating that micro-enterprises constitute a structurally misclassified group in current energy statistics and policy frameworks. While SMEs are often treated as a homogeneous category, micro-enterprises are rarely analysed and are instead implicitly absorbed into household, commercial, or industrial sectors. By using established policy evaluation indicators as an analytical benchmark and assessing their observability across ten EU Member States, we show that this invisibility is not merely the result of missing data, but of the way energy consumption is allocated by contract arrangements.

The Croatian case study provides one of the first empirical assessments of household-business energy overlap among micro-enterprises. Existing research on home working has largely focused on employees, whereas our results show that similar overlaps are pervasive among entrepreneurs and family-run businesses. Crucially, these overlaps affect not only firm-level analysis but also the interpretation of household energy demand. The findings therefore have implications for both energy efficiency policy targeting micro-enterprises and for household-focused policies, including energy poverty assessment and compensation mechanisms.

8.6.1. Effect on energy demand determinants

A key implication of our findings concerns how determinants of energy consumption are interpreted in sectoral energy statistics and policy models. Household, service, industrial, and transport energy demand are typically analysed using sector specific drivers, such as income, household size, building characteristics, operating hours, floor area, value added, or vehicle stock. These determinants implicitly assume that energy consumption within each sector reflects a single type of economic or social activity. Our results show that this assumption does not hold for a substantial share of micro enterprises, whose energy use is embedded within household or aggregated sectoral categories due to contract and metering arrangements.

In household energy models, demand is commonly explained by socio demographic characteristics, dwelling attributes, and behavioural factors. When micro enterprises operate from home and share energy bills, business related energy use is statistically attributed to households. This inflates observed household energy demand relative to household income, floor area, or occupancy, and introduces unobserved productive activity as an omitted variable. As a result, household energy demand may appear more income elastic or more sensitive to dwelling size than it actually is. This has direct implications for energy poverty analysis, where higher energy expenditure may be interpreted as inefficiency or vulnerability, rather than partially reflecting embedded business activity.

In service and industrial sector statistics, the opposite bias arises. Micro enterprise energy consumption that is billed under household contracts is excluded from commercial and industrial aggregates, leading to systematic underestimation of energy intensity and baseline consumption for the smallest firms. Sectoral benchmarks and energy productivity indicators therefore reflect larger firms disproportionately, while micro enterprises appear artificially energy light. This weakens the relevance of sector-based policy instruments and benchmarking tools when applied to micro enterprises, particularly those with zero or one employee.

Transport energy demand is affected in a similar way. Our finding that 64 percent of surveyed micro enterprises share vehicles between business and private use indicates that a large share of business-related fuel consumption is likely recorded as private transport expenditure. This distorts both household transport energy statistics and business energy accounts and complicates the interpretation of transport related policy measures targeting either households or firms.

Importantly, the Croatian case study demonstrates that these overlaps are not random. The degree of household business overlap is systematically related to firm size and sector. Very small firms and specific sectors, such as construction, passenger transport or digital services exhibit significantly higher levels of overlap. This means that misclassification disproportionately affects precisely those micro enterprises that are most numerous and most vulnerable to energy price increases. Consequently, determinants estimated from sectoral aggregates may systematically misrepresent the energy demand characteristics of these groups.

Taken together, these findings suggest that the invisibility of micro enterprises in energy statistics does not merely reduce data precision but alters the apparent drivers of energy demand used in modelling and policy design. Policies calibrated on distorted determinants risk mistargeting both households and firms. Household based measures may overlook mixed use dwellings with embedded business activity, while SME or service sector policies may underestimate baseline energy needs of micro enterprises. Explicit recognition of household business overlap is therefore necessary to improve the adequacy of energy efficiency, vulnerability, and compensation policies, particularly in the context of distributional instruments such as ETS2 and the Social Climate Fund.

8.6.2. Policy implications

The cross-country assessment of data availability highlights substantial gaps in sector-specific information on micro-enterprises. Key indicators required for policy design and evaluation, including energy consumption, financial variables, and size-specific sectoral classification, are either missing or only partially available in most Member States. While a

small number of countries provide limited financial data, these are rarely comparable across size classes. The absence of systematic information on energy consumption and workspace use necessitates estimation and modelling approaches, but the results of this study underline the need for more consistent data collection and improved alignment across statistical sources.

- Strengthening statistical baselines: Without systematic and disaggregated data on micro-enterprises, EU and national policymakers lack the evidence base needed to design, target, and evaluate energy efficiency interventions. Continued reliance on aggregate SME data risks misrepresenting distributional effects, including those associated with instruments such as ETS2.
- Explicitly addressing household- business overlap: Policies targeting energy poverty, household energy efficiency, or SME competitiveness should explicitly account for mixed-use arrangements. For example, renovation programmes could be adapted to address dwellings with embedded business activities, and transport measures could recognise the prevalence of shared vehicle use.
- Improving targeting of support measures: While mechanisms such as the Social Climate Fund aim to mitigate energy cost burdens, households hosting home-based micro-enterprises may be misclassified under current frameworks. These households may face both elevated energy costs and business-related risks, increasing their vulnerability.
- Enhancing and harmonising data collection: A coordinated effort at EU level is needed to better link existing data sources, such as Structural Business Statistics, Physical Energy Flow Accounts, and household surveys, while introducing micro-enterprise-specific indicators. Even limited additions- such as identifying whether households host home-based businesses - would significantly improve policy design and evaluation.

8.6.3. Future research directions

Future research should build on these findings by extending the empirical analysis of household–business energy overlap among micro enterprises to additional countries and sectors, in order to assess the scale, persistence, and variability of this phenomenon across different institutional, regulatory, and statistical contexts. Beyond geographic extension, there is a clear need to revisit the underlying determinants and indicators used to explain energy consumption in both household and business sectors.

Methodological development should focus on adjusting standard energy demand indicators to explicitly account for productive activities embedded within dwellings and private assets. This includes developing approaches that can systematically disentangle business related

energy use from household consumption, for example by attributing shares of residential energy demand to productive activities based on firm size, sector, workspace use, or vehicle usage patterns, rather than relying on ad hoc assumptions or residual estimates.

Such advances would improve the validity of household energy demand models, sectoral energy intensity indicators, and distributional impact assessments. In turn, this would enable more accurate evaluation of energy efficiency policies, vulnerability measures, and compensation instruments affecting micro enterprises and households, particularly in policy areas where eligibility and targeting depend on observed energy use.

8.7. Conclusions

The findings provide answers to the four research questions posed in the Introduction. First, micro-enterprises are not represented as a distinct analytical category in existing energy statistics, as energy consumption is allocated according to contractual classifications rather than enterprise size. Second, the assessment across ten EU Member States shows that current statistical systems do not allow the systematic identification of micro-enterprise energy consumption, with key indicators remaining unavailable or only partially observable. Third, although complementary data sources and approximation methods can improve the availability of structural and financial information, they cannot overcome the fundamental classification problem or provide direct observations of micro-enterprise energy use. Finally, the Croatian case study demonstrates that household–business overlap is widespread among micro-enterprises, leading to potential misattribution of energy consumption in official statistics and affecting the design and evaluation of energy efficiency and vulnerability policies. Among the 470 surveyed micro-enterprises, nearly half report shared household and business energy bills and almost two thirds share vehicles between business and private use.

Taken together, these findings show that the invisibility of micro-enterprises in energy statistics is not merely a technical data gap, but a policy relevant classification problem. Improving the design and evaluation of energy efficiency and vulnerability policies requires better alignment between micro-enterprise data and household level datasets, such as the Household Budget Survey, as well as greater recognition of business-related energy use within household statistics, including EU SILC. Explicitly accounting for household and business overlap is therefore essential to ensure that micro-enterprises, despite forming the backbone of EU economies, are neither overlooked nor disproportionately burdened in the transition under the European Green Deal.

9. IMPACTS OF DECARBONISATION POLICIES ON VULNERABLITY

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9.1. Abstract

The decarbonisation policies for the EU building stock can improve living conditions, including thermal comfort and lower energy bills. However, these measures may impose financial burdens on low-income households, reducing their disposable income and exacerbating their vulnerability. The current study investigates the impact of decarbonisation policies on the EU's building stock, with a specific focus on Minimum Energy Performance Standards (MEPS), the new Emissions Trading System (ETS2) for buildings, and the phase-out of fossil heating systems. By employing a linear, static latest version of Microsoft Excel (Microsoft 365)-based model and analysing Eurostat data, this study quantifies the effects of these policies on energy consumption, costs, and necessary investments. Moreover, the study emphasizes their implications for low-income groups using vulnerability indicators. The findings demonstrate that a combination of MEPs, ETS2, and phasing out fossil heating systems effectively reduces energy consumption and costs across most countries. However, implementing ETS2 alone may lead to energy reduction and discomfort for low-income groups without addressing underlying demand-side issues. To address this, this study recommends the implementation of more ambitious MEPs or the provision of additional funding alongside ETS2. The phase-out of fossil fuel boilers emerges as the most cost-effective measure in the medium to long term. While MEPS and the phase-out of fossil fuel boilers improve living conditions, they also impose upfront cost burdens and reduce disposable income for low-income households. Therefore, high subsidy rates and supportive policies are necessary to ensure equitable access to investments. The main recommendations include (a) shifting financing to renewable heating systems for low-income households by 2025, addressing cost issues and policies favouring gas boilers; (b) implementing high-funding rate subsidies for energy efficiency in low-income households before 2025, with technical guidance; (c) prioritising the Energy Efficiency First principle in planning to avoid additional emissions or higher costs for low-income households; and (d)

considering the energy behaviour of low-income groups in regulations, employing a combination of policies to achieve desired outcomes and ensure thermal comfort.

Keywords: energy policy; EU Emissions Trading System; fossil fuel boiler phase-out; minimum energy performance standards; energy poverty; residential sector; energy efficiency; decarbonisation policy; low-income households; Eastern Europe

9.2. Introduction

Europe's most important and threatening crisis is climate change affecting different sectors in different ways, posing uncertainties regarding the continent's future. The reduction in greenhouse gas (GHG) emissions simultaneously requires higher implementation of renewable energy sources (RES) and an improvement in energy efficiency. Buildings account for more than 40% of final energy consumption and at least 36% of energy-related GHG emissions. (European Commission, 2022) Therefore, there is a need for renewable and less polluting energy systems for domestic and public buildings. This will result not only in the reduction in GHG emissions but also in the promotion of energy saving, tackling energy poverty, improving health and well-being, as well as creating new opportunities for growth and work. Most EU countries present low levels of energy efficiency in the residential sector due to the ageing of the buildings and the lack of renovation strategies in the last years. Hence, measures promoting the energy efficiency of dwellings in the residential sector must be advanced. This is also illustrated by the Energy Efficiency First (EE1st) principle, part of Article 3 of the new Energy Efficiency Directive (EED) recast proposal, and it "means taking utmost account of cost-efficient energy efficiency measures in shaping energy policy and making relevant investment decisions" (European Commission, 2021). In practice, the EE1st principle balances demand and supply options in order to prioritise the least expensive investments for the energy system from a societal perspective.

This paper aims to understand which policy measures proposed by the European Commission, aimed at decarbonising the residential sector, would have the greatest impact in reducing energy poverty among low-income households and contemporarily improving household energy efficiency in central and southern Eastern European countries.

The following paper will start with a literature review providing theoretical background on the concepts of household energy efficiency, energy poverty, and the relation of these with low-income groups; but also an explanation as to why a focus on central and southern Eastern Europe was chosen and the European energy policy framework (Section 2). This will be followed by a section illustrating the methodology chosen (Section 3), followed by an explanation of the general results obtained (Section 4). Thereafter, these will be discussed

(Section 5), followed by an explanation of the entailed policy implications (Section 6), and the final general conclusions (Section 7).

9.3. Literature Review

9.3.1. Household Energy Efficiency, Energy Poverty and the Relation of These to Low-Income Groups

As recognised in the European Green Deal, 50 million citizens across the European Union (EU) do not have access to indoor thermal comfort (European Commission, 2019). (Bouzarovski,2018) (p. 1) defines energy poverty as a situation which "occurs when a household is unable to secure a level and quality of domestic energy services–space cooling and heating, cooking, appliances, information technology - sufficient for its social and material needs". Nonetheless, various definitions of energy poverty can be found throughout the literature. This can be traced back to its multifaceted nature, as energy poverty is a socioeconomic issue that presents many ramifications. For this reason, definitions vary also across countries, dictated by national socioeconomic conditions which play an important role in defining energy poverty. Within the EU, not all nations present an official, legally recognised definition. Additionally, energy poverty is unevenly distributed across Europe, with eastern and southern regions presenting higher prominence of the latter. (Bouzarovski, Tirado Herrero, 2017) This is also due to the environmental and geographical factors of one location which will inevitably affect its vulnerability to energy poverty. (Adly, El-Khouly, 2022) Nonetheless, it is agreed within the literature that this intricate phenomenon will always include both economic components, such as the fuel prices, and energy components, such as the energy performance of the dwelling where one household lives, and all the socioeconomic interactions that can result, such as the inability to keep the home adequately warm. The importance of energy performance is enhanced through regulation and existing building codes. However, this phenomenon does not have only socioeconomic ramifications but, for example, also environmental ones. Indeed, households in a situation of energy poverty will utilise more outdated forms of technology for energy consumption, resulting in more environmental harm.

Energy poverty is closely related to household energy efficiency (Thompson et al., 2017), with the latter being defined as the needed energy to power one household to generate a certain energy output. (World Bank, 2013) Improving energy efficiency in general is one of the main objectives of the European Green Deal, with a set target of achieving at least 36% in energy efficiency by 2030. (European Commission, 2021) Energy refurbishments of buildings could reduce energy poverty and concurrently increase household energy efficiency [10]. In fact, measures aimed at tackling energy poverty from the demand side have the potential to alleviate energy poverty while providing direct and tangible benefits

to the residents. (Bouzarovski, 2014) In addition, greenhouse gas emissions, total energy consumption, and consequently energy expenditures could be lessened. (Filippidou et al., 2017) Nations that present a higher range of low-quality and energy-inefficient dwellings tend to present higher levels of energy poverty (and vice versa). (Omić, 2019) In fact, higher expenditures will result from more inefficient buildings (e.g., low thermal insulation). Another correlation that is found is that residents living in energy inefficient households present below-average disposable incomes. In a similar way, low-income groups are more probable to become energy poor (Deller, Waddams Pierce, 2018) to the extent that the gravity of one household's energy burden is often considered as a solid predictor of which groups will be affected by energy poverty. (Omić, 2019) For this reason, this particular segment of society was the focus of the present study.

An extensive array of studies has been undertaken to thoroughly examine the multifaceted factors that contribute to the pervasive issue of energy poverty. These meticulous investigations delve into crucial aspects such as financial market participation, energy efficiency, and the significance of human capital. By delving into these critical dimensions, these studies provide invaluable policy insights that not only shed light on the root causes of energy poverty but also offer practical recommendations to address and overcome this pressing challenge.

Among these studies, (Cheng et al.,2023) conducted an insightful investigation on the impact of financial market participation on household energy poverty. Using data from the 2015 Chinese General Social Survey, their findings suggest that engaging in financial markets significantly reduces energy poverty, primarily through the mediation of future expectations. However, the study also reveals that higher financial risk weakens the effect of future expectations on energy poverty by destabilising household finances. Consequently, promoting financial market participation emerges as a potential avenue for alleviating household energy poverty.

Another noteworthy study by (Moteng et al., 2023) explores the mechanisms through which sanctions affect energy poverty, highlighting the significance of factors such as human capital, energy efficiency, income inequality, and economic growth. By identifying these interconnected mechanisms, the study offers valuable policy insights that can inform policymakers in designing effective strategies and interventions to tackle energy poverty.

Collectively, these studies contribute to a robust foundation of knowledge for policymakers, enabling them to devise and implement targeted strategies, programs, and interventions that can effectively alleviate energy poverty and improve the overall well-being of affected communities.

9.3.2. Delineation, Explanation, and Selection of the Case Studies

The present research analyses seven countries from central and southern Eastern Europe, as these two regions were found to be particularly characterised by energy poverty. Eastern European states are additionally affected by a late liberalisation of the energy market, a historically unstable energy supply mix, and inefficient thermal insulation of buildings. (Bouzarovski, Tirado Herrero, 2017) The countries analysed include Bulgaria, Czechia, Greece, Hungary, Poland, Romania, and Slovakia. As most EU member states, they opted to alleviate the higher burden of energy costs with price regulations, energy bill assistance, as well as tax reductions on the energy bills. Nevertheless, these are not considered as structural measures for the low-income groups and thus should be combined with energy efficiency upgrades and measures for decarbonising the space heating facilities. Moreover, the higher upfront costs of energy efficiency investments combined with the well-known and documented structural barriers do not make energy efficiency a key priority of low- and middle-income groups, notwithstanding the shortened payback period of these investments due to the higher energy prices. The households' reduced disposable income (due to the higher energy prices) is hampering the possibility of investment in refurbishments and clean heating solutions, while the incumbent fossil fuel subsidies further delay such investments. Therefore, if the available funding, such as subsidies on energy efficiency and heat pumps, is not increased for the low-income households, the energy crisis and inflation may even delay energy efficiency investments to remove fossil-fuel-heating in such households. Hence, to counter such trend, a complementary package of supporting measures which includes financial, informational, and technical measures from the national and local authorities is needed to help accelerate energy efficiency investments and finally switch to clean and sustainable space heating.

An interesting aspect to consider is the country's dependence on imported gas and the share it has in its final energy consumption and other energy end-uses. The dependence on imported gas influences the energy price, and with it, the member states' new expenditures to cover the energy costs of households via bill aid. Various figures related to gas utilisation in the considered countries are presented in Table 9-1. In addition to the analysed countries, France and Germany, Europe's richest countries, are also presented in this table. This is done to see the extent to which economic and geographic indicators play a role. It can be seen how Romania presents the lowest dependency on Russian gas (even lower than France and Germany). Interestingly, Bulgaria is the only country presenting a lower gas share when considering only household energy consumption rather than the total final energy consumption. This table shows how every country's data in relation to natural gas is unique and how data cannot be easily generalised. With regards to electricity generation, Greece

stands out with almost 40% of gas share in its electricity production. Stemming from this data, various scatterplots relating to general gas import dependency and the different gas shares per end-use were delineated for the analysed countries in Figure 9-1

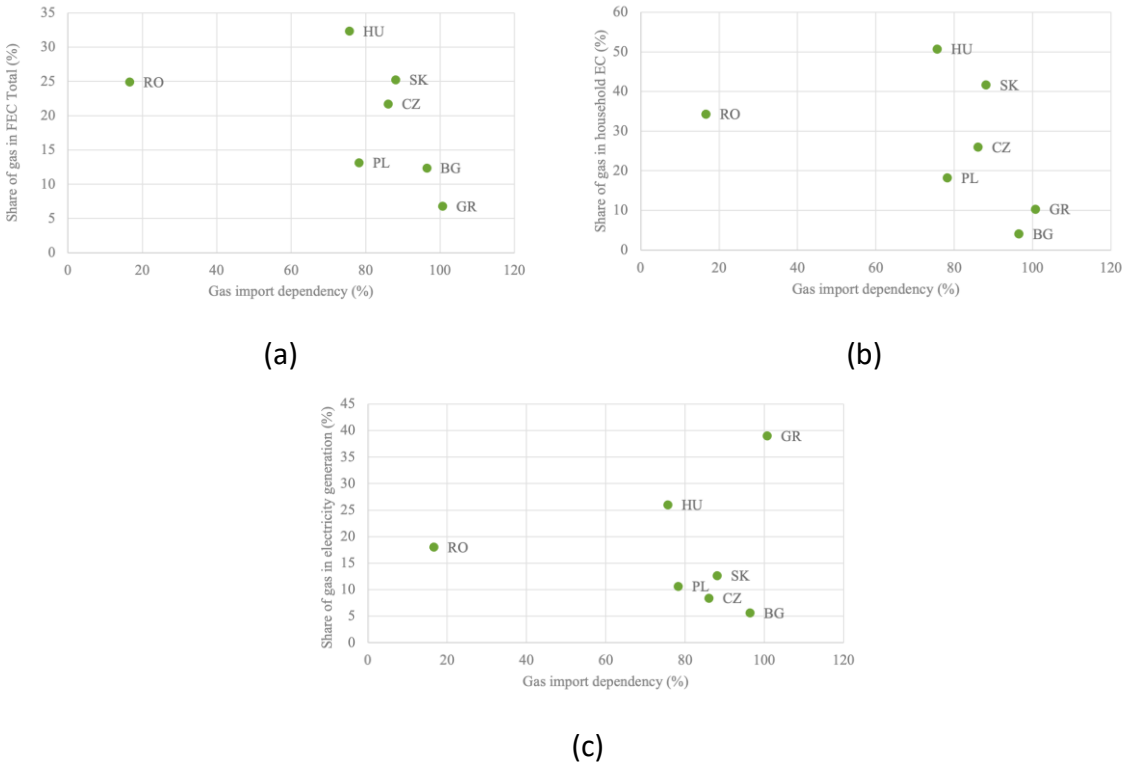


*Figure 9-1 Comparing graphically the dependence on gas per energy end-use per country compared to its gas import dependency. (**a**) Share of gas in final energy consumption compared to gas import dependency. (**b**) Share of gas in household energy consumption compared to gas import dependency. (**c**) Share of gas in electricity generation compared to gas import dependency.*

Table 9-1 Comparing graphically the dependence on gas per energy end-use per country compared to its gas import dependency.

Countries	BG	CZ	EL	HU	PL	RO	SL	FR	DE
Dependency on Russian gas (IEA, 2023)	77%	92%	40%	64%	48%	22%	65%	24%	60%
General gas import dependency (EUROSTAT, 2022)	96%	86%	100%	76%	78%	17%	88%	95%	89%
Gas share in FEC (EUROSTAT, 2023)	12%	22%	7%	32%	13%	25%	25%	21%	27%

Gas share in household EC (EUROSTAT, 2022)	4%	26%	10%	51%	18%	34%	42%	28%	38%
Gas share in electricity generation (IEA, 2022)	6%	8%	39%	26%	11%	18%	13%	6%	16%

The scatterplots illustrate how big of a role gas plays in the energy consumption of the analysed countries and how dependent the latter are from gas-exporting partner countries. Firstly, it can be noticed how Romania can "afford" to have rather high gas consumption patterns as it imports a rather small percentage of its consumed gas. On the other hand, the country presenting the highest gas import dependency, Greece, is particularly reliant on partner countries as it produces a high proportion of its electricity from gas. Thus, even though Greece has rather low consumption patterns of gas, it is still the most gas-reliant of the analysed countries due to its high share of gas in electricity generation. Bulgaria also presents high gas import dependency; nonetheless, unlike Greece, it utilises a very small percentage of gas and thus is not deemed as a very gas-reliant country. Poland is also another country not too reliant on gas, however on a minor scale. The other analysed countries, and in particular Hungary, can all be defined as gas - reliant.

On another note, Figure 9-2 shows the allocated funding (in billion EUR) in each country for tackling the energy crisis between September 2021 and October 2022. The burden on state budgets will strongly affect the possibility of member states implementing low-carbon policies. Therefore, strategic planning to develop complementary policies is of the highest relevance. Poland presents the highest budget, as expected from the largest of analysed countries both demographically and economically. Surprising is perhaps Greece, which presents the second highest budget even though having a lower economic force compared to other countries. The rest of the analysed countries seem to have an allocated budget that reflects their socioeconomic conditions.

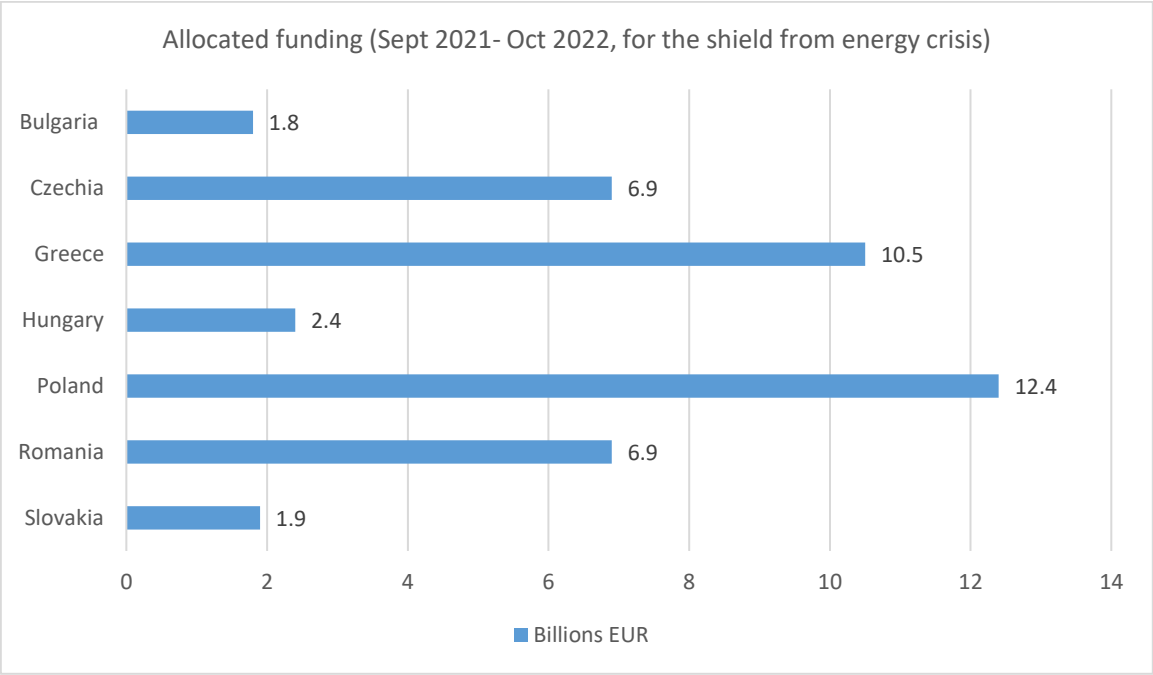


Figure 9-2 Governments earmarked and allocated funding (September 2021–October 2022) to shield households and businesses from the energy crisis (Bruegel report) (Sgaravatti et al., 2023)

The presented data aimed to reflect that each country presents unique gas-related characteristics with different allocated budgets. A generalisation of such starting characteristics for central and southern Eastern European nations is thus not possible. Hence, each country will be analysed on its own and only once national results are obtained will these be analysed together, considering the hereby described national characteristics.

9.3.3. European Energy Policy Framework

The EU aims to be the first continent with neutral carbon emissions by 2050 and has been at the forefront of the promotion and implementation of decarbonisation policy measures (European Commission, 2021). As part of this effort is the European Green Deal, which "aims to transform the EU into a fair and prosperous society, with a modern, resource-efficient and competitive economy where there are no net emissions of greenhouse gases in 2050 and where economic growth is decoupled from resource use" (European Commission, 2019) (p. 2). The proposed policy mix focuses on three key principles related to energy. Firstly, to ensure an affordable, clean, and secure EU energy supply. Secondly, to prioritise the renovation and improvement of buildings in a resource and energy-efficient way. Thirdly, to develop a fully digitalised, and interconnected EU energy market, promoting circular economy.

Part of the European Green Deal is the "Fit for 55" package. This set of policy proposals also includes revisions of previous directives, such as the EED and Energy Performance of

Buildings Directive (EPBD). The name of the package stems from the EU's objective of reducing by 55% its net greenhouse gas (GHG) emissions by the year 2030 compared to its 1990 levels. To ensure, a competitive and just energy transition by 2030, the package offers a careful combination of pricing, standards, support measures, and targets. Following the breakout of the war in Ukraine, the European Commission fastened its process of independence from Russian fossil fuels and thus, on 18 May 2022, presented the "REPower EU Plan". The latter foresees reducing dependence on Russian fossil fuel by further increasing some of the objectives set in the Fit for 55 package and fast-forwarding the sustainable transition. For example, the target for the renewable energy share in 2030 was increased from 40% to 45%, envisioning a doubled installation rate of heat pumps. (European Commission, 2022) For the present research, three specific policy measures (present in the Fit for 55 package) were chosen to be analysed, simulated, and discussed. These will be further described in the following paragraphs.

Extension of the EU Emissions Trading System to the Residential Sector

The European Commission developed and put in force the new emission trading system (ETS2 here), which puts numbers on the fossil fuel emissions in buildings and transport sectors. It is a cap-and-trade kind of system like the ongoing ETS. It is regulated upstream, it does not directly involve buildings or vehicles but fuel suppliers, and will begin in 2026. These sectors will still be covered by the Effort Sharing Regulation, meaning member states' policies will continue to contribute to reducing emissions in the sectors. Carbon pricing is the measure that creates the market for new innovations, but the degree of this depends on (a) energy price elasticities and (b) cross-price elasticities. The impacts of the ETS price in these sectors could however generate higher costs to households, hence leading to higher energy poverty, in central and southern Eastern Europe.

Phasing out of Fossil Fuel Boilers

To enable the decarbonisation of space heating and cooling in the households, the installation or sale of new fossil fuel boilers is to be phased out by 2030, plus the fossil fuel boiler lifetime. This might create a lock-in effect for households that are in the situation of energy poverty. They will use cheaper technologies due to the fact that more advanced technologies like heat pumps have higher upfront costs, despite their operational and ongoing costs being lower. To secure the avoiding of a lock-in is a policy framework that can give low-income households the possibility to switch to low-carbon heating systems. A revision of the Ecodesign and energy labelling regulation for heaters is going to lead to a downgrading of gas boilers to the low-energy (the two lowest) labels and more interest in the phase-out of the inefficient heating systems. A previous study from (Rogulj et al.,2022) announced that governments choose (a) natural gas for space heating, enlarging existing

gas pipelines in the domestic sector, and (b) make use of subsidies for fossil fuel heating with the gas boilers, considering it an energy efficiency measure. The phasing out of fossil fuel boilers should indicate a clear timeline to avoid lock-ins and increase the costs of shifting to natural gas boilers.

Minimum Energy Performance Standards (MEPS)

Minimum Energy Performance Standards (MEPS) target buildings with renovations aimed at improving the energy efficiency in the residential sector reducing energy poverty, taking into account possible socio-economic differences. The EPBD recast (European Commission, 2021) announced that the minimum energy performance standards shall at least ensure that all non-residential buildings are below (i) the 15% threshold as of 1 January 2030 and (ii) the 25% threshold as of 1 January 2034. The trajectory is expressed as a decrease in the average primary energy use in kWh/(m^2y) of the whole residential building stock over the period from 2025 to 2050. The average primary energy use in kWh/(m^2y) of the whole residential building stock needs to be at least equivalent to:

(a) The D energy performance class level by 2033;

(b) By 2040, a nationally determined value derived from a gradual decrease in the average primary energy use from 2033 to 2050 in line with the transformation of the residential building stock into a zero-emission building stock. Although evidence of the impacts of MEPS is not yet available, there was an impact assessment of the EPBD with the result that MEPS is a crucial instrument for the final energy savings and for the cost reduction, as well as for generating construction activity. The impact assessment did not isolate the impacts of MEPS on energy poverty, nor did it address specificity regarding the central and southern Eastern European regions.

9.4. Methodology

In the following section, the methodology utilised to analyse, model, and simulate the three different considered policy measures will be explained. Firstly, it must be noted that a linear, static and Microsoft-Excel-based model was employed. In fact, the tool utilises simple predefined formulas, interconnecting various Excel sheets at the same time. More sophisticated models can be found in the literature, with the most notorious one being PRIMES, used by the European Commission and Directorate-General for Energy to delineate the EU Reference Scenario 2020. The latter combines multiple objectives with different detailed constraints and, since 2016, was upgraded to include PRIMES-BuiMo (covering the residential sector), and PRIMES-Maritime (covering the maritime sector) [25]. Other models found include CAPRI, GAINS, GEM-E3, GLOBIOM, and POLES-JRC. Nonetheless, such complexity in modelling would be overwrought for the issue at hand. Thus, the simplified

Microsoft Excel model was chosen, as it allows for modelling practices with Eurostat data in a simplified manner which allows also for more direct and simple communication of results. In fact, all the considered data were gathered from the Eurostat repository. The baseline year was chosen to be 2019, and a time horizon until 2050 was considered when performing simulations. Finally, as only linear and static data were examined, non-linear behaviours were not visible. Behaviours such as final energy consumption and energy price trends, which in real life are non-linear and affected by a multitude of factors, in this case will be represented linearly.

The Eurostat energy prices from the first semester of 2022 were considered for the separate national energy prices per fossil fuel type. Additionally, in this study, low-income groups were considered as all those households corresponding to the first income decile.

9.4.1. Assumptions

ETS1: The estimated ETS1 prices originate from the EU recommendations to member states (September 2022) (De Vita et al, 2021) as the analytical basis for updating the National Energy and Climate Plans (NECPs). The assumptions are based on the average price of EUR 80/t CO2 eq that were reported since the beginning of 2022 and will be increasing following the expected trends as to achieve the 55% GHG reduction target and the expected energy price trends. The simulation with PRIMES is done in a way that the reductions come as response to prices and other policy drivers plus additional market considerations. Prices are then derived with iterations until achievement of the ETS cap (Figure 9-3).

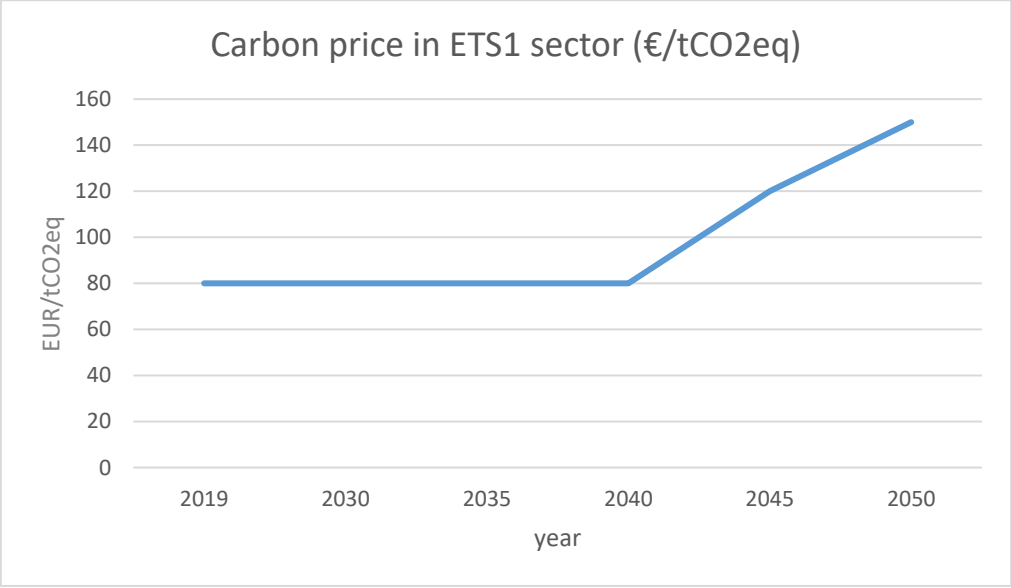


Figure 9-3 ETS1 price development.

ETS2: The estimated ETS2 prices are a result of a study conducted by Vivid Economics (EEA, 2012). Two existing scenarios from Vivid Economics are evaluated for the purpose of modelling the electricity price evolution until 2040. Scenario 1 was used for carbon pricing policy (Central_MSR1), while the second one (Reg_MSR1) is used for their combination. The ETS2 price will remain constant after 2040 (Figure 9-4).

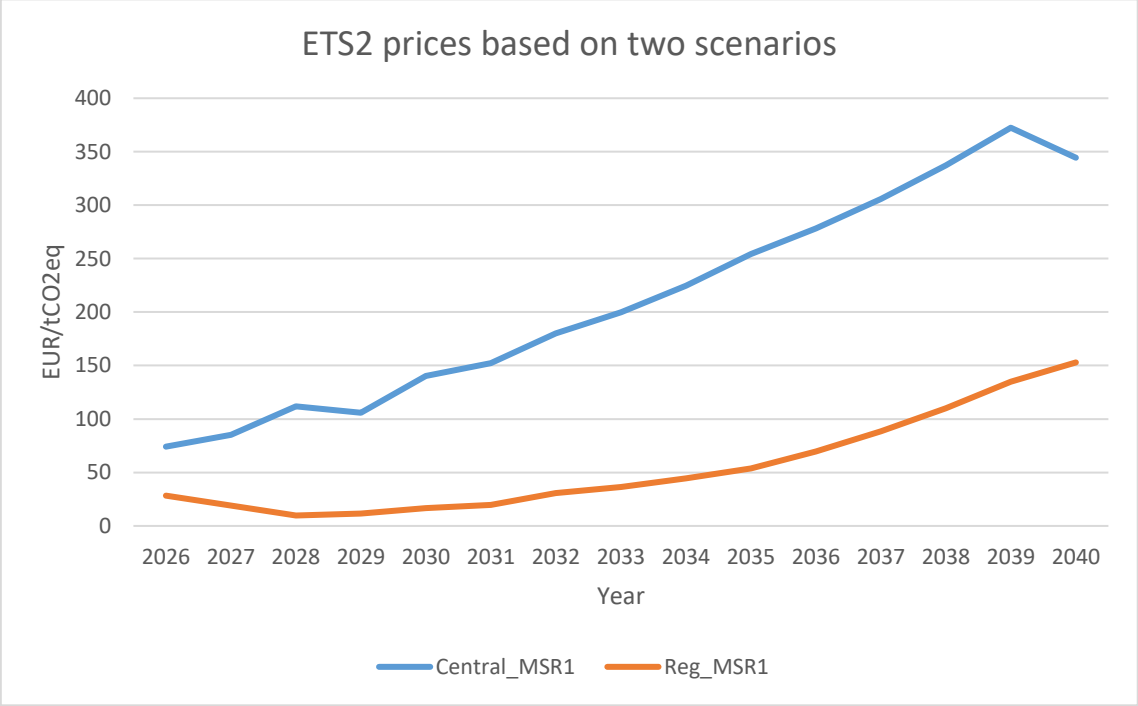


Figure 9-4 ETS2 prices until 2040.

Fossil fuel prices: The EU Reference Scenario 2020 was used for the forecast of 2019–2050 fossil fuel prices (heating oil, natural gas, coal, and LPG). The estimations are derived from the EU recommendations to member states (September 2022) (de Vita et al., 2021) as an analytical basis for updating the NECPs.

Furthermore, the prices of the first quarter of 2022 (Eurostat) were used as a basis and upon that the price growths were derived (Figure 9-5).

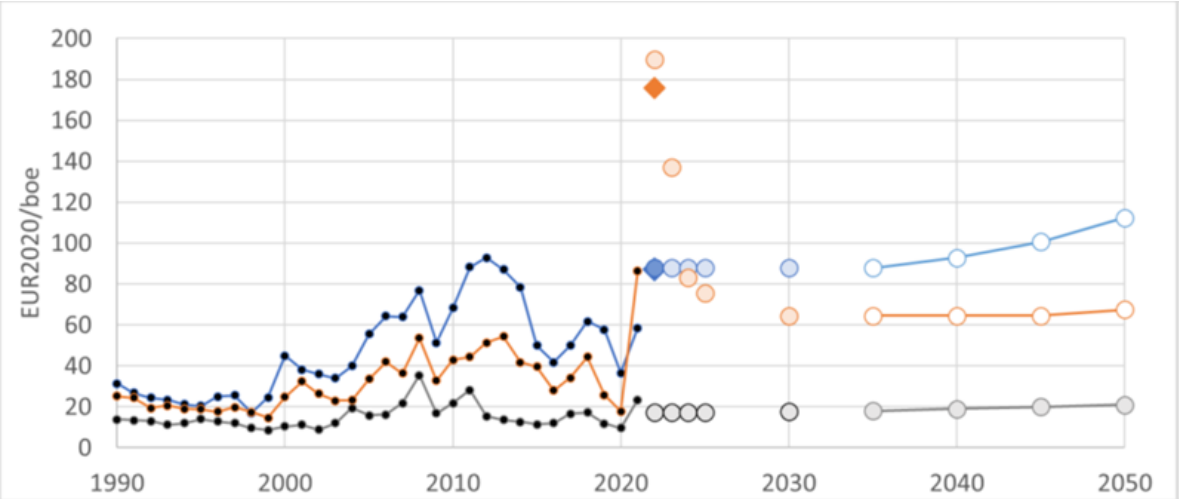


Figure 9-5 Envisioned fossil fuel price in the EU Reference Scenario 2020 (blue: oil, red: natural gas, grey: coal; BOE: Barrel of Oil Equivalent)

Price elasticity of energy demand: Due to the unavailability of data for price elasticities of low-income households' energy demand, an average elasticity is used. The IAEE research (Charlier et al., 2017) shows that energy poor households for our target group do not have high elasticities of energy demand. Therefore, our assumption of average elasticities coming from ETS2 introduction, in the case of low-income households, would mean that the consumption decrease comes without private investments in energy efficiency and thus only from a reduction in thermal comfort.

9.4.2. Scenario Analysis

Stemming from the proposed measures, six different scenarios were delineated. A linear calculation logic was applied based on the estimation of the final energy consumption by end-use (e.g., space heating, space cooling, and domestic hot water) for six different time intervals separately up to 2050 (e.g., 2019–2025, 2026–2030, 2031–2035, 2036–2040, 2041–2045, and 2046–2050), taking into consideration: (1) The increase in energy prices, as resulted by their forecast increase until 2050 and the imposition of carbon price (ETS2) and the subsequent reduction in the final energy consumption in accordance with the price elasticity of the energy demand. (2) The implementation of energy efficiency interventions and the delivered energy savings due to the implementation of the examined policy measures (MEPS and phasing out of fossil fuel boilers).

- Baseline Scenario assumes that no policy measures have been put in place (departing from the EU reference scenario) and it follows the European Commission's recommendations to member states (MSs) concerning their updating of the NECPs. This scenario is expected to present the highest energy consumption figures for all countries as no effort is made to reduce it in this scenario. On the other

hand, the energy expenditure will depend on the energy mix of countries as countries presenting a higher share of fossil fuels will incur higher expenditures due to future energy price rises.

- Scenario 1 considers the implementation of the first proposed policy measure (ETS2) solely. Here, an additional increase in prices due to carbon pricing is considered. This is the same logic employed in the study. An initial decrease in consumption is to be expected as the costs of fossil fuels will increase greatly. Nonetheless, this will not be a structured reform, but rather people will consume less for purely economic reasons, as they will not be able to afford energy services as before. This policy is expected to provide undesirable results as it does not foresee a phase out of fossil fuels, but rather relies on the "market phase out" of fossil fuels for monetary reasons, a tactic which would greatly hamper low-income groups. Poland will be an exception due to its high reliance on coal and low prices of the latter, meaning that a switch to other forms of fuel could be more costly than sticking to coal. Additionally, due to its high reliance on coal, the expenditure under scenario 1 for Poland can be expected to reduce greater than in other countries.
- Scenario 2 takes into account the sole implementation of the second proposed policy measure, that being the phasing out of fossil fuel boilers. In this case, it is assumed that all fossil fuel boilers (using heating oil and solid fossil fuels but also natural gas) will be phased out in 2035. It is envisioned that the actual phase-out will take 5 years and thus be de facto phased out in 2040. The investment cost per heat pump is considered to be EUR 10,000 for all countries. The energy consumption is not expected to greatly reduce as this is rather a quick and short-team measure, as the residential efficiency cannot be expected to be reduced by only improving boilers. Similarly, expenditures are not expected to greatly reduce except in countries highly reliant on heating oil (e.g., Greece) as this fossil fuel is the most expensive one with the the highest envisioned price rise.
- Scenario 3 represents the application of the third proposed policy measure (MEPS) solely. N.B. In the present report, the term MEPS is generally used to indicate the refurbishment of buildings according to some proposed standards. However, these are not necessarily the minimum requirements set in the European directive. In fact, it is hereby further assumed that 75% of all buildings will be renovated to reach energy class D by 2030, resulting in 40% energy savings and EUR 15,000 renovation costs per building. Thereafter, these buildings will be renovated to reach energy class C in 2035, resulting in 10% additional energy savings and EUR 10,000 renovation costs per building. These assumptions differ from the previous study,

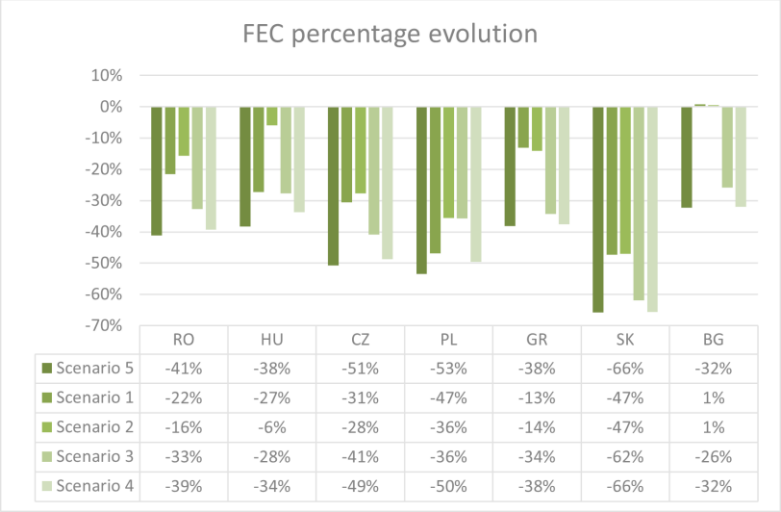
where it was assumed that 50% of the affected households would reach energy class E in 2030, followed by the remaining half in 2035, resulting in 30% energy savings and EUR 10,000 renovation costs per building. Additionally, it was assumed that all households would reach energy class D in 2040, resulting in 10% additional energy savings and EUR 5000 renovation costs per building. Furthermore, in this study, the same renovation costs are assumed for all considered countries (whereas in the previous study, higher renovation costs were considered for Hungary). This is expected to be the best-performing stand-alone policy as it is a structured policy improving the general efficiency of the building.

- Scenario 4 considers the combination of both scenarios 2 and 3. This scenario is expected to provide better results compared to scenario 3 in general from an energy consumption perspective. Nonetheless, when considering also expenditures, countries that are highly reliant on fossil fuels (e.g., Poland and/or Hungary) might present higher expenditures compared to scenario 3 due to the presence of more fossil fuel boilers, which, considering also the low price of fossil fuels, might not give economically beneficial results in the short term.
- Scenario 5 considers the combination of all scenarios. The combination of all three policy measures is expected to provide the best results, as it tackles the energy efficiency issue globally and from all perspectives. It greatly combines policy measures more focused on short-term gains with other ones that consider long-term gains specifically.

9.5. Results

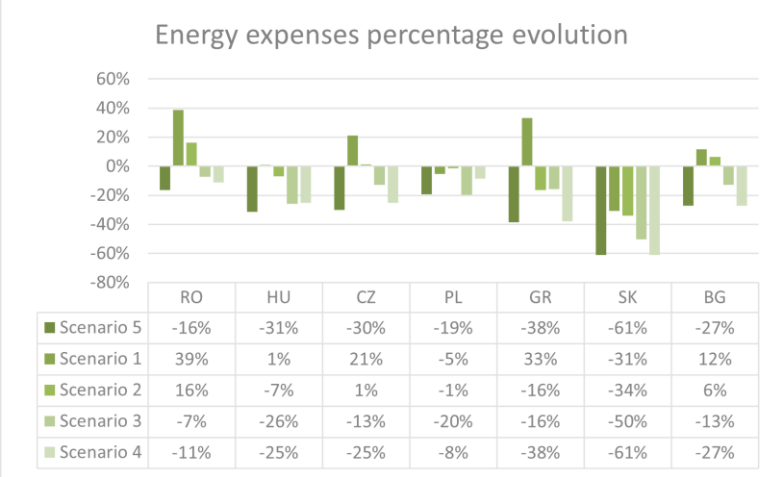
In general, for all analysed countries, the combination of all scenarios, namely Scenario 5, provided the most desirable results in terms of final energy consumption reduction in the low-income households (without reducing thermal comfort) in 2050. Moreover, the combination of policies led to the highest reduction in energy expenses in 2050, excluding Poland, where the introduction of MEPS as a stand-alone policy resulted in the lowest energy expenses. Nonetheless, the difference in the final energy expense reduction in 2050 compared to 2019 levels for Poland between scenarios 3 and 5 was only 1%. However, this underlines Poland's great dependency on coal, as 34% of its energy consumed comes from coal (141 times higher when compared to the percentage of utilised coal in Greece). This will entail higher expenditure costs in scenario 5 due to the higher carbon costs related to the ETS2 pricing (unlike scenario 3 where the envisioned baseline fuel price increase is considered). The two graphs below (Figure 9-6 and Figure 9-7) provide a percentage comparison of the envisioned savings in final energy consumption and in energy-related

expenses from 2019 to 2050 for each country when implementing the policy measures assumed in each scenario. Essentially, the difference in values between 2050 and 2019 was expressed as a percentage, where scenario 5 provides the best results. In the rest of this section, a detailed deconstruction of the results per scenario per country can be found, differentiating between energy consumption and expenditure.



	RO	HU	CZ	PL	GR	SK	BG
Scenario 5	-41%	-38%	-51%	-53%	-38%	-66%	-32%
Scenario 1	-22%	-27%	-31%	-47%	-13%	-47%	1%
Scenario 2	-16%	-6%	-28%	-36%	-14%	-47%	1%
Scenario 3	-33%	-28%	-41%	-36%	-34%	-62%	-26%
Scenario 4	-39%	-34%	-49%	-50%	-38%	-66%	-32%

Figure 9-6 Resulting energy consumption changes in 2050 compared to 2019 as a percentage per country.



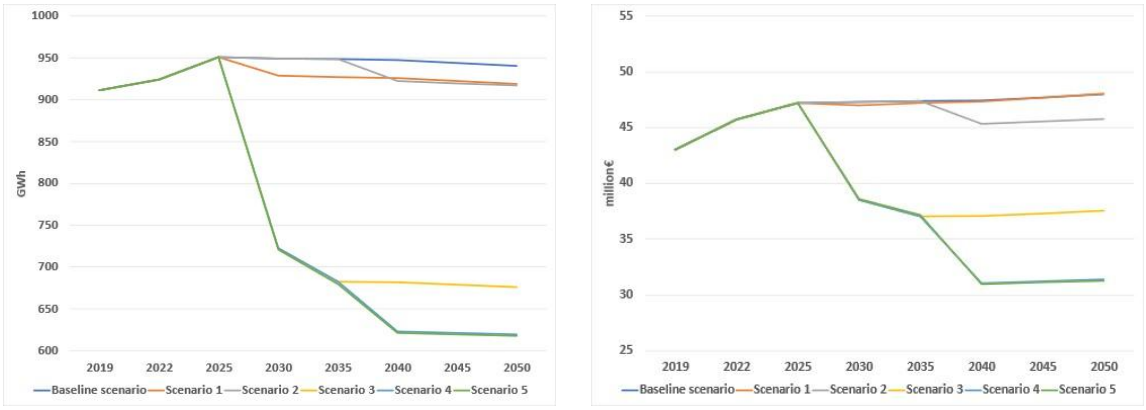
	RO	HU	CZ	PL	GR	SK	BG
Scenario 5	-16%	-31%	-30%	-19%	-38%	-61%	-27%
Scenario 1	39%	1%	21%	-5%	33%	-31%	12%
Scenario 2	16%	-7%	1%	-1%	-16%	-34%	6%
Scenario 3	-7%	-26%	-13%	-20%	-16%	-50%	-13%
Scenario 4	-11%	-25%	-25%	-8%	-38%	-61%	-27%

Figure 9-7 Resulting energy expenses changes in 2050 compared to 2019 as a percentage per country.

Bulgaria

Bulgaria clearly illustrates how policy measures not designed ad hoc for the country can present great counter effects. In fact, scenarios 1 and 2, together with the baseline scenario, present higher energy consumption and expenditures in 2050 compared to 2019. The case of Bulgaria clearly shows how short-term measures such as that in scenario 2 will provide

only short-term gains (in this case resulting only from the initial implementation of the measure). Similarly, an unstructured measure such as that of scenario 1 will only damage low-income groups in the long run (Figure 9-8)

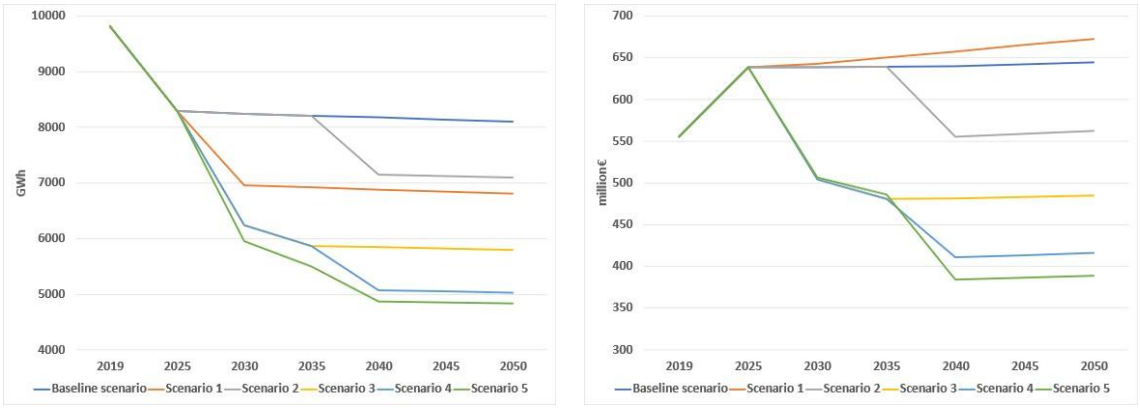


(a) (b)

Figure 9-8 Country analysis for Bulgaria. (a) Final energy consumption: comparison of different scenarios in Bulgaria. (b) Final energy costs: comparison between scenarios in Bulgaria.

Czechia

All proposed policies will present a reduced energy consumption in the long run in Czechia, although not a reduced expenditure. As for Bulgaria, scenarios 1 and 2 together with the baseline scenario would entail higher expenditures in 2050 compared to 2019. This is once again due to the unstructured nature of the measures. In the case of scenario 2 specifically, the gains of this measure only bring the expenditure levels in 2040 back to what they were in 2019. Nonetheless, due to rising energy prices, these will continue to rise in the period 2040–2050 (Figure 9-9).

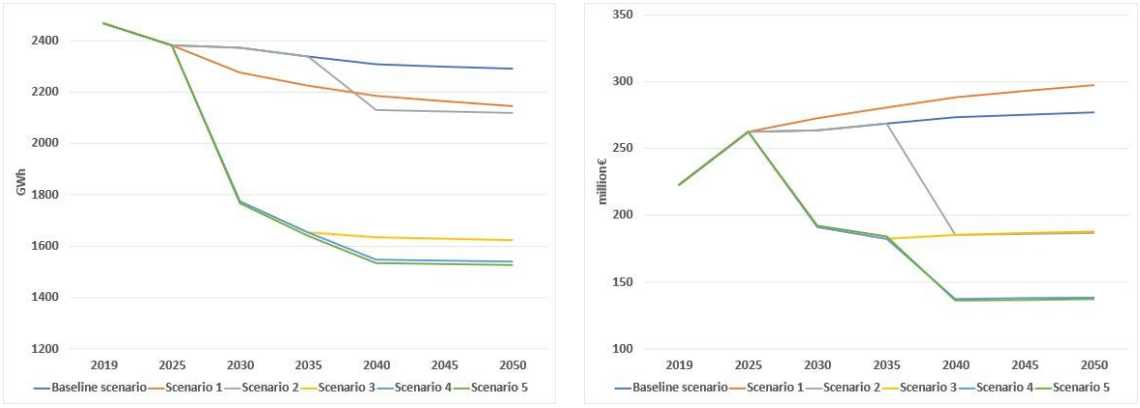


(a) (b)

Figure 9-9 Country analysis for Czechia. (a) Final energy consumption: comparison of different scenarios in Czechia. (b) Final energy costs: comparison between scenarios in Czechia.

Greece

All scenarios lead to lower energy consumption in Greece with only the baseline and scenario 1 leading to higher expenditures. In this case, scenario 2 leads to lower expenditures due to the high share of heating oil in Greece. In fact, this is the most expensive fossil fuel, and its phase out will thus lead to great price reductions. Specifically, in Greece scenarios 2 and 3 have the same expenditure decrease, although with the latter presenting a drastically higher reduction in energy consumption. This is preferable, as essentially in scenario 2 what is happening is a detachment from an expensive fossil fuel rather than an increase in energy efficiency (Figure 9-10)

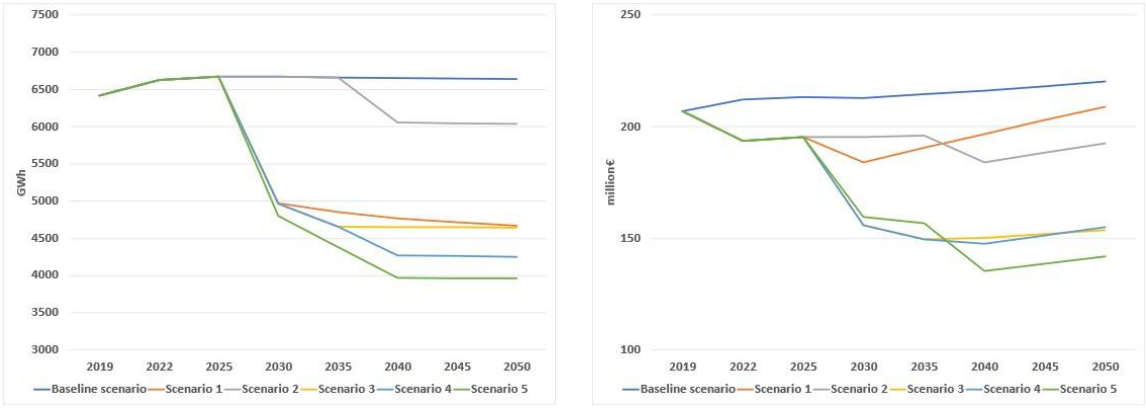


(a) (b)

Figure 9-10 Country analysis for Greece. (a) Final energy consumption: comparison of different scenarios in Greece. (b) Final energy costs: comparison between scenarios in Greece.

Hungary

In Hungary, the baseline scenario entails both a higher energy consumption and expenditure in 2050 compared to 2019. Interestingly, scenario 1 presents a substantial decrease in energy consumption however coupled with an increase in expenditures. This is due to a high share of gas in its final energy consumption. In fact, since it will not be possible to phase it out completely just by applying the ETS to the residential sector, low-income groups will try to reduce its consumption as much as possible although still incurring higher energy costs (Figure 9-11).

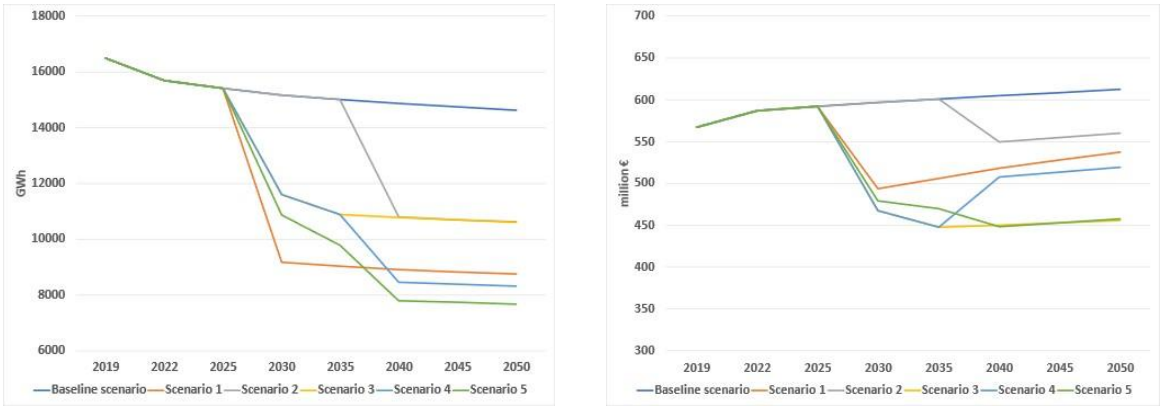


(a) (b)

Figure 9-11 Country analysis for Hungary. (a) Final energy consumption: comparison of different scenarios in Hungary. (b) Final energy costs: comparison between scenarios in Hungary.

Poland

All scenarios result in lower energy consumption in Poland whereas all scenarios except the baseline one result in lower expenditures. Due to Poland's high coal share in its energy mix, scenario 1 results in a greater reduction in energy consumption compared to scenarios 2 and 3. Additionally, scenario 1 presents also lower energy expenditures in 2050 compared to scenario 2. It can be thus argued that scenario 1 is effective in a greatly solid fossil-fuel-dependent country (Figure 9-12).



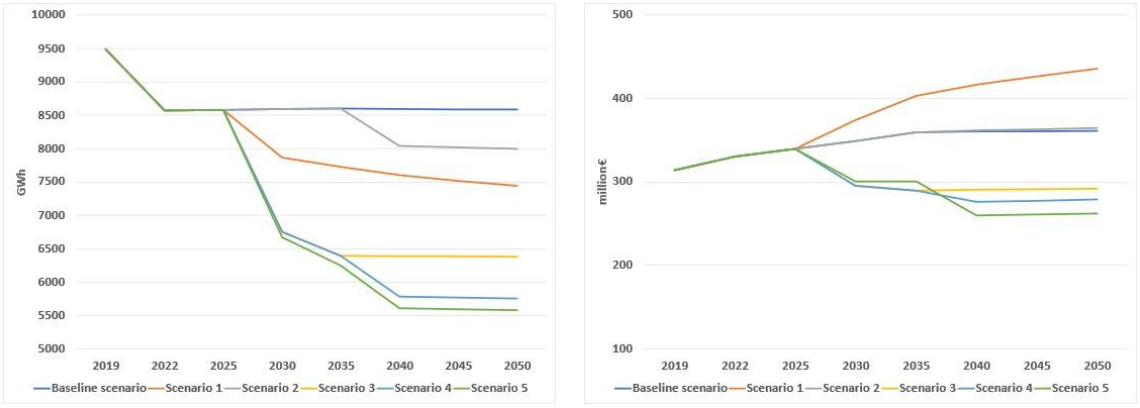
(a) (b)

Figure 9-12 Country analysis for Poland. (a) Final energy consumption: comparison of different scenarios in Poland. (b) Final energy costs: comparison between scenarios in Poland.

Romania

Romania presents lower energy consumption with all suggested scenarios. Interestingly, scenario 1 performs better than scenario 2 in terms of consumption. However, in terms of

expenditure, scenario 1 presents higher values even when compared to the baseline scenario. Romania is highly dependent on biomass, which was assumed to remain constant in usage and price. Natural gas being the second most used fuel, its reduction will be minimal compared to the incurred costs in scenario 1 (Figure 9-12)

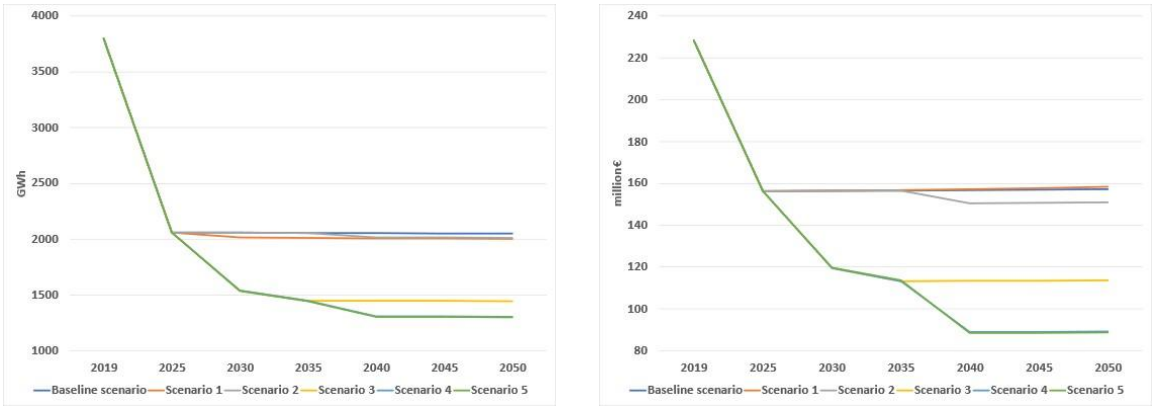


(a) (b)

Figure 9-13 Country analysis for Romania. (a) Final energy consumption: comparison of different scenarios in Romania. (b) Final energy costs: comparison between scenarios in Romania.

Slovakia

Slovakia presents lower energy consumption and expenditure in all scenarios. The scenarios yield similar results when comparing the energy consumption and expenditure. Interestingly, scenarios 4 and 5 present practically the same results, highlighting how the ETS extension does not have a great influence and effect in Slovakia (Figure 9-14)



(a) (b)

Figure 9-14 Country analysis for Slovakia. (a) Final energy consumption: comparison of different scenarios in Slovakia. (b) Final energy costs: comparison between scenarios in Slovakia.

9.5.1. Discussion

Insights on the Low-Income Households Policy Specifics

How these results transfer to the specific household is evaluated using qualitative and quantitative indicators. Energy poverty indicators are well known and include five dimensions (low income compared to costs, high share of income spent on energy, inability to pay bills, housing faults, and the inability to keep warm). To avoid redundancies for precision (Sokolowski et al, 2020), distributional aspects of the three policies on low-income households for every scenario are described using three factors (energy costs, income, and energy efficiency) (Tundys et al., 2021), where the quantified adverse effect is based on the income dimensions. In addition to compensation variation showing that energy poor households without proper public funding end up with higher levels of income poverty, research (Streimikiene, Kyriakopoulos, 2023) shows that energy poverty not only changes living conditions but also influences health, social activity and inclusion (Robic et al., 2018), local environment, education, and many other aspects of life. It is, therefore, important to also look closely at the non-energy impacts of the proposed policies that are to help with the adverse effects of transition to the low-income groups. In all the aspects of any of the policies targeting energy poverty alleviation (like evaluation or monitoring), all the indicators should be taken into consideration to avoid additional negative effects on the low-income households (Figure 9-15).

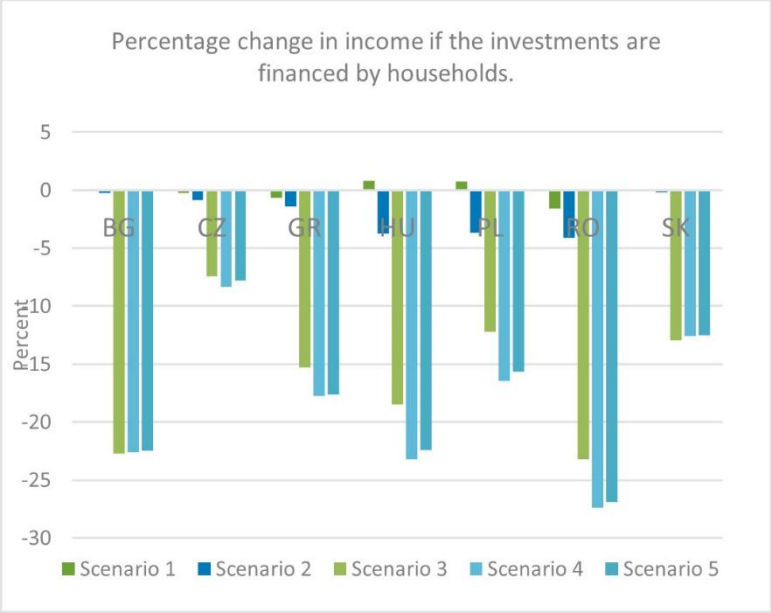


Figure 9-15 Percentage change in average income of the low-income group in 2050 compared to 2019 without investment financing.

From the percentage change of the average income without financing, it becomes clear that, no matter the expenditure decreases in the medium run and the thermal comfort improves, the disposable income is too low and therefore blocks the investments, making it impossible for low-income households. Additionally, evidence (Damigos et al., 2021) shows that vulnerable households use a higher discount rate compared with average, therefore choosing short-term solutions as opposed to long-term investments. Covering the upfront costs using the Social Climate Fund and additional funding directed to vulnerable groups would result in a positive change of the average income of the low-income groups and external positive effects (Figure 9-16).

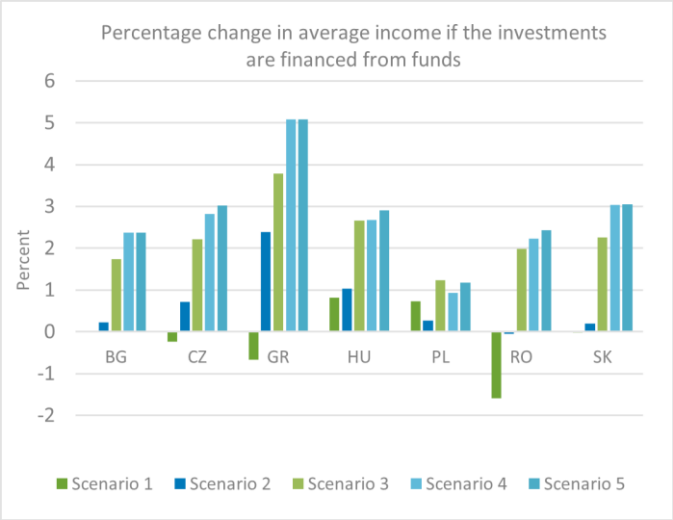


Figure 9-16 Percentage change in average income of the low-income group in 2050 compared to 2019 with investment financing.

9.6. Policy Implications

The study investigated the impacts of the recent energy policies on the low-income group of households. Based on the analyses, the following recommendations are suggested:

- The financing possibilities should be shifted from new and upgraded fossil fuel boilers to new and renewable heating systems before 2025. Phasing out of fossil fuel boilers from the market will not automatically lead to the replacement of existing fossil boilers, especially in the case of low-income households due to the existing high upfront costs as well as policies encouraging the installation of gas boilers. In the countries' short-term measures for the energy crisis (next to the income-support ones), there are still subsidies for fossil fuel use in heating as well as for installing fossil fuel heating systems, for example, in Bulgaria, Greece, Poland, and partly in Croatia. Therefore, it is important to phase out such subsidies even before 2025, as

on average boilers have a lifetime of 20 years and it would require a minimum of 5 years to fully implement the phase-out (thus, to be carbon neutral by 2050, these changes would have to be made 25 years before). This process will speed up if funds are allocated for phasing out fossil fuel boilers and shifting to clean heating systems.

- Include subsidy schemes for the energy efficiency with as high as possible funding rates (total investment wherever possible) for low-income households. Measures should also include technical guidance and assistance. These subsidies should be starting before 2025, with information available for the low-income groups. It is also relevant to emphasise that the introduction of MEPS should accompany such phase-out as important in low-income households. For example, the Clean Air Program, 22.7 billion EUR, is planned to run until 2029 in Poland, providing 90% of investment costs for low-income groups of households to invest on efficient heat resources.
- Prioritise the Energy Efficiency First principle. In view of the updates of the NECPs and the new EED Article 3 (for the E1st principle), countries can benefit and start planning based on the energy efficiency requirements. Through MEPS, for instance, (when introduced with the phasing out of fossil fuel boilers) their implementation is not resulted in additional emissions, or higher costs for the low-income, despite the extra costs of the plan.
- Scenario 5 (all three measures included) provides a relevant signal and generates important effects on the consumption and energy expenditure of low-income groups. Even if we consider the phase-out as significant and cost-effective for using simplified repayment analysis, without MEPS there is no change in the quality of life and thermal comfort of the low-income households plus there is no lower energy demand and costs.
- The Social Climate Fund (for which it is obvious), the ETS2 auctioned revenues and the funding streams from Recovery and Resilience plan should include concrete energy efficiency actions for low-income citizens. In some countries, the Social Climate Fund and expected revenues from ETS2 allowances are enough for covering the cost of three measures (increased energy expenditure, investment costs for new heating and refurbishments), but only for low-income households. Part of the available funding allocated to the residential sector will focus on energy and transport poverty as a whole, thereby including a much larger number of households in each country than the specific target group of this study (the lowest income decile households). All of these programmes (even SCF in some way) include a budget for the bigger energy efficiency programs (with an average of 40–50% financing rate),

with no specific support to low-income households. Those are to be financed with a higher percentage.

- Regulation is to include insight into the energy behaviour of low-income groups. There is a lack of data to determine the price elasticity and changes in energy consumption, all the behaviour changes. An incentive based on the price, ETS2, for example, results in lower thermal comfort deriving from lower energy consumption. This is why it is important to provide a good combination of policies and measures.

9.7. Summary and Conclusions

Despite the unavailability of data concerning energy poverty indicators from the months following the start of the Ukrainian war and price increases, a disruption of positive trends in energy poverty reduction can be observed beginning in 2021. These trends, in combination with price rises, expected inflation, risk of increased poverty, lower GDP, and weakened growth indicate the existing burden on countries to lower these adverse effects. Considering the inflation due to energy prices, energy poverty indicators will likely worsen in 2022 compared to 2021. EU member states have opted to alleviate the higher burden of energy costs with price regulations, energy bill assistance as well as tax reductions on energy bills. Nevertheless, these are not considered structural measures for the low-income groups and they should be combined with energy efficiency upgrades and heating decarbonisation. Moreover, the higher upfront costs of energy efficiency investments combined with the well-known and documented structural barriers do not make energy efficiency as a key priority of low- and middle-income groups, although the payback time of such investments is shortened due to the higher energy prices. Their reduced disposable income (due to the higher energy prices) is hampering the possibility to invest in renovations and clean heating solutions, while the incumbent fossil fuel subsidies further delay the investments in clean heating. Therefore, if the available funding, such as subsidies on energy efficiency and heat pumps are not increased for low-income households, the energy crisis and inflation may even delay energy efficiency investments to remove fossil fuels for heating in these households. To combat this, a complementary package of support with financial, technical, and information measures from the national and local authorities can help accelerate energy efficiency investments and a switch to clean heating. Additionally, the dependence on imported gas of the analysed countries varies widely. This needs to be considered when evaluating the ability of a country to react to the changes deriving from the implementation of three targeted Fit for 55 policies. The dependence on imported gas influences the energy price, and with it, member states' new expenditures to cover the energy costs of households via bill aid. However, the EU Emissions Trading System

extension (ETS2) and phasing out of fossil fuel boilers will lead to the diversification of energy sources due to the requirement of cleaner sources or electrification in heating and price incentives (in the case of ETS2). A lower fossil fuel usage and therefore a lower gas import are expected due to these policies. The combination of the three policies can provide the best results both in terms of utilisation of energy and expense reduction for all countries (except Poland). When no additional policy measures were implemented, the highest envisioned energy consumption was incurred. With regards to energy expenditures, for half of the analysed countries, these would be higher when implementing the ETS2 prices than in the baseline scenario. This is due to the higher ETS2 energy prices and an inefficient phase-out of solid fossil fuels, as the latter would happen only due to higher fuel prices, without a coordinated phase-out policy measure. Moreover, new ETS2 as an alone policy measure can incur the highest energy reduction, which also results in thermal comfort loss for low-income groups, as no structural effects in the demand reduction take place. In addition, the implementation of measures aimed at improving energy efficiency in general, such as the introduction of MEPS, rather than targeting energy prices will provide more homogenous energy improvements throughout, resulting in homogenous price trends and more equally spread benefits to low-income households.

9.8. Recommendations for Future Research

The present study suggests several areas that could be explored in future research. These areas primarily stem from the lack of data on crucial parameters necessary for accurate calculations. The authors aim at gathering more detailed data in one EU member state (presumably Croatia) and test the developed methodology. The subsequent paragraphs delineate the key parameters that require further investigation and were not encompassed in the current research:

(a) Evaluation of price elasticities among low-income groups: Price elasticity plays a crucial role in evaluating the susceptibility of low-income households to price hikes stemming from the execution of ETS2 and other policy scenarios. It is important to delve into the non-linear effects of ETS2 and other policy scenarios, as indicated in a prior study. The response to heightened energy prices involves investing in energy efficiency measures and switching fuels or suppliers. However, low-income groups typically possess limited options, and their reduction in energy consumption primarily stems from decreased demand. Consequently, if the average elasticity is considered, any savings in energy expenditure that do not arise from fuel switches or energy efficiency measures will negatively impact the vulnerability of low-income groups. Factors such as wealth distribution and income disparity should be examined to attain accurate elasticities, as different countries exhibit distinct

socioeconomic characteristics. Additionally, elasticities will be influenced by the fuel composition in final energy consumption.

(b) Determination of replacement rates for fossil fuel boilers across different income groups: Information regarding the rate of boiler replacement is necessary for calculating the overall costs of fossil fuel boilers as well as reductions in energy consumption and CO2 emissions. Research has indicated lower rates of boiler replacement among low-income households compared to other groups. However, the response rates specifically for these groups are not available. In general, low-income households might exhibit slower responses to market ban measures due to their higher discount rates in comparison to the average household. This implies that low-income households may prefer short-term solutions or find themselves in situations where they have limited choices for long-term investments.

10. EVALUATING THE EFFECTS OF DECARBONISATION POLICY ON MICRO-ENTERPRISES

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Title: Evaluating the effects of carbon pricing on micro-enterprises: a methodological study with a focus on the EU ETS2

Journal: Climate Policy, Online ISSN: 1752-7457, Taylor & Francis

In 2nd review round

10.1. Abstract

This paper demonstrates a transparent, policy-oriented methodology to quantify carbon-pricing impacts on micro-enterprises, with focus on the Emissions Trading Scheme for buildings and transport (ETS2), under severe data constraints. We build a representative bottom-up baseline of final energy consumption for micro-enterprises to approximate heterogeneity by sector and operational profile. ETS2 impacts are simulated for 2027–2032 using fuel-specific carbon-cost pass-through and demand responses based on available price elasticities, distinguishing building-only, mixed-use, and transport-intensive micro-enterprises. We then operationalise a Social Climate Fund - consistent vulnerability indicator, applying a sectoral relevance filter to avoid misclassification where energy costs are marginal. Results from selected Member States show strongly heterogeneous burdens, with transport-intensive activities facing the highest per-firm impacts, and the framework identifies a non-trivial vulnerable tail that is highly sensitive to baseline profitability and investment assumptions. The approach enables comparable, auditable targeting of compensatory and investment-support measures in Social Climate Plans and highlights priority data improvements needed to reduce governance risk and mistargeting under ETS2.

10.2. Introduction

10.2.1. Role of carbon pricing policies in decarbonisation with the focus on the emissions trading systems (ETS)

Carbon pricing mechanisms, including carbon taxation and emissions trading systems (ETS), are established policy tools for addressing greenhouse gas (GHG) emissions. These instruments operate on the principle of internalising environmental externalities by assigning a monetary cost to emissions. (Trinks et al., 2022) By increasing the cost of carbon-intensive activities, they incentivise emission reductions, energy efficiency improvements, and the adoption of cleaner technologies. (Samuel, 2025) Research shows they seem to be effective in reaching the objective or emissions' reduction. (Ahmad et al., 2024)

The ETS operates on a cap-and-trade principle, setting an overall limit (cap) on emissions and distributing allowances that entities can trade. This system provides economic flexibility for participants. The European Union (EU) ETS, initiated in 2005, was the world's first large-scale implementation of such a policy and the cornerstone of the EU's climate policy. (Verbruggen et al., 2019) It sets a declining cap on emissions and allows regulated entities to trade emission allowances within a carbon market. (Narassimhan et al., 2018) The EU ETS has undergone several phases of development, with reforms aimed at enhancing its effectiveness and addressing issues such as allowance overallocation and price volatility. (European Commission, 2020)

10.2.2. ETS extension to buildings and transport

To expand sectoral coverage, the EU will launch an extension of the emissions trading system (ETS2) in 2027, targeting fuel suppliers for buildings, road transport, and small industries not covered by the current ETS. ETS2 regulates upstream actors based on the carbon content of fuels, with some costs expected to pass to end-users. (European Commission, 2025a) Of course, many questions were raised on the topic, for example the evaluation possibilities for combination with other decarbonisation policies. (Nysten, 2024) This emphasises the relevance on how complementary policies are designed, how they are sequenced and, most importantly, what is the distribution of the social burden. (Günther et al., 2025)

10.2.3. Micro-enterprises in Europe

A micro-enterprise (M-E) is a business with fewer than ten employees and an annual turnover or balance sheet total not exceeding EUR 2 million. (European Commission, 2003) The role of M-Es in the European economy is evident: they account for 93.7% of businesses in the EU, forming the backbone of many industrial ecosystems and value chains. (European Commission, 2024) Their economic contribution is also substantial, generating nearly 17% of the EU's total net turnover, according to Eurostat's Structural Business Statistics. Their sectoral distribution is heterogeneous but concentrated in selected economic activities. At EU level, the largest shares of M-Es are found in wholesale and retail trade (approximately 22%), construction (around 26.2%), and accommodation, food services and other personal services (together roughly 15–20%, depending on Member State). (European Commission, 2024) This distribution implies exposure to both building-related energy use and transport-related fuel consumption, although intensity varies across sectors. M-Es face structural challenges, limited financial and human resources, lack of strategic capacity, and minimal influence on policy. (Pedraza, 2021)

Compared to households, they represent a far more heterogeneous and underexplored group. Their small size belies their collective impact, yet their energy consumption is often statistically embedded within aggregated sectoral data, which limits its visibility in many national and EU-level energy transition strategies. In recent years, SMEs, including M-Es, have begun to receive increased attention in EU energy and climate policy frameworks. Scholars have increasingly recognized this as a policy gap, as also for SMEs. (Herce et al., 2024) One of the key structural limitations concerns the lack of energy data disaggregated by firm size and economic activity (NACE classification) specific to M-Es. They are not separately available in energy statistics, making it difficult to design targeted and effective policies. They are required to juggle multiple competing business priorities, including efforts toward digital transformation, international expansion, and the optimization of operational models like just-in-time production. (Agrawal et al., 2023) All of this makes them particularly vulnerable to energy price changes, such as the forthcoming ETS2.

10.3. Literature review and research context

10.3.1. Effect of carbon pricing on vulnerable groups

A central concern in literature is the regressive nature of carbon pricing, as low-income groups typically allocate a higher share of their income to energy and energy-intensive goods. Systematic evaluations of carbon market design emphasise the need for continuous refinement. Experts and researchers highlight the importance of considering economic factors in the design of carbon pricing mechanisms. (Ford, 2024) EU ETS is considered by researchers as somewhat unjust climate policy in its existing form, due to inequitable burden-sharing caused by ambition rather than inherent flaws in emissions trading. (Dirix et al., 2015) (Dorband et al., 2019) provide empirical evidence from 87 countries, demonstrating that in the absence of redistributive measures, carbon pricing leads to a higher relative burden on poorer income deciles, especially in developing economies. This is corroborated by recent analysis on the distributional effects across the EU showing that despite the environmental effectiveness of carbon-pricing related mechanisms, without accompanying compensation, vulnerable households and M-Es are disproportionately affected. (Cui et al., 2025)

Besides income disparities, regions heavily reliant on carbon-intensive industries also face structural challenges. The transition away from fossil fuels can lead to concentrated job losses, particularly in coal-dependent areas. As the World Bank observes, just transition policies must accompany carbon pricing to mitigate regional disparities and support re-skilling initiatives for affected workers. (World Bank, 2023) An additional aspect of vulnerability is on the structural level, where rural areas or areas with limited low-carbon

infrastructure are more vulnerable, indicating a regressive distribution of burdens.(Perdana and Vielle, 2026) However, only limited empirical research currently examines the effect of energy prices on micro-enterprises. (Rogulj, 2025), (SME United, 2025) Consequently, the financial burden imposed by carbon pricing tends to weigh more heavily on these consumers, potentially exacerbating existing socio-economic inequalities.

Nevertheless, several studies propose that the regressivity of carbon pricing can be effectively addressed through revenue recycling. Redistributing the revenues via lump-sum rebates, targeted subsidies benefitting micro-enterprises, or social welfare programmes can offset negative distributional impacts. Recycling 40%–50% of carbon tax revenues towards low-income groups can not only neutralise but also reverse regressivity, yielding a net progressive outcome. (Black, 2022) (Green and Denniss, 2018)

Distributional concerns of new ETS2, within and across countries, are considered key to policy design by multiple authors.(Haywood and Jakob, 2023; Ohlendorf et al., 2021), (Rogulj et al., 2023) This is also recognised by the legislator, therefore the part of the revenue will fund the Social Climate Fund, aimed at offsetting impacts on low-income households and micro-enterprises through support for energy efficiency, income aid, and infrastructure.(European Commission, 2025b),(Ritter, 2022) In its parts, Social Climate Fund addresses the vulnerabilities of micro-enterprise coming from the effects of the new ETS2 on them, and that is what we address further on.

10.3.2. Objective and concept of the research

In our literature review, we show that the effects of the carbon pricing and in particular ETS2 on the vulnerable groups, has been already evaluated using multiple indicators. However, the focus has rarely been on the business sector and particularly M-Es. The SCF regulation has recognised this group as vulnerable to energy expenditure changes. Therefore, we:

- focus on developing the calculation model to evaluate effects of carbon pricing on M-Es. The model is best described as a bottom-up calculation model designed to estimate final energy consumption of M-Es across the building and transport sectors,
- use micro-simulations to evaluate how M-Es are burdened in terms of profit loss and transfer, while defining vulnerability indicator,
- evaluate what this means in terms of numbers, a population of M-Es, type, size and sector, vulnerable to the effects of carbon pricing mechanisms like ETS2.

We conclude with recommendations for further research, with a primary focus on policy implications, returning to key themes already identified in the literature, such as the design and sequencing of complementary measures.

10.4. Methodology

10.4.1. Data used and assumptions

To better understand how the introduction of ETS 2 might impact M-Es across the EU, we assess different elements including energy consumption, business activities, and financial resilience. The assessment of data availability for M-Es reveals a gap in the accessibility and reliability of key information.

At the sectoral level, information on the distribution of M-Es by economic activity is available through Eurostat Structural Business Statistics (SBS), notably the *sbs_sc_ovw* dataset. While this source provides a detailed overview by size class, it relies on a size-based definition of M-Es that does not fully align with the official EU definition used in policy contexts. With respect to energy expenditure for on-site fossil fuel use, partial data are available from Eurostat energy statistics, such as *nrg_10m* for gas consumption, disaggregated by consumer size. However, these datasets do not clearly include M-Es that do not use commercial- tariff energy. As a result, overlaps between household and business consumption remain unresolved, making it difficult to isolate M-E energy expenditure. Energy expenditure related to transport is even more constrained. Eurostat datasets such as *ten00127* provide information on transport energy use, but only at the level of the entire transport sector. There is no statistical disaggregation that would allow identification of transport energy costs or fuel use attributable specifically to M-Es. In addition, vehicle registration statistics do not systematically distinguish between vehicles registered for private use but utilised for business activities, and vehicles formally registered to companies but used for mixed personal and commercial purposes. This lack of clarity regarding ownership and usage patterns further constrains the accurate attribution of transport-related energy consumption to M-Es.

Indicators intended to proxy financial capacity, such as company turnover from Eurostat SBS (*sbs_sc_sca_r2*), are available in principle, but turnover and turnover-related indicators are not reported by both size class and economic activity in a way that allows consistent M-E analysis. This significantly limits the ability to assess the means of M-Es to invest in energy efficiency or renovation measures. Data on the investment needs of M-Es for building renovation are not available at the European level. Information that would be required for such an assessment, such as the energy performance of buildings used by M-Es, the age of the building stock, or the existence of energy audits or EPCs, is not systematically collected

or linked to enterprise characteristics. A similar gap exists for transport transition needs: there is no harmonised European data on current transport usage by M-Es, fleet composition, number of vehicles, or investment needs related to switching to alternative fuels or mobility options.

At the regional level, while GDP data could in principle be used as a proxy for regional economic development and investment capacity, there is no direct European-level dataset linking regional economic performance to the ability of M-Es to invest in energy alternatives or renovation measures. (Rogulj et al., 2025) Therefore, EU level data is complemented with national data on number of companies, energy prices and tariffs, along with available statistics on turnover and value added. This does not, still, provide all the needed information.

To address these limitations, this study employs complementary approaches, including the use of research databases (Moody's ORBIS database, "Orbis | Company information across the globe | BvD"), approximation techniques, and modelling methods. Research databases provide secondary data that offer valuable insights and serve as proxies for missing information, while approximation techniques enable the estimation of key variables based on available data or relevant benchmarks. As Orbis covers only samples of firms in each country, M-E data are extrapolated to sectoral totals, with country-level coverage assessed against official statistics. Despite uneven coverage, the use of Orbis enables bottom-up modelling of energy consumption and intensity for M-Es, offering a more granular and context-specific assessment than aggregate statistics.

The energy consumption baseline for M-Es is estimated across two components: buildings and processes (including space heating, domestic hot water, cooking, and activities) and transport. Building-related energy use is derived from the JRC IDEES 2021 database, which provides Member State- level energy consumption by end use but not by sector or firm size. (Rozsai et al., 2024) This database focuses exclusively on thermal energy uses within buildings, namely space heating, domestic hot water, and cooking. The impacts of ETS2 on the energy costs of buildings are assessed by analysing national fuel price data in conjunction with fuel-specific CO_2 emission factors, while also incorporating projections of future changes in the ETS2 carbon price.

Discussion on elasticities

The responsiveness of M-Es to changes in energy prices is not well established in literature. While energy demand elasticity has been studied for households and larger firms, much less is known about how small, or especially M-Es adjust their energy use in response to price increases. It is likely that responses vary widely depending on the sector, energy intensity

of operations, and access to financial or technical resources. Some M-Es may have limited flexibility to adapt due to financial constraints or fixed energy needs, while others may be more agile and able to shift behaviours or invest in efficiency when incentives are in place.

To approximate potential responses, we applied a hybrid approach, drawing on available elasticity estimates from both the commercial and household sectors, acknowledging that M-Es often exhibit characteristics of both and using literature. (Labandeira et al., 2017) This approach allows for a more informed, though still approximate, assessment of likely behavioural and consumption shifts in response to energy price changes under ETS 2.

10.4.2. Establishing the energy consumption baseline using representative bottom-up estimation (without available data)

We first estimate the baseline energy consumption of M-Es in two principal domains: building energy use and transport energy use. A bottom-up modelling approach is used, combining engineering-based energy demand estimation with a representative agent framework. (Sanchez-Escobar et al., 2021) and (Raggio et al., 2020) argue that for cross-sector comparison, the most relevant indicator of energy efficiency should be energy productivity. However, the most used indicators of energy efficiency are rather straightforward and link energy consumption to an economic activity in physical terms. (Kotsopoulos et al., 2023) In the case of M-E, the simplest indicator can be energy consumption per employee, due to differences among M-E.

For both domains, we simulate typical consumption patterns using disaggregated sectors' energy use data and assumptions tailored to the M-E scale.

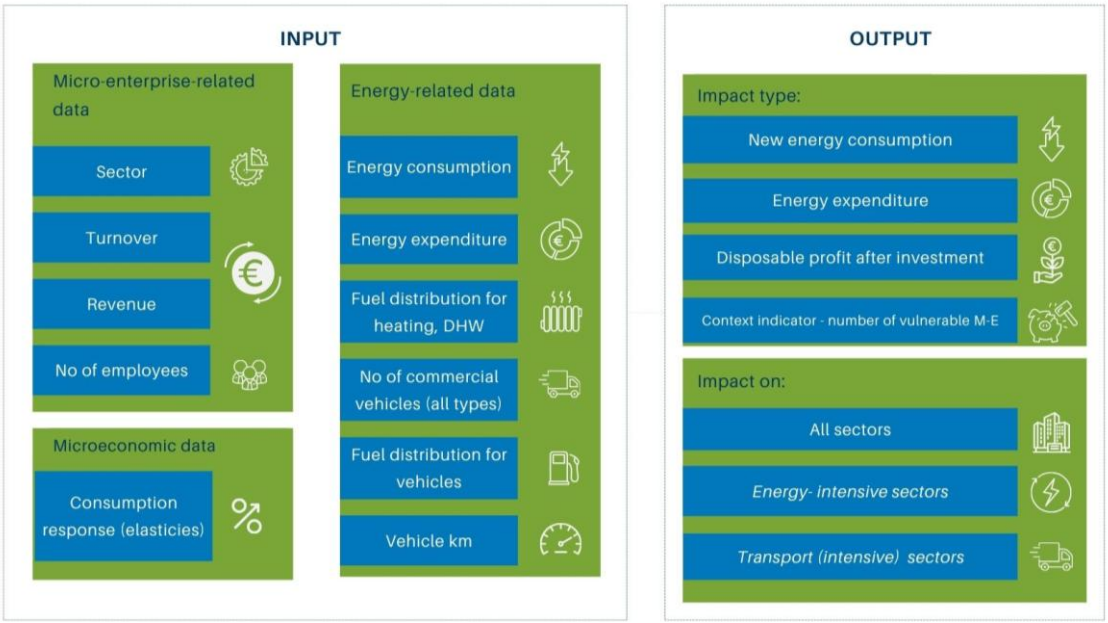


Figure 10-1 Calculation inputs and outputs, authors

10.4.3. Estimating Building Energy Consumption

The calculation of building-related energy consumption is based on the analysis of thermal energy use: space heating, domestic hot water (DHW), and cooking. The primary data source is the Integrated Database of the European Energy System, which provides energy consumption profiles for service-sector buildings at the Member State level. (Rozsai et al., 2024) As IDEES does not distinguish consumption by firm size, a scaling approach is employed to estimate M-E consumption.

Deriving Useful Energy Consumption Per Employee

Useful energy consumption is first normalized per employee using the following relationship:

$$UEC_E(kWh) = \frac{UEC_B(kWh)}{SIZE}$$

- *UEC_B= Useful energy consumption/building for different purposes – available data*
- *UEC_E = Useful energy consumption/employee*
- *SIZE= Representative building cell size (employees/representative building cell) – available data*

Useful energy values are adjusted to reflect final energy consumption based on the efficiency of energy conversion technologies:

$$FEC_{E(HNG)}(kWh) = FEC_{E(HNG)}(kWh) \times Eff$$

- *FEC_E = Final energy consumption/employee- calculated*
- *FEC_E = Useful energy consumption/employee- calculated*
- *Eff = Efficiency of certain energy transformations (useful to final energy) – known data*
- *NG= natural gas (used as example)*
- *H= heating (used as example)*

This calculation is repeated across relevant fuels (gas, oil, LPG) and thermal end uses (heating, DHW, cooking). The result is an estimate of final energy consumption per M-E, scaled by the number of employees:

$$FEC_{ME(HNG)}(kWh) = FEC_{E(HNG)}(kWh) \times N_{emp/ME}$$

- *FEC_{ME} = Final energy consumption/ME- calculated*
- *NG= natural gas (used as example)*
- *H= heating (used as example)*
- *$N_{emp/ME}$= number of employees/ M-E*

Fuel Mix Scenarios

To capture differences in fuel use, several scenarios are developed based on the share of buildings with different installed energy carriers for each thermal service. These include:

- Natural gas used for all thermal services.
- Oil for heating and DHW, LPG for cooking.
- Oil for heating; electricity for other services.
- LPG for cooking; electricity for heating and DHW.

The percentage distribution of each energy carrier by end use is drawn from IDEES:

- F_P = Percentage of buildings using certain energy carrier for different energy us -available data (F_{PHeat}, F_{PDHW}, F_{PCook})- available data

Note: Due to a lack of data distinguishing between commercial and private premises, it is assumed that all M-Es operate in commercial buildings, though in practice many operate from residential spaces.

10.4.4. Estimation of Baseline Energy (Fuel) Consumption in the Transport Sector

The estimation of baseline energy consumption in the transport sector presents a greater level of complexity compared to the building sector. The adopted methodology distinguishes two categories of M-Es:

- Typical M-Es owning a single vehicle.
- Transport-intensive M-Es, which typically operate multiple vehicles due to the nature of their business activities, machinery excluded

As an initial step, vehicle distribution is categorized by fuel type and ownership status, utilising national datasets (JRC IDEES), supplemented with informed assumptions. The vehicle fleet was segmented into fuel categories (gasoline, diesel, LPG, and others) and further disaggregated by ownership (private, corporate, or public). This classification establishes the analytical foundation for estimating energy consumption patterns and emissions differentiated by ownership structure and fuel type.

GROUP1: Average M-Es

Based on the total fleet of commercially owned cars, we estimate the proportion of vehicle owned by M-Es by analysing ownership patterns and distribution trends within the commercial fleet. We allocate passenger cars to M-Es based on the number of employees. We use turnover to allocate a share of other vehicle ownership on M-Es.

Fuel consumption data per car is averaged based on data available in literature, while vehicle-kilometres statistics are derived from the JRC IDEES database, supplemented with national resources for greater accuracy and timeliness.

$$FEC_{car} = \frac{D_{car}(km)}{100} * C_{fg}\left(\frac{l}{100km}\right) * F_{fg}$$

- *FEC_{car}= Final energy consumption/car (kWh)- calculated*
- *D_{car}= Average distance/car in a year – available data*
- *C_{fg} = Fuel consumption per car - available data*
- *F_{fg} = Fuel factor (kWh/l) - available data*
- *G= gasoline (used as example)*

GROUP2: Transport-intensive M-Es

We define as transport-intensive M-Es those operating in sector or economic activities that rely heavily on transportation for the movement of goods, services, or personnel. Examples include logistics, delivery services, passenger transport services (NACE codes: Construction of residential and non-residential buildings – NACE F4120, Urban and suburban passenger transport - H493, Taxi operations - H4932, Other passenger transport by land - H4939, Freight transport by road - H4941, Other postal and courier activities - H5320, Event catering activities - I5621 and Tour operator activities - N7912) and certain companies where material inputs and distribution require substantial transport infrastructure.

Transport-intensive sectors are assigned an average number of vehicles based on a combination of national data, informed assumptions, and survey results, where such data is available. This approach ensures a reasonable estimation tailored to the specific characteristics and operational needs of these sectors. The problem with transport is the same as for buildings, consistent data on the exact number of vehicles owned by M-Es is lacking, particularly given that many M-Es use privately owned vehicles for business purposes. Consequently, our estimates account for both the per-company use and the total use.

10.4.5. Scenario- based impact assessment methodology for carbon pricing effects

As part of the analytical framework, we evaluate the projected impact of energy price changes resulting from the implementation of the second phase of the Emissions Trading System (ETS2). This component of the analysis facilitates a quantitative assessment of how the revised carbon pricing mechanism influences energy-related expenditures across varying consumption profiles. Data sources and additional information include UNFCCC: Greenhouse Gas Emissions Calculator; 2021 Emission Factors (UNFCCC); Eurostat (2024): Gas prices for non-household consumers (CBI dataset); national prices for all fuels in consumption (example: average price of oil distributed to non-household consumers),

country-level information: for example VAT in Croatia on natural gas was 5%, and from 2025 returned to 13% etc.

The analysis models the annual progression of ETS2-related price impacts over the period 2027–2032, assuming a linear increase in carbon prices. This evaluation encompasses a variety of building energy use configurations and vehicle categories. Other concurrent or future policy interventions are excluded to isolate the effect of ETS2. Each scenario is constructed to reflect distinct energy consumption patterns, both in terms of magnitude and composition, corresponding to specific business activity types. Energy price adjustments are applied to baseline consumption figures to determine changes in total energy expenditure under ETS2.

Example: M-Es with cars using diesel

The first step is to calculate energy price increase:

$$\delta P_{EDn} = EF_D X \delta P_{ETS2(n,n-1)}$$

- *δP_{ED} = (Diesel) energy price increase*
- *EFD= Diesel emission factor (kg CO2/kWh)- available data*
- *δP_{ETS2} = ETS2 price increase (€/tn) – calculated*
- *n= year*

1. Using baseline energy consumption and price elasticities, final energy consumption for every year is calculated as:

$$FEC_{D,n} = FEC_{D,n-1} \times (1 + \delta P_{ED} \times \frac{PED}{P_{ED,n-1}})$$

- *$FEC_{D,n}$ = Final energy consumption of diesel fuel for year n– calculated*
- *$FEC_{D,n}$ = Final energy consumption of diesel fuel for year n-1– calculated*
- *δP_{ED} = (Diesel) energy price increase– calculated*
- *P_{ED} = (Diesel) energy price– calculated*
- *PED = price elasticity of demand- available data*
  /in case of country different elasticities from documented sources or national plans (such as NECPs), the new elasticities can be used/

We estimate the energy consumption of diesel/ car after the introduction of the ETS2, for every year of the period 2027-2032, as well as the new energy expenditure based on the

energy price which includes ETS2 costs ($Additional\ expenditure = FEC_{D,n} \times P_{ED,n}$) We expect that M-Es will reduce their energy consumption in response to the increase of the fuel price (at a rate determined by the elasticity of each fuel).

10.4.6. Microsimulation for determination of effects

Building on the baseline energy consumption estimates, a microsimulation framework is applied to assess the effects of ETS2-related energy price changes on M-Es. The microsimulation is implemented as a bottom-up, representative-agent model that simulates the evolution of energy consumption and energy expenditures at the level of individual M-E profiles over the period 2027–2032. Each M-E is characterised by a specific combination of attributes, including sector affiliation, number of employees, building energy carrier mix, vehicle ownership and fuel type, and baseline energy consumption derived from the bottom-up estimation described above.

Fuel-specific price adjustments are applied based on emission factors and carbon price trajectories, with behavioural responses modelled through price elasticities that allow energy consumption to adjust over time. The simulation updates energy use, prices, and expenditures across representative micro-enterprise profiles, capturing heterogeneous impacts that are not visible in aggregate statistics. The microsimulation outputs provide a quantitative basis for comparing the relative burden of ETS2 across different M-E types and energy use structures.

10.5. Determination of effects on vulnerability

The SCF regulation describes a category of vulnerable MEs, which "…are significantly affected by the price impacts of the inclusion of greenhouse gas emissions from buildings or road transport within the scope of Directive 2003/87/EC and that, for the purpose of their activity, lack the means either to renovate the building they occupy, or to purchase zero- and low-emission vehicles or to switch to alternative sustainable modes of transport, including public transport, as relevant…".(European Commission, 2025b) The definition places explicit emphasis on the ability to invest, rather than on energy expenditure alone.

Operationally, this condition is identified where a firm's net income (profit or loss) is insufficient to cover the minimum investment required for at least one of the above transition actions. The indicator therefore excludes firms that are not directly affected by carbon pricing due to the absence of fossil fuel use in buildings or transport. To avoid classifying firms as vulnerable where energy costs are economically marginal, the analysis applies an additional relevance filter: only M-Es operating in sectors with significant energy expenditure are retained for vulnerability assessment.

Our estimation of vulnerable M-Es follows the definition. The calculation represents the number of companies whose economic capacity does not allow them to absorb these combined burdens in the reference year 2027, while investment needs are assumed to be distributed over the period 2027–2032. Let N_{ME} denote the total number of active M-Es. For a representative M-E, baseline annual operating costs are defined as C^0, including baseline building-related energy expenditure E_b^0 and transport-related energy expenditure E_t^0. Baseline net income is denoted by NI^0. Under a given price or policy scenario, additional energy costs arise from buildings ΔE_b and transport ΔE_t, such that total additional energy costs are:

$$\Delta E = \Delta E_b + \Delta E_t$$

In addition, M-Es face annualised investment costs related to building renovation and/or transport transition. Let I denote the total required investment, which is distributed over the investment period $T = 2027–2032$, resulting in an annualised investment burden $I^{ann} = \frac{I}{T}$.

Investment costs for building renovation are derived from average deep renovation costs per square metre, based on literature sources and translated into costs per employee and per average M-E using standard employment and floor-area assumptions. The resulting total renovation cost for an average M-E is then annualised over the 2027–2032 period, yielding an annual investment requirement.(BPIE, 2020; “Construction Analytics,” 2026) Transport investment costs are calculated using average market prices of electric vehicles by vehicle category (passenger cars, light-duty vehicles, freight vehicles and buses). These upfront costs are linearly annualised over the same 2027–2032 period to obtain an annual transport investment burden consistent with the SCP implementation horizon.

Total operating costs, energy expenditure and share are therefore:

$$C^1 = C^0 + \Delta E + I^{ann}; E^1 = E_b^0 + E_t^0 + \Delta E; s_E = \frac{E^1}{C^1}$$

In line with the SCP definition, a M-E is classified as energy-vulnerable if its net income is insufficient to cover the combined burden of additional energy costs and annualised investment needs:

$$NI^0 < \Delta E + I^{ann}$$

Complementary vulnerability indicators

To further refine the identification of vulnerable M-Es, the framework includes a set of additional indicators that can be applied by national authorities, analysts, or business

associations, depending on data availability and policy objectives. These indicators allow for contextual adjustment and prioritisation and include:

- Limited access to capital: Firms with restricted access to credit, guarantees, or public funding instruments, which constrains their ability to finance energy-related investments.
- Market structure and competitiveness: Firms operating in highly competitive or low-margin markets, where cost pass-through is limited and financial resilience is weak.
- Geographical concentration: Regional clustering of vulnerable firms, including areas with structural disadvantages or limited infrastructure.
- Availability of public transport alternatives: Assessment of whether viable public or shared transport options exist, particularly relevant for firms reliant on private vehicles.
- Structural and locational constraints: Firms operating in remote, peripheral, or island locations, or in sectors facing specific transition barriers.

These complementary indicators are not mandatory but serve to narrow and contextualise vulnerability assessments, supporting more nuanced policy design.

10.5.1. Limitations and caveats

Several limitations should be acknowledged when interpreting the results of the microsimulation. First, energy use is estimated using representative bottom-up assumptions derived from sectoral statistics and engineering parameters. While this approach ensures transparency and internal consistency, it cannot fully capture the diversity of real-world operating conditions. Second, the representative-agent structure of the microsimulation simplifies heterogeneity within M-E groups. Although the distinction between average and transport-intensive M-Es captures major structural differences, variation within sectors and regions may be larger than reflected in the model.

Third, behavioural responses are modelled exclusively through price elasticities, which represent short- to medium-term demand adjustments. Structural changes such as relocation, changes in business models, vehicle electrification, or deep renovation investments are not explicitly modelled, nor are potential rebound effects. This is because our modelling timeframe was expected to be short. Fourth, the analysis isolates the effects of ETS2 by excluding other concurrent policy measures, such as targeted subsidies, compensation mechanisms, or energy efficiency support schemes. In practice, the net impact on M-Es will depend on the interaction between carbon pricing and accompanying policy instruments.

10.6. Results / impacts of ETS2 prices in M-Es in four countries

10.6.1. Micro-enterprises sector impacts (example)

This section presents the country-level results of the micro-modelling analysis for M-Es carried out across four EU Member States (Belgium, Czechia, Denmark, Croatia). For each of the countries presented, results are reported separately for building-related energy use, transport-related energy use for standard M-Es, transport-intensive M-Es, and the identification of vulnerable M-Es. Across all four countries, ETS2 leads to sustained increases in energy expenditure for M-Es.

Building-related energy cost impacts

Building energy use represents the dominant exposure channel to ETS2. Across fossil-fuel-using M-Es, relative increases in building energy expenditure rise progressively over time, reaching approximately 14–15% by 2030, after which they stabilise. Initial impacts are more moderate (around 6–8% in 2027) before increasing as carbon prices rise.

Transport-related energy cost impacts for standard M-Es

Transport-related impacts are lower than those for buildings but show greater variability depending on vehicle use and intensity. On average, relative increases in transport energy expenditure rise from approximately 3–4% in 2027 to 7–9% by 2030. Lower impacts are observed among M-Es with limited vehicle use, while higher impacts occur in cases with greater reliance on road transport. Despite being smaller in magnitude, these increases remain relevant for M-Es with tight profit margins.

Combined building and transport impacts at firm level are shown in Figure 10-2 and figures 10-3,4,5.

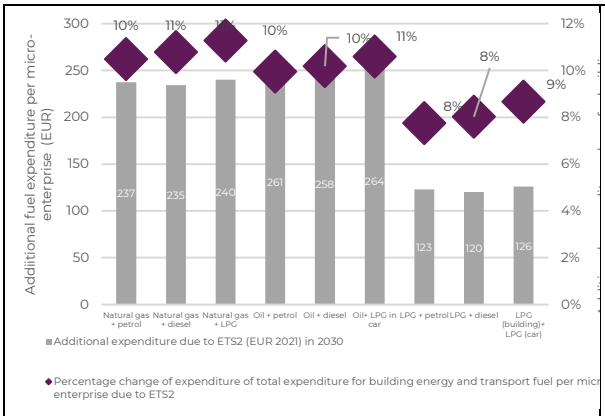


Figure 10-2. Additional costs per micro-enterprises that have energy expenditure in buildings and transport in 2030 – Belgium

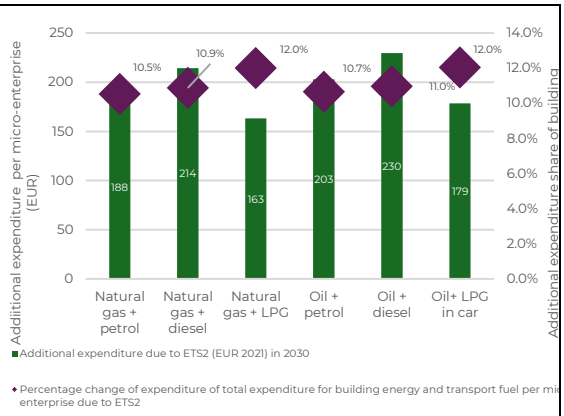


Figure 10-3. Additional costs per micro-enterprises that have energy expenditure in buildings and transport in 2030 – Czechia

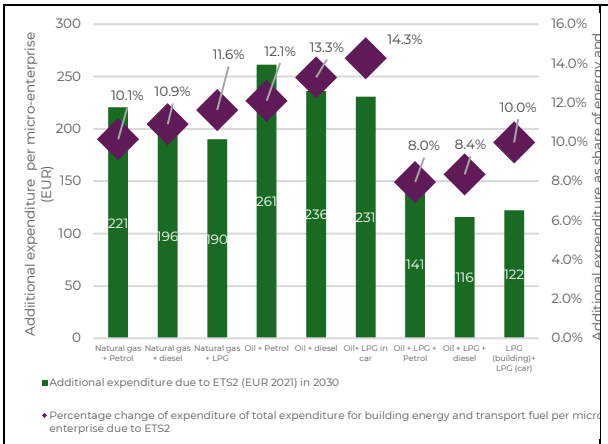


Figure 10-4. Additional costs per micro-enterprises that have energy expenditure in buildings and transport in 2030 – Croatia

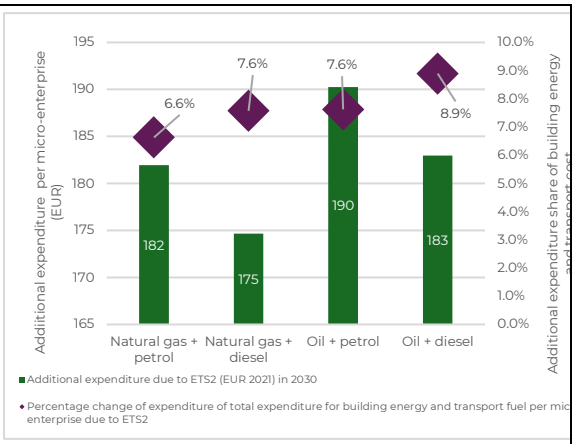


Figure 10-5. Additional costs per micro-enterprises that have energy expenditure in buildings and transport in 2030 – Denmark

Figure 10-6

Transport-intensive M-Es

Transport-intensive M-Es face significantly higher impacts than standard M-Es. Across sectors, relative increases in transport-related energy expenditure are typically in the range of 5–9% by 2030, with some variation depending on activity type. In absolute terms, additional annual costs can exceed EUR 4 000 per enterprise in high-intensity sectors such as freight and passenger transport. These results highlight the disproportionate exposure of transport-intensive activities to ETS2.

The distribution of vulnerable M-Es closely mirrors the observed relative cost dynamics. The lowest vulnerability incidence is observed in Denmark, with approximately 1% of M-Es classified as vulnerable when both core indicators are applied. Higher shares are identified in Czechia (approximately 5.9%) and Croatia (7.5%), reflecting combined exposure to significant relative increases in both building- and transport-related energy expenditure.

While relative impacts for buildings converge across countries by 2030, transport-related impacts remain more heterogeneous. Transport-intensive M-Es consistently experience the highest relative cost increases and account for a disproportionate share of vulnerable firms across the four countries.

10.6.2. Effects on companies' profit and induced effects

The analysis builds directly on the cost results reported and interprets them in relation to observed profit levels, cost structures, and adjustment behaviour of small firms exposed to carbon pricing and energy price increases. We show it on the example of Belgium.

Direct effects on operating profits

For M-Es, ETS2 affects profitability primarily through higher expenditures on fossil fuels used in buildings and transport. In the absence of immediate price or activity adjustments, the additional energy costs estimated by the micro-modelling correspond to a direct reduction in operating profits.

For Belgian M-Es combining fossil fuel use in buildings with limited vehicle ownership, ETS2-related costs exceed EUR 280 per enterprise per year from 2030 onwards. For transport-intensive M-Es, the estimated additional costs are substantially higher, reaching approximately EUR 3 600 per enterprise per year in road freight transport and EUR 2 900 per enterprise per year in passenger transport and travel-related activities.

Firm-level evidence indicates that small and M-Es typically have low profit margins and limited financial buffers. When faced with energy cost shocks, they exhibit measurable declines in profitability, particularly in energy-intensive sectors. (Herman et al., 2023)

Heterogeneity and distribution of profit effects

Firms with energy consumption limited to buildings show comparatively smaller profit reductions, while M-Es combining building energy use with transport incur larger impacts. Transport-intensive activities, such as road freight and passenger transport, demonstrate the largest reductions in operating surplus.

This uneven distribution aligns with empirical evidence that the effects of carbon pricing and energy cost shocks are heterogeneous across sectors and depend on energy intensity and substitution possibilities (Fontagné et al., 2024). In markets where firms have limited pricing power and face elastic demand, the ability to pass carbon-induced cost increases into output prices is muted, leading to a stronger compression of profit margins (Manuel et al., 2023).

Induced effects: pricing behaviour and activity adjustments

Beyond the direct cost effect, ETS2 induces behavioural responses that affect profitability. Firms may attempt to adjust output prices, reduce activity levels, or modify input use in response to higher energy costs. However, empirical evidence indicates that cost pass-through under carbon pricing is incomplete, particularly for small firms operating in competitive markets.

(Perdichizzi et al., 2024) in their recent study provide direct evidence that anticipated carbon cost increases influence firms' pricing strategies and margin expectations. The study finds that firms adjust pricing behaviour and expected margins in anticipation of higher

carbon costs, but that these adjustments do not fully compensate for the increase in operating costs.

10.7. Discussion, conclusions and policy implications

10.7.1. Needs for further research

Data gaps and assumption

While the applied micro-modelling framework provides a structured assessment of ETS2 impacts on micro-enterprises, several data gaps and modelling assumptions limit the precision of the results and point to clear priorities for further research. Existing European datasets primarily provide sector-level averages and rarely distinguish energy use. As a result, the analysis relies on representative assumptions regarding fuel use in buildings and transport, which do not fully capture intra-sectoral heterogeneity in operational practices, building characteristics, or energy intensity.

Data limitations are particularly pronounced for transport activity. Information on vehicle ownership, mileage, fuel consumption, and usage intensity is largely inferred from national statistics and sectoral proxies. This approach masks significant variation within sectors, especially for activities combining stationery and mobile operations. Improved access to firm-level transport data, including vehicle type, age, and utilisation patterns, would enhance the assessment of ETS2 exposure for transport-intensive micro-enterprises.

The assessment of vulnerability also depends on approximations of profitability and financial capacity. Structural business statistics provide only partial insight into micro-enterprises' financial resilience, as they do not capture firm-specific liquidity constraints, access to credit, or short-term volatility in profits. However, there is the need to evaluate how much data collection is cost-efficient in comparison to assessments as this one.

Demand elasticities

Behavioural responses to price increases are incorporated through fuel-specific elasticity assumptions, reflecting reductions in energy and fuel consumption as prices rise. These elasticities are necessarily simplified and applied uniformly within sectors, despite evidence that micro-enterprises may exhibit lower short-term responsiveness than larger firms, particularly in transport-dependent activities. Further empirical work is required to estimate elasticity parameters specific to micro-enterprises and to distinguish between short-term and longer-term adjustment behaviour.

10.7.2. Policy implications

Our findings highlight several policy implications for how ETS2-related burdens on micro-enterprises are identified, targeted, and mitigated through complementary instruments

such as the Social Climate Fund, bearing in mind that targeting should follow the definition of vulnerability:

- *Data limitations are not just a research constraint: they are a governance risk*

Our limitations section implies that the credibility of distributional assessment depends on assumptions about baseline energy use, representative micro-enterprise profiles, and behavioural responses. This motivates a policy recommendation to gradually strengthen micro-enterprise observability in statistical systems and to align policy targeting with data that can be verified and updated over time (including better linkage between business and household contexts where relevant).

- *Sector differentiation is essential because ETS2 impacts are uneven and concentrated.*

Our work implies strong heterogeneity across micro-enterprise profiles. This supports sector-coded instruments (NACE-based) and differentiated support packages (building-focused measures vs vehicle/transport measures), rather than uniform support assumptions for "micro-enterprises" as a single group.

- *Competitiveness and cost pass-through constraints should be treated as vulnerability amplifiers.*

Micro-enterprises often operate in low-margin, highly competitive markets where cost pass-through is limited. Our approach implies that, in such contexts, cost increases are more likely to translate into profit reductions than into customer price adjustments. This strengthens the case for pairing carbon pricing with targeted transition support for the most exposed activities, to avoid erosion of viability and delayed investment.

- *Administrative feasibility is a policy condition.*

Because micro-enterprises have limited time and administrative capacity, complex eligibility documentation and application processes will systematically exclude intended beneficiaries. Our indicator approach points towards low-friction delivery mechanisms: pre-filled eligibility where possible, standardised support bundles, and delivery through intermediaries (business associations, chambers, local agencies), while maintaining auditable thresholds.

- *Policy sequencing matters: pricing without an accessible 'exit route' risks locking in vulnerability.*

Where micro-enterprises lack realistic access to renovation finance, vehicle replacement options, or transport alternatives, ETS2 can compress margins without enabling

decarbonisation. Our findings therefore support an Energy Efficiency First sequencing in SCF implementation: front-load measures that create feasible pathways to renovate or switch vehicles (including guarantees, leasing, standardised packages, and simplified procedures) before ETS2 cost increases become material.

- *Monitoring and evaluation should track "investment enabled" outcomes, not only compensation.*

Since the SCF definition centres on means to renovate or switch vehicles, monitoring should track whether support enables concrete transition actions (renovations undertaken, vehicles replaced, modal shifts supported), not only budget execution or average cost burdens. Our microsimulation outputs can support this by identifying profiles where investment constraints are binding and where specific measures are likely to unlock action.

11. CONCLUDING REMARKS

The contribution of this doctoral dissertation can be interpreted from both a theoretical and an applied perspective, reflecting its dual objective of advancing the understanding of energy vulnerability and supporting the design of effective decarbonisation policies. From a theoretical standpoint, the dissertation contributes to the fields of energy economics, climate policy, and distributional analysis by extending the concept of energy vulnerability beyond households to include micro enterprises. In doing so, it develops a structured and multidimensional framework that captures the interaction between energy system characteristics, financial constraints, and business specific determinants of vulnerability. This represents a conceptual advancement, as it provides a basis for analysing vulnerability in a segment of the economy that has so far remained insufficiently defined and empirically explored within the literature.

A further theoretical contribution is reflected in the development and application of the composite indicator for measuring energy vulnerability of micro enterprises. By integrating macro level indicators with expert based weighting and statistical normalisation, the dissertation provides a systematic and comparable approach to assessing structural vulnerability across European Union Member States. This contributes to the methodological literature on composite indicators and vulnerability assessment by demonstrating how limited and heterogeneous data environments can be addressed through structured modelling approaches. In addition, the integration of energy economic modelling with micro simulation techniques enables the analysis of distributional impacts at both household and firm level, thereby strengthening the link between macroeconomic policy interventions and micro level welfare and financial outcomes.

From an applied perspective, the dissertation contributes through the development of analytical tools and empirical insights that are directly relevant for policy design and evaluation. The MEVI index provides a screening instrument for identifying structural exposure to energy vulnerability across countries, allowing policymakers to distinguish between different drivers of vulnerability, including energy system characteristics, market conditions, and business level constraints. The micro simulation framework complements this approach by quantifying the effects of policy induced changes in energy costs on household welfare and micro enterprise performance, including profitability and financial stability. Together, these tools provide a basis for evidence-based policy design, particularly in the context of emerging instruments such as carbon pricing in buildings and transport, energy efficiency obligations, and targeted support measures.

The empirical results of the dissertation show that the impacts of decarbonisation policies are strongly dependent on structural conditions and cannot be assumed to be uniform across consumer groups. The analysis demonstrates that low-income households tend to respond to increasing energy costs primarily through reductions in consumption, which may lead to negative implications for comfort, health, and overall welfare. At the same time, micro enterprises are shown to adjust through financial channels, including reduced profitability, delayed or foregone investments, and increased exposure to liquidity constraints. These effects are particularly pronounced in cases where household and business finances are closely interconnected, reinforcing the need to analyse vulnerability across these domains jointly rather than separately.

The results further indicate that the effectiveness of decarbonisation policies depends on their timing, sequencing, and the availability of detailed and reliable data. Policies that are implemented without sufficient consideration of structural constraints and adaptive capacity may increase vulnerability in the short to medium term, even if they contribute to long term climate objectives. In contrast, appropriately sequenced and targeted measures, including financial support, regulatory flexibility, and access to energy efficiency investments, can mitigate negative impacts and support a more balanced transition.

The dissertation also identifies several limitations that are relevant for the interpretation of results and for future research. A key limitation relates to the availability and quality of data on micro enterprise energy use, financial performance, and behavioural responses, which constrains the level of granularity in the analysis. In addition, the modelling framework relies on assumptions regarding price elasticities, future energy prices, and policy implementation pathways, which are inherently uncertain, particularly in the context of ongoing energy market volatility. Despite these limitations, the developed models provide a consistent and adaptable framework that can be further refined as more detailed data becomes available.

The analytical framework developed in this dissertation can be extended in several directions. Future research could incorporate more detailed firm level datasets, including sector specific energy use and investment behaviour, as well as dynamic modelling approaches that capture long term adjustment processes. Additional work could also focus on integrating behavioural aspects of decision making, particularly in relation to investment in energy efficiency and responses to price signals. Furthermore, the application of the framework to specific policy instruments, such as the EU Emissions Trading System for buildings and transport or minimum energy performance standards, could provide further insights into the distributional implications of decarbonisation pathways.

Overall, the dissertation provides a structured and empirically grounded contribution to the analysis of energy vulnerability and its interaction with decarbonisation policies. By combining conceptual development, indicator construction, and quantitative modelling, it offers both a theoretical basis and practical tools for understanding and addressing vulnerability in the energy transition. The findings support the need for policy approaches that are differentiated, data informed, and explicitly attentive to distributional effects, to ensure that the transition towards climate neutrality is not only environmentally effective, but also economically feasible and *just*.

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13. LIST OF FIGURES AND TABLES

Figure 5-1 Share of micro-enterprises in EU industries' ecosystems, source Di Bella et al.,2023 16

Figure 5-2 Share of small companies in total net turnover, source: EUROSTAT SBS, 2024. 17

Figure 6-1 Gas prices for non-household consumers (relative to 2019-S2), countries with highest, medium and lowest prices in the EU, source: EUROSTAT, 2019S2-2024S1..... 27

Figure 6-2 Electricity prices for non-household consumers in the EU, Consumption less than 20 MWh - band IA, with and without taxies and levies, EUROSTAT, 2024-S1 28

Figure 6-3 Experts educational background and experience, source: EU-survey, interpretation by authors 37

Figure 6-4 Contribution of different indicators to total MEVI (BE, BG, HR), authors 41

Figure 6-5Every group of MEVI indicator - contribution for the three chosen countries, authors..... 42

Figure 6-6 Calculated MEVI index for EU Member States, authors with MapCharts 43

Figure 7-1 Presentation of the research concept, authors with Canva tool 50

Figure 7-2 Share of micro-enterprises answering the survey by NUTS2, authors from survey 59

Figure 7-3 Fuel expenditure in total expenditure (%), authors from survey 60

Figure 7-4 Most relevant determinants of vulnerability (p-values), results from analysis, authors with Canva tool 68

Figure 8-1 Coverage of M-Es in ORBIS, sources: national statistics, EUROSTAT SBS, ORBIS Moody's (BvD) 86

Figure 8-2 Distribution of workspace types, EU-survey with own analysis 87

Figure 8-3 Distribution of vehicle ownership, source: EU-survey with own analysis 88

Figure 8-4 Energy bills overlap by number of employees in M-E, authors' analysis of the survey 89

Figure 9-1 Comparing graphically the dependence on gas per energy end-use per country compared to its gas import dependency. (**a**) Share of gas in final energy consumption compared to gas import dependency. (**b**) Share of gas in household energy consumption compared to gas import dependency. (**c**) Share of gas in electricity generation compared to gas import dependency. 100

Figure 9-2 Governments earmarked and allocated funding (September 2021–October 2022) to shield households and businesses from the energy crisis (Bruegel report) (Sgaravatti et al., 2023) 102
Figure 9-3 ETS1 price development..... 105
Figure 9-4 ETS2 prices until 2040. 106
Figure 9-5 Envisioned fossil fuel price in the EU Reference Scenario 2020 (blue: oil, red: natural gas, grey: coal; BOE: Barrel of Oil Equivalent) 107
Figure 9-6 Resulting energy consumption changes in 2050 compared to 2019 as a percentage per country. 110
Figure 9-7 Resulting energy expenses changes in 2050 compared to 2019 as a percentage per country. 110
Figure 9-8 Country analysis for Bulgaria. (a) Final energy consumption: comparison of different scenarios in Bulgaria. (b) Final energy costs: comparison between scenarios in Bulgaria. 111
Figure 9-9 Country analysis for Czechia. (a) Final energy consumption: comparison of different scenarios in Czechia. (b) Final energy costs: comparison between scenarios in Czechia. 112
Figure 9-10 Country analysis for Greece. (a) Final energy consumption: comparison of different scenarios in Greece. (b) Final energy costs: comparison between scenarios in Greece..... 112
Figure 9-11 Country analysis for Hungary. (a) Final energy consumption: comparison of different scenarios in Hungary. (b) Final energy costs: comparison between scenarios in Hungary. 113
Figure 9-12 Country analysis for Poland. (a) Final energy consumption: comparison of different scenarios in Poland. (b) Final energy costs: comparison between scenarios in Poland. 113
Figure 9-13 Country analysis for Romania. (a) Final energy consumption: comparison of different scenarios in Romania. (b) Final energy costs: comparison between scenarios in Romania. 114
Figure 9-14 Country analysis for Slovakia. (a) Final energy consumption: comparison of different scenarios in Slovakia. (b) Final energy costs: comparison between scenarios in Slovakia. 114
Figure 9-15 Percentage change in average income of the low-income group in 2050 compared to 2019 without investment financing. 115

Figure 9-16 Percentage change in average income of the low-income group in 2050 compared to 2019 with investment financing. 116
Figure 10-1 Calculation inputs and outputs, authors 127
Figure 10-2. Additional costs per micro-enterprises that have energy expenditure in buildings and transport in 2030 – Belgium 135
Figure 10-3. Additional costs per micro-enterprises that have energy expenditure in buildings and transport in 2030 – Czechia 135
Figure 10-4. Additional costs per micro-enterprises that have energy expenditure in buildings and transport in 2030 – Croatia 136
Figure 10-5. Additional costs per micro-enterprises that have energy expenditure in buildings and transport in 2030 – Denmark 136
Figure 10-6 136

Table 5-1 Part of the recognised indicators of vulnerability to energy poverty 15
Table 5-2 Barriers to implementation of energy efficiency projects in SMEs 17
Table 6-1 Indicators showing energy vulnerability of micro-enterprises, literature references and dataset sources 31
Table 6-2 Experts' employment background, Source: Authors based on EU survey results 36
Table 6-3 Experts' weighting of indicators by group 37
Table 6-4 Correlation between the groups of indictors, using R+ 40
Table 6-5 Contribution of normalized indicators to MEVI, Source: authors' calculation 43
Table 7-1 Independent variables for statistical analysis of vulnerability, authors 61
Table 7-2 Dependant variables detecting vulnerability, authors 62
Table 7-3 Relation between dependent variables, authors with Python 62
Table 7-4 Answers related to dependent variables, authors from survey 63
Table 7-5 Independent variables with statistical significance to investment in energy efficiency, authors, R+ 64
Table 7-6 Payment issues and perceived risk based on location, authors from survey 64
Table 7-7 Relation between significant independent variables (IVs) with payment issues and risk perception (DV), authors, Python 65
Table 8-1 Types of working from home by type of employees, various sources ..... **Pogreška! Knjižna oznaka nije definirana.**

Table 8-2 List of indicators for micro-enterprises energy efficiency, adjusted from indicators in (ODYSEE-MURE, 2020)..... 77
Table 8-3 Simplified pedigree matrix of data availability, authors with experts' inputs..... 84
Table 8-4 Energy bills overlap by number of employees in M-E, authors' analysis of the survey 89
Table 9-1 Comparing graphically the dependence on gas per energy end-use per country compared to its gas import dependency. 100

14. PROŠIRENI SAŽETAK NA HRVATSKOM JEZIKU

Doktorska disertacija istražuje utjecaj dekarbonizacijskih politika u energetskom sektoru na ranjive skupine potrošača energije, s posebnim naglaskom na mikro poduzeća kao gospodarski značajnu, ali u postojećim energetskim politikama, statističkim sustavima i znanstvenim istraživanjima još uvijek nedovoljno prepoznatu skupinu. Polazište istraživanja jest činjenica da tranzicija prema klimatskoj neutralnosti, iako nužna za ostvarivanje klimatskih ciljeva Europske unije, smanjenje ovisnosti o fosilnim gorivima i povećanje dugoročne energetske sigurnosti, nema jednake distribucijske učinke na sve potrošače. Sposobnost odgovora na promjene cijena energije, nove regulatorne zahtjeve i potrebu ulaganja u energetsku učinkovitost i dekarbonizirane tehnologije ovisi o gospodarskom i socijalnom položaju potrošača, njegovoj početnoj razini energetske potrošnje, strukturi korištenih energenata, investicijskom kapacitetu, dostupnosti financiranja i infrastrukture te mogućnosti promjene ponašanja ili tehnologije. Dekarbonizacijska mjera koja za jednog potrošača predstavlja učinkovit poticaj za ulaganje i smanjenje potrošnje, može za drugoga predstavljati trošak kojemu se u promatranom razdoblju ne može prilagoditi. Upravo je ta heterogenost u središtu istraživanja.

Energetska tranzicija čini jedan od glavnih stupova razvojne politike Europske unije. Europski zeleni plan, „Fit for 55“, politike energetske učinkovitosti, povećanje udjela obnovljivih izvora energije, postupno ukidanje fosilnih tehnologija, standardi energetskih svojstava zgrada te širenje trgovanja emisijama, oblikuju novi energetski i gospodarski okvir. Cilj takvih politika nije samo smanjenje emisija stakleničkih plinova nego i stvaranje energetski učinkovitijeg, otpornijeg i sigurnijeg gospodarstva. Međutim, razdoblje tranzicije podrazumijeva dodatne troškove i investicijske potrebe. Cjenovni instrumenti povećavaju relativni trošak ugljično-intenzivnih izvora energije kako bi potaknuli potrošače na njihovu zamjenu, dok regulatorni instrumenti mogu zahtijevati energetsku obnovu zgrada, zamjenu sustava grijanja ili prelazak na učinkovitije tehnologije. U oba slučaja njihova učinkovitost pretpostavlja da krajnji potrošač raspolaže stvarnom mogućnošću prilagodbe. Ako takva mogućnost ne postoji, veća cijena energije ne mora rezultirati poželjnom tehnološkom tranzicijom, nego smanjenjem potrošnje osnovnih energetskih usluga, gubitkom raspoloživog dohotka, smanjenjem dobiti ili odgodom ulaganja.

Potreba za analizom distribucijskih učinaka posebno je postala vidljiva tijekom razdoblja izrazite nestabilnosti energetskih tržišta i porasta cijena energije. Energetska kriza pokazala je da izloženost nije ograničena na energetski intenzivnu industriju. Povećanje cijena električne energije, plina i goriva snažno utječe i na kućanstva i na vrlo male poslovne subjekte, čak i ako je njihova pojedinačna potrošnja relativno mala. Učinak dodatno ovisi o nacionalnim okolnostima. Države se razlikuju prema energetskoj ovisnosti, dostupnosti

alternativnih dobavnih pravaca, udjelu pojedinih energenata, kvaliteti fonda zgrada, razini gospodarskog razvoja, cijenama energenata, prometnoj infrastrukturi i sposobnosti javnog sektora da financira kompenzacijske mjere. Zbog toga se ista europska politika može odraziti različito na potrošače u različitim državama, ali i na različite potrošače unutar iste države.

U području kućanstava ta se heterogenost već dugo istražuje kroz koncepte energetskog siromaštva i energetske ranjivosti. Postojeći pokazatelji promatraju različite dimenzije problema: odnos energetskih rashoda i dohotka, nemogućnost podmirivanja računa, nemogućnost održavanja odgovarajuće temperature u domu, izrazito nisku potrošnju, svojstva stambene zgrade i druge čimbenike koji određuju pristup odgovarajućoj razini energetskih usluga. Ključan je zaključak da ranjivost nije moguće svesti na jednu varijablu. Jednako tako, niska potrošnja energije ne mora biti pokazatelj energetske učinkovitosti. Kod kućanstva s niskim dohotkom ona može biti rezultat odricanja od ugode. Slično tome, visok udio energetskog troška u dohotku može proizlaziti iz loših energetskih svojstava zgrade, niskog prihoda, specifičnih potreba članova kućanstva ili kombinacije tih čimbenika. Socioekonomski položaj posebno utječe na mogućnost investicija. Kućanstva s nižim prihodima daju veću težinu kratkoročnim troškovima nego dugoročnim uštedama. To je osobito važno kod energetske obnove i zamjene sustava grijanja, gdje je početni trošak visok, a korist se ostvaruje tijekom duljeg razdoblja. Ekonomski opravdana investicija stoga nije nužno i financijski dostupna investicija. Isti problem pojavljuje se kod mikro-poduzeća. Poduzeće može biti svjesno da bi učinkovitija oprema ili obnovljena zgrada smanjila njegovu dugoročnu izloženost cijenama energije, ali bez likvidnih sredstava ili pristupa odgovarajućem financiranju takvu investiciju ne može provesti.

Mikro-poduzeća u ovom radu promatraju se kao posebna skupina upravo zbog kombinacije njihove gospodarske važnosti i ograničenih mogućnosti prilagodbe. Ona čine veliku većinu poduzeća u Europskoj uniji i imaju značajan udio u ukupnom prometu, dodanoj vrijednosti i zaposlenosti. Istodobno su u energetskim politikama najčešće uključena u širu skupinu malih i srednjih poduzeća, unatoč tome što se njihova struktura bitno razlikuje od strukture većih MSP-ova. Mikro poduzeće s jednim ili dva zaposlena, u kojem vlasnik obavlja većinu poslovnih funkcija, nema jednake administrativne, tehničke i financijske kapacitete kao poduzeće s nekoliko desetaka ili stotina zaposlenih. Upravljanje energijom najčešće nije zasebna poslovna funkcija, a investicijske odluke gube prednost pred drugim prioritetima kao što su digitalizacija, oprema, zapošljavanje ili internacionalizacija.

Uz to, mikro poduzeća su iznimno heterogena. Uslužno poduzeće koje pretežno koristi računalo i uredski prostor ima posve drukčiji energetski profil od restorana, male proizvodne djelatnosti, prijevoznika ili građevinskog obrta. Zbog toga prosječna potrošnja

mikro poduzeća ima vrlo ograničenu analitičku vrijednost. Sektor, mjesto obavljanja djelatnosti, broj i vrsta vozila, način grijanja prostora, broj zaposlenih i intenzitet korištenja opreme mogu proizvesti velike razlike u energetskim rashodima. Dodatnu specifičnost predstavlja činjenica da dio mikro poduzeća posluje na granici između kućanstva i poslovnog sektora. Vlasnici rade iz vlastitih kuća i stanova, tvrtka ima isti račun za energiju kao kućanstvo, privatna vozila koriste se za potrebe poduzeća, a poslovni i kućanski prihodi i rashodi međusobno se nadopunjuju. Upravo ta obilježja otežavaju i samo definiranje energetske ranjivosti mikro poduzeća.

Temeljna hipoteza disertacije jest da dekarbonizacijske mjere smanjuju energetsku ranjivost kada se provode u adekvatnim uvjetima i kada su praćene odgovarajuće vremenski usklađenim i na podatcima utemeljenim mjerama ublažavanja negativnih učinaka. Takva formulacija odražava osnovnu ideju cijelog istraživanja: dekarbonizacija sama po sebi nije uzrok povećanja ranjivosti niti je zaštita ranjivih skupina argument protiv dekarbonizacije. Pitanje je načina, redoslijeda i uvjeta njezine provedbe. Ako se potrošaču omogući realna mogućnost ulaganja ili promjene prije nego što se u punoj mjeri suoči s dodatnim troškom, dekarbonizacija može smanjiti njegovu dugoročnu energetsku ranjivost. Ako cjenovni ili regulatorni teret nastupi prije dostupnosti tehnologije, financiranja ili infrastrukture, ranjivost se u kratkom i srednjem roku može povećati.

Uz glavnu hipotezu postavljena su dva pomoćna istraživačka pitanja. Prvim se ispituje koliko učinkovito kompozitni multidimenzionalni pokazatelji mogu identificirati i mjeriti energetsku ranjivost mikro-poduzeća među državama, a drugim se ispituje kako socioekonomske karakteristike oblikuju stupanj njihove ranjivosti. Prije procjene konkretnog učinka dekarbonizacijske politike bilo je, naime, potrebno utvrditi postoje li kod mikro-poduzeća usporedive dimenzije ranjivosti kakve su već dobro dokumentirane kod kućanstava: izloženost energetskim cijenama, ograničen adaptacijski kapacitet, strukturne prepreke energetskim ulaganjima i financijska ograničenja. Bez takvog prethodnog konceptualnog i empirijskog temelja, procjena učinka politike na mikro poduzeća bila bi nepotpuna.

Disertacija je izrađena prema skandinavskom modelu te uz uvodno i zaključno poglavlje uključuje pet međusobno povezanih znanstvenih radova. Četiri rada objavljena su u znanstvenim časopisima, dok se jedan nalazi u postupku recenzije. Takva struktura omogućila je postupno razvijanje istraživačkog problema. Prvi rad uspostavlja multidimenzionalni okvir i razvija kompozitni indeks energetske ranjivosti mikro poduzeća. Drugi empirijski ispituje determinante ranjivosti na uzorku hrvatskih mikro poduzeća. Treći istražuje nedostatak podataka i statističku nevidljivost ove skupine, uključujući preklapanje potrošnje energije kućanstva i poduzeća. Četvrti razvija model za procjenu učinaka

dekarbonizacijskih politika na kućanstva s niskim prihodima, dok peti razvija *bottom-up* mikrosimulacijski okvir za procjenu utjecaja trgovanja emisijama stakleničkih plinova na mikro-poduzeća. Metodološki se stoga kombiniraju konstrukcija kompozitnih pokazatelja, strukturirano ekspertno vrednovanje, prikupljanje primarnih podataka, deskriptivna i inferencijalna statistika, regresijska analiza, procjena potpunosti podataka, analiza osjetljivosti, vlastiti statički energetsko-ekonomski model, kompenzacijska varijacija te mikrosimulacija poslovnih učinaka.

Prvi rad polazi od problema nepostojanja usuglašene definicije i načina mjerenja energetske ranjivosti mikro-poduzeća. Iz postojećih istraživanja energetske ranjivosti kućanstava, prepreka energetskoj učinkovitosti MSP-ova te dostupnih statističkih podataka izdvojene su varijable koje mogu opisivati vanjske i unutarnje čimbenike ranjivosti. Razvijen je kompozitni indeks MEVI, odnosno *Micro-Enterprise Energy Vulnerability Index*, kao alat za preliminarnu procjenu strukturnih uvjeta koji utječu na ranjivost mikro-poduzeća u državama članicama Europske unije. Cilj indeksa nije utvrditi je li pojedino poduzeće ranjivo, nego identificirati nacionalne okolnosti u kojima je takva ranjivost vjerojatnija i razlikovati dominantne izvore izloženosti među državama. Pokazatelji su podijeljeni u četiri skupine. Prva obuhvaća vanjske čimbenike povezane s energijom i klimom: potrebe za grijanjem i hlađenjem, energetsku ovisnost i strukturu energetskog miksa, finalnu potrošnju energije u zgradama i prometu, kvalitetu fonda zgrada, razvijenost energetske infrastrukture i regulatorni okvir energetske učinkovitosti za mala poduzeća. Drugu skupinu čine vanjski financijski, tržišni i razvojni čimbenici: stupanj liberalizacije energetskog tržišta, razina cijena energije, gospodarska razvijenost, pristup financiranju i potporama te kvaliteta prometne infrastrukture. Treća skupina uključuje poslovne determinante koje mogu povećati ranjivost, poput veličine i starosti poduzeća, godišnjeg prometa i lokacije. Četvrta obuhvaća determinante sposobnosti prilagodbe, poput vlasništva poslovnog prostora, poslovnog povjerenja, digitalne razvijenosti te dobi i obrazovanja vlasnika i zaposlenika. Relativna važnost indikatora određena je strukturiranim ekspertnim vrednovanjem. Stručnjaci su procjenjivali i rangirali čimbenike prema njihovoj važnosti za energetsku ranjivost mikro-poduzeća, nakon čega su rezultati korišteni kao ponderi u konstrukciji indeksa. Među energetskim i klimatskim čimbenicima najveću je težinu dobila energetska ovisnost i energetski miks zemlje, nakon čega slijedi finalna potrošnja u zgradama i prometu te kvaliteta fonda zgrada. U skupini financijskih i tržišnih čimbenika najveća je važnost pridana dostupnosti financiranja i cijenama energije. Kod poslovnih karakteristika relevantnima su se pokazali promet, lokacija i veličina poduzeća, dok je među čimbenicima sposobnosti prilagodbe najviši ponder dodijeljen vlasništvu poslovnog prostora. Statistička analiza ekspertnog istraživanja nije utvrdila značajne razlike među različitim skupinama stručnjaka,

što upućuje na relativno visok stupanj suglasnosti o glavnim determinantama. Podatci iz različitih izvora normalizirani su min-max metodom, vodeći računa o smjeru povezanosti svakog pokazatelja s ranjivošću. Nakon ponderiranja izračunati su sintetizirani pokazatelji četiriju skupina i konačna vrijednost MEVI indeksa. Rezultati potvrđuju značajnu heterogenost među državama članicama i pokazuju da visoka ranjivost može biti rezultat različitih kombinacija čimbenika. Mađarsku i Slovačku karakterizira snažan doprinos financijskih i tržišnih pritisaka te ograničenog adaptacijskog kapaciteta. U Bugarskoj i Rumunjskoj istaknutiji su poslovni čimbenici. U Hrvatskoj su posebno izraženi vanjski financijski i tržišni čimbenici te determinante sposobnosti prilagodbe, dok kod nekih zapadnoeuropskih država veći doprinos ukupnom rezultatu proizlazi iz energetskih i klimatskih uvjeta. Rezultat prvog istraživanja potvrđuje opravdanost višedimenzionalnog pristupa. Energetska ranjivost mikro poduzeća ne može se objasniti jednom varijablom poput cijene električne energije ili godišnjeg prometa. Poduzeće može djelovati u zemlji s relativno visokim cijenama energije, ali imati dobar pristup financiranju, kvalitetnu infrastrukturu i visoku sposobnost prilagodbe. Drugo može biti izloženo nešto nižim energetskim cijenama, ali poslovati s vrlo malom dobiti, slabim pristupom kapitalu i u energetski neučinkovitom prostoru koji nije u njegovu vlasništvu. MEVI stoga predstavlja alat za prepoznavanje strukturnog okruženja i dominantnih izvora rizika, ali ujedno otkriva i ograničenje makrorazinskog pristupa: dostupni statistički podatci nisu dovoljni za identifikaciju pojedinačnih ranjivih mikro poduzeća.

Zbog toga je sljedeći korak istraživanja usmjeren na prikupljanje primarnih podataka i ispitivanje determinanti ranjivosti na razini poduzeća. Hrvatska je odabrana kao studija slučaja. U anketnom istraživanju prikupljena su 503 odgovora, od kojih je 470 zadovoljilo definiciju mikro poduzeća i uključeno je u analizu. Uzorak ima dobru geografsku zastupljenost i uključuje poduzeća iz svih hrvatskih NUTS 2 regija. Prosječan broj zaposlenih, uključujući vlasnika, iznosi 1,93, a medijan jedan zaposleni. Ti se rezultati gotovo podudaraju s podatcima Financijske agencije prema kojima je prosječan broj zaposlenih u hrvatskim mikro poduzećima 1,98, uz isti medijan, što podupire reprezentativnost uzorka prema veličini poduzeća. Sektorski je uzorak heterogen. Najveći udio čine uslužne djelatnosti, uključujući savjetovanje, s 36,5 %, dok su kulturne i kreativne djelatnosti, digitalni sektor, građevinarstvo i turizam pojedinačno zastupljeni s približno sedam posto. Putnički i teretni promet zajedno obuhvaćaju oko deset posto uzorka te pokazuju najviše udjele goriva u ukupnim rashodima. Većina poduzeća ima mali godišnji promet: 331, odnosno 71,3 % poduzeća, ostvaruje godišnji promet do 100.000 eura, a više od 70 % ostvaruje dobit ispod 20.000 eura. Financijska analiza šire populacije hrvatskih mikro-poduzeća iz baze ORBIS dodatno potvrđuje relativno niske razine dobiti. Nakon uklanjanja ekstremnih vrijednosti

prosječna neto dobit iznosila je približno 6.746 eura, dok je medijan bio približno 2.955 eura. Prosječni energetski izdaci mikro poduzeća u Hrvatskoj za 2021. godinu iznosili su približno 2.807 eura, što pokazuje da energija za tipično poduzeće može predstavljati vrlo značajan izdatak u odnosu na ostvarenu dobit. Anketom su prikupljeni i detaljniji podatci o energetskim karakteristikama. Približno 34,3 % poduzeća koristi prirodni plin za grijanje i toplu vodu, oko trećine električnu energiju, približno 22 % drvo, a nešto više od šest posto daljinsko grijanje. Vozila su pretežno dizelska, nakon čega slijede benzinska, dok su alternativna goriva rijetka. Velik dio mikro poduzeća djeluje iz objekata namijenjenih stanovanju ili u pretežno stambenim zgradama. Energetski certifikat posjeduje 26,4 % uzorka, a velik broj prostora relativno je star i potencijalno zahtijeva energetsku obnovu.

Analizirani su čimbenici povezani s prethodnim ulaganjem u energetsku učinkovitost ili zamjenu vozila, s problemima u plaćanju energetskih troškova, s percepcijom rizika budućih promjena cijena energije te s utjecajem poslovnih energetskih troškova na kućanstvo vlasnika. Rezultati pokazuju da se sposobnost prilagodbe povećava s određenim obilježjima poslovne stabilnosti. Starija poduzeća statistički su značajno sklonija prethodnim ulaganjima u energetsku učinkovitost ili vozila, kao i poduzeća s većim brojem zaposlenih. Najizraženija pojedinačna povezanost utvrđena je kod vlasništva poslovnog prostora. Poduzeća koja posjeduju prostor znatno češće ulažu u energetsku učinkovitost, što je u skladu s problemom podijeljenih poticaja (tzv. *split incentive*): vlasnik nekretnine ima veću mogućnost i motivaciju provesti dugoročnu intervenciju jer izravno ostvaruje korist od ulaganja. Poduzeća sa starijim voznim parkom i poduzeća bez energetskog certifikata manje su sklona energetskim ulaganjima. Godišnja dobit statistički je značajno povezana i s poteškoćama u plaćanju računa i s percepcijom rizika povezanog s energetskim cijenama, dok godišnji promet ne pokazuje takvu statistički značajnu povezanost. To je važan nalaz jer potvrđuje da sama veličina poslovne aktivnosti nije dovoljna za procjenu mogućnosti poduzeća da podnese energetski šok. Troškovi energije pokazali su se među najsnažnijim determinantama. Ukupni trošak grijanja i pripreme tople vode statistički je značajno povezan s poteškoćama u plaćanju i izrazito snažno povezan s percepcijom budućeg energetskog rizika. Udio goriva u ukupnim troškovima također je snažno povezan s percepcijom rizika, iako nije utvrđena statistički značajna veza sa stvarnim poteškoćama plaćanja. Lokacija i sektor, s druge strane, nisu pokazali statistički značajnu povezanost s promatranim ishodima na razini cijelog uzorka, iako su pojedine skupine, poput transportnih poduzeća ili onih u područjima posebne državne skrbi, imale više nominalne razine pojedinih oblika ranjivosti. Ovi rezultati upućuju na to da strukturni i financijski položaj konkretnog poduzeća može imati veću važnost od njegove same sektorske ili regionalne pripadnosti. Jedan od najvažnijih empirijskih nalaza odnosi se na odnos poslovne

i kućanske financijske stabilnosti. Na pitanje utječu li rastući energetski troškovi njihova poduzeća na financije kućanstva 353 ispitanika, odnosno 75,1 %, odgovorilo je potvrdno. Dodatnih 16,4 % nije bilo sigurno, dok je samo 8,5 % odgovorilo da utjecaja nema. Rezultat pokazuje da za velik dio mikro-poduzetnika energetska ranjivost ne završava na granici pravne osobe ili obrta. Smanjena poslovna dobit može izravno smanjiti raspoloživi dohodak kućanstva, dok istodobno financijski položaj kućanstva određuje koliko vlasnik može financijski poduprijeti poduzeće. Time se potvrđuje potreba za analizom mikro-poduzeća kao skupine koja je po nekim obilježjima između klasičnog poslovnog i kućanskog sektora. Rezultati studije potvrđuju pomoćno istraživačko pitanje o ulozi socioekonomskih karakteristika. Energetska ranjivost povezana je s vlasništvom, veličinom, starošću, dobiti i energetskim izdacima poduzeća, dok sposobnost ulaganja raste s većom poslovnom stabilnošću i kontrolom nad imovinom. Istodobno istraživanje otvara dodatni problem: velik dio podataka potrebnih za takvu analizu u službenim statistikama nije dostupan. Informacije o stvarnoj potrošnji energije, vrsti prostora, vozilima koja se koriste za poslovanje, mješovitoj privatnoj i poslovnoj uporabi energije te profitabilnosti po odgovarajućoj sektorskoj i veličinskoj klasifikaciji uglavnom nije moguće povezati.

Treći rad disertacije stoga istražuje utjecaj nedostatka podataka na oblikovanje energetskih politika. Polazi se od pretpostavke da statistička nevidljivost mikro poduzeća nije samo posljedica toga što nedostaju pojedine varijable, nego i samog načina na koji se energija klasificira. U energetskim statistikama potrošnja se raspoređuje prema sektorima, mjernim mjestima i ugovorima, dok se veličina poduzeća evidentira u poslovnoj statistici. Mikro poduzeće koje djeluje iz privatne kuće ili stana može stoga svu energiju koristiti zajedno, zbog čega se njegova poslovna potrošnja bilježi kao rezidencijalna potrošnja. S druge strane, u statistici poslovnog sektora takvo poduzeće izgleda energetski gotovo neaktivno. Kako bi se procijenio opseg problema, analizirana je dostupnost i sljedivost podataka u deset država članica Europske unije. Uspostavljena je jednostavna matrica potpunosti u kojoj vrijednost nula označava podatak koji za mikro-poduzeća nije moguće identificirati, vrijednost jedan djelomičnu dostupnost uz agregaciju ili jake pretpostavke, a vrijednost dva izravnu i dovoljno granuliranu dostupnost. Promatrani su pokazatelji potrebni za standardnu evaluaciju politika energetske učinkovitosti, uključujući broj i strukturu poduzeća, potrošnju energije, vrstu i svojstva poslovnog prostora, transportnu aktivnost i financijske karakteristike. Rezultati pokazuju da ni u jednoj promatranoj državi podatci nisu dovoljno cjeloviti za potpunu analizu energetske potrošnje mikro poduzeća. Najviši rezultat potpunosti doseže samo 56 % teorijskog maksimuma. Strukturni poslovni podatci, poput broja poduzeća i zaposlenih, uglavnom su dostupni. Financijske informacije dostupne su djelomično i nisu uvijek harmonizirane. Međutim, ključne energetske informacije, poput

potrošnje energije prema veličini poduzeća, korištenja prostora, karakteristika zgrade, broja i stvarne uporabe vozila te energetskog intenziteta mikro poduzeća, uglavnom su nedostupne ili se mogu procijeniti samo uz snažne pretpostavke. Dodatne baze poput ORBIS-a mogu poboljšati financijski opis poduzeća, ali ne mogu riješiti osnovni problem. Središnji empirijski doprinos trećeg rada zato je analiza preklapanja uporabe energije u kućanstvu i poduzeću na hrvatskom uzorku. Ukupno 60,9 % ispitanika ima barem neki oblik zajedničkog evidentiranja potrošnje energije u kućanstvu i poduzeću. Gotovo dvije trećine ispitanih mikro-poduzeća koristi ista vozila u privatne i poslovne svrhe. Time se potvrđuje da statistički izazov nije marginalan, nego zahvaća većinu analiziranih vrlo malih poduzeća. Kako bi se ilustrirao potencijalni utjecaj takve klasifikacije na energetsku statistiku, provedena je analiza osjetljivosti. Vrijednosti potpunog i djelomičnog preklapanja dobivene su iz ankete, dok su udjeli poslovne energije u zajedničkim računima modelirani kroz dva scenarija. U konzervativnom scenariju pretpostavljeno je da 20 % energije na potpuno preklopljenom računu i 10 % energije na djelomično preklopljenom računu pripada poslovnoj aktivnosti. U scenariju gornje granice pretpostavljeni su udjeli od 60 % odnosno 40 %. Cilj nije procijeniti stvarni udio poslovne energije, nego pokazati koliko se mogu promijeniti rezultati ovisno o pretpostavljenoj atribuciji. Čak i konzervativni scenarij pokazuje da bi približno desetina energije evidentirane na zajedničkim kućanskim računima mogla proizlaziti iz poslovne aktivnosti, dok scenarij gornje granice povećava taj mogući udio na približno jednu trećinu. Ako se energija korištena za poslovnu aktivnost evidentira kao kućanska, rezidencijalna potrošnja i energetski rashodi kućanstva mogu biti precijenjeni u odnosu na dohodak, površinu stana ili broj članova kućanstva. Energetski modeli mogu takvu dodatnu potrošnju pogrešno pripisati demografskim ili stambenim karakteristikama, dok se u analizama energetskog siromaštva poslovni trošak može interpretirati kao znak stambene neučinkovitosti ili kućanske ranjivosti. U poslovnim statistikama pojavljuje se suprotan problem. Poslovna potrošnja najmanjih poduzeća podcjenjuje se, zbog čega se njihova energetska intenzivnost može činiti manjom nego što jest. Posebno je značajan i promet: budući da 64 % ispitanih mikro-poduzeća dijeli vozila između poslovne i privatne uporabe, velik dio poslovne potrošnje goriva može se statistički prikazivati kao privatna prometna potrošnja. U kontekstu dekarbonizacijske politike to postaje problem upravljanja, a ne samo statističke preciznosti. Socijalni fond za klimatsku politiku, primjerice, istodobno cilja ranjiva kućanstva, ranjiva mikro-poduzeća i ranjive korisnike prijevoza. Ako se poslovna i privatna uporaba energije ne mogu razlikovati, postoji rizik pogrešnog financiranja, dvostrukog računanja ili izostavljanja pojedinih korisnika. Rezultati stoga upućuju na potrebu povezivanja poslovnih statistika s podatcima o kućanstvima, uključivanja pitanja o poslovnim aktivnostima u stambenim prostorima te boljeg evidentiranja mješovite uporabe vozila i energije.

Prva tri rada zajedno izgrađuju konceptualnu i empirijsku osnovu za analizu distribucijskih posljedica konkretnih dekarbonizacijskih mjera. Prvi pokazuje da je ranjivost višedimenzionalna i da se nacionalni strukturni uvjeti razlikuju. Drugi pokazuje da na razini pojedinačnog poduzeća najveću ulogu imaju financijski i strukturni čimbenici poput dobiti, energetskih troškova, vlasništva, veličine i starosti. Treći pokazuje da upravo za najvažnije aspekte ranjivosti postoje ozbiljne podatkovne i klasifikacijske praznine. Iz toga slijedi da politike ne mogu biti pravilno ciljane samo na temelju općih kategorija „MSP“ ili „kućanstvo“, već zahtijevaju detaljniji pogled na stvarne potrošačke profile.

Četvrti rad usmjerava se na kućanstva s niskim prihodima te ispituje kako različite dekarbonizacijske politike stambenog sektora utječu na njihovu potrošnju energije, rashode i dobrobit. Analizirani su minimalni standardi energetskih svojstava zgrada, postupno ukidanje sustava grijanja na fosilna goriva i novi sustav trgovanja emisijama ETS2. Fokus je stavljen na države srednje, istočne i jugoistočne Europe, čije se energetske strukture, razine dohotka, fondovi zgrada i ovisnost o pojedinim fosilnim gorivima značajno razlikuju. U analizi se kućanstvima s niskim prihodima smatra prvi dohodovni decil. Razvijen je linearni statički energetsko-ekonomski model temeljen na podatcima iz Eurostata. Bazna godina je 2019., a projekcije se provode do 2050. godine. Model povezuje finalnu potrošnju energije po namjeni, nacionalni miks goriva, projekcije njihovih cijena, cijenu ugljika, cjenovne elastičnosti potražnje, uštede od energetskih mjera i investicijske troškove. Odabir pojednostavljenog modela omogućuje transparentno praćenje pojedinačnih učinaka i usporedbu različitih scenarija, iako istodobno znači da složeniji nelinearni i dinamički učinci nisu potpuno obuhvaćeni. Kod primjene ETS2 pretpostavlja se dodatni rast cijena fosilnih goriva zbog cijene emisija. Promjena potrošnje računa se korištenjem cjenovne elastičnosti. Međutim, raspoloživi podatci ne omogućuju pouzdanu procjenu elastičnosti specifične za najniži dohodovni decil, pa su korištene prosječne vrijednosti. To je važno ograničenje jer reakcija ranjivog kućanstva na višu cijenu nije jednaka reakciji prosječnog potrošača. Potrošač s dostatnim financijskim sredstvima može odgovoriti ulaganjem u učinkovitiju zgradu, dizalicu topline ili drugi izvor energije. Kućanstvo s vrlo niskim dohotkom takvu mogućnost često nema. Njegova reakcija može se svesti na smanjivanje temperature, reducirano grijanje ili smanjivanje druge osnovne potrošnje. U tom slučaju smanjenje potrošnje energije nije rezultat povećanja učinkovitosti, nego smanjenja razine energetskih usluga.

Modelirano je šest scenarija. Referentni scenarij pretpostavlja razvoj bez dodatne primjene analiziranih mjera. Prvi scenarij uključuje samo ETS2. Drugi uključuje postupno ukidanje kotlova na fosilna goriva uz prelazak na dizalice topline. Treći modelira energetsku obnovu kroz MEPS, odnosno minimalne standarde energetskih svojstava. Pretpostavljeno je da se

75 % zgrada obnovi do energetskog razreda D do 2030. godine, uz energetsku uštedu od 40 % i trošak od 15.000 eura po zgradi, a zatim do razreda C uz dodatnu uštedu od 10 % i dodatni trošak od 10.000 eura. Četvrti scenarij kombinira obnovu i postupno ukidanje fosilnih sustava grijanja, dok peti kombinira sve tri mjere, uključujući i ETS2. Rezultati pokazuju da kombinirana provedba mjera u pravilu daje bolje dugoročne rezultate od izolirane primjene pojedinačnih instrumenata. U svim analiziranim državama scenarij koji kombinira sve mjere daje najpovoljniji rezultat za finalnu potrošnju energije do 2050. godine bez pretpostavke da se ušteda ostvaruje smanjenjem toplinske ugode. Isti scenarij u većini država daje i najveće smanjenje energetskih izdataka. Iznimka je Poljska, gdje samostalna primjena MEPS-a rezultira tek neznatno nižim izdacima od kombiniranog scenarija, s razlikom od približno jednoga postotnog boda, što je povezano sa specifično velikim udjelom ugljena u poljskom energetskom miksu. Rezultati po državama potvrđuju važnost početnih strukturnih uvjeta. U Bugarskoj scenarij koji se oslanja samo na cjenovni signal ETS2 može dugoročno povećati teret za niskodohodovna kućanstva bez dovoljne strukturne promjene. U Češkoj različite mjere smanjuju potrošnju, ali ne nužno i izdatke. U Grčkoj zamjena fosilnih sustava grijanja pokazuje snažan učinak zbog važnosti relativno skupog loživog ulja. U Mađarskoj samostalni ETS2 rezultira znatnim smanjenjem potrošnje uz istodobno povećanje energetskih troškova zbog visoke ovisnosti kućanstava o prirodnom plinu. Taj je primjer posebno važan jer jasno pokazuje zašto smanjena potrošnja ne može sama po sebi biti kriterij uspješnosti politike. Ako kućanstvo troši manje energije zato što si više ne može priuštiti prethodnu razinu grijanja, smanjenje potrošnje popraćeno je padom dobrobiti.

Za procjenu dobrobiti korišten je koncept kompenzacijske varijacije, odnosno iznosa dohotka koji bi nakon promjene cijene bio potreban da se potrošač vrati na početnu razinu korisnosti. Ovaj pristup omogućuje razlikovanje nominalnog energetskog rashoda od stvarnog gubitka dobrobiti. Analiza pokazuje da investicijski troškovi predstavljaju ključnu prepreku za kućanstva s niskim prihodima. Čak i kada obnova ili prelazak na novu tehnologiju nakon nekoliko godina smanjuje račune, početni izdatak može biti toliko velik u odnosu na njihov raspoloživi dohodak da investicija bez vrlo visoke potpore nije izvediva. Dekarbonizacijska politika koja se temelji na pretpostavci da će kućanstvo odgovoriti na rast cijene samostalnom investicijom stoga može imati regresivne učinke. Poseban problem predstavlja odnos kratkoročnih i dugoročnih mjera. Izravna pomoć za račune, porezne olakšice i regulacija energetskih cijena mogu biti potrebne u razdoblju izrazitog cjenovnog šoka, ali ne uklanjaju strukturne uzroke ranjivosti. S druge strane, energetska obnova i zamjena fosilnih sustava grijanja smanjuju dugoročnu potrošnju i izloženost cijenama, ali zahtijevaju visoki početni kapital. Optimalna politika zato mora kombinirati privremenu

zaštitu s investicijskim mjerama. Rezultati upućuju na potrebu visokih stopa financiranja za kućanstva s najnižim prihodima, zajedno s tehničkom pomoći, informacijama i pravodobnim pristupom programima. Socijalni fond za klimatsku politiku, prihodi ETS2 i drugi europski i nacionalni izvori financiranja trebali bi stoga biti usmjereni ne samo na kompenzaciju dodatnog troška nego ponajprije na omogućavanje strukturne prilagodbe. Rezultati potvrđuju i važnost načela „energetska učinkovitost na prvom mjestu*" („energy efficiency first").* Sam ETS2 može uspješno poslati cjenovni signal i smanjiti uporabu fosilnih goriva, ali kod ranjivog potrošača bez mogućnosti ulaganja, smanjenje potražnje može nastati na društveno nepoželjan način. Ako se cjenovni signal kombinira s energetskom obnovom i dostupnim niskougljičnim sustavom grijanja, potrošač može smanjiti količinu energije potrebnu za istu ili višu razinu toplinske ugode. U prvom slučaju dekarbonizacija se dijelom ostvaruje odricanjem, dok se u drugom ostvaruje kroz učinkovitost i tehnološku promjenu. Upravo ta razlika predstavlja jedan od najvažnijih zaključaka cijele disertacije.

Peti rad primjenjuje istu temeljnu logiku na mikro-poduzeća, uz fokus na ETS2. Novi sustav trgovanja emisijama za zgrade, cestovni promet i dodatne sektore od posebne je važnosti jer Socijalni fond za klimatsku politiku eksplicitno prepoznaje ranjiva mikro-poduzeća kao ciljanu skupinu. Prema regulatornoj definiciji, riječ je o mikro-poduzećima koja su značajno pogođena cjenovnim učincima ETS2, a nemaju sredstva za obnovu zgrade koju koriste, nabavu vozila s niskim ili nultim emisijama ili prelazak na održiviji oblik prijevoza. Time se ranjivost ne definira samo kroz visinu dodatnog računa, nego i kroz nedostatak sredstava za izlazak iz fosilno intenzivnog obrasca potrošnje. Procjena učinaka suočena je upravo s podatkovnim problemima identificiranima u prethodnom radu. EUROSTAT strukturne poslovne statistike (SBS) pružaju podatke o broju mikro-poduzeća prema djelatnosti, ali se definicije i razine detalja ne mogu uvijek izravno povezati s energetskim statistikama. Podatci o prirodnom plinu postoje prema kategorijama potrošnje, no nije moguće pouzdano utvrditi koja mikro-poduzeća koriste poslovne, a koja kućanske tarife. Podaci o prometu još su ograničeniji: ne postoji harmonizirana statistika potrošnje goriva, kilometraže i broja vozila posebno za mikro-poduzeća, a privatno registrirana vozila mogu se koristiti u poslovanju i obrnuto. Financijski podaci također se ne mogu uvijek istodobno raščlaniti prema veličini poduzeća i preciznoj djelatnosti. Zbog toga je razvijen reprezentativni *bottom-up* model kojim se rekonstruira bazna potrošnja energije mikro-poduzeća. Analiza odvaja dvije osnovne kategorije potrošnje: energiju povezanu sa zgradama i procesima te energiju povezanu s prometom. Za zgrade se koriste podatci baze JRC IDEES o korisnoj energiji za grijanje prostora, pripremu potrošne tople vode i kuhanje. Budući da IDEES ne razlikuje poduzeća prema veličini, potrošnja se skalira prema broju zaposlenih i pretvara iz korisne u finalnu energiju primjenom učinkovitosti relevantnih

tehnologija. Modeliraju se različite kombinacije energenata, uključujući prirodni plin, loživo ulje, LPG i električnu energiju. Prometna potrošnja modelira se zasebno za tipično mikro-poduzeće s ograničenom uporabom jednog vozila i za transportno intenzivne djelatnosti. U transportno intenzivne profile uključene su djelatnosti u kojima je prijevoz robe, zaposlenika ili korisnika sastavni dio poslovnog modela, primjerice cestovni teretni i putnički prijevoz, taksi djelatnosti, dostavne i kurirske usluge, pojedine građevinske djelatnosti i druge aktivnosti s većim brojem vozila. Potrošnja se procjenjuje na temelju prosječne kilometraže, potrošnje goriva, energetskog sadržaja goriva, strukture voznog parka i raspoloživih nacionalnih podataka. Na tako uspostavljenu bazu primjenjuje se cjenovni učinak ETS2 za razdoblje od 2027. do 2032. godine. Za pojedina goriva računa se povećanje cijene na temelju emisijskog faktora i cijene emisijskih jedinica. Promjena potrošnje zatim se procjenjuje korištenjem cjenovnih elastičnosti. Budući da ne postoje pouzdane elastičnosti specifične za mikro-poduzeća, korišten je hibridni pristup koji se oslanja na raspoložive vrijednosti za kućanstva i komercijalni sektor, što odgovara ranijem empirijskom nalazu da mikro-poduzeća u praksi dijele obilježja oba sektora. Razvijena mikrosimulacija simulira učinak na različite reprezentativne profile mikro-poduzeća prema sektoru, broju zaposlenih, energentu korištenom u zgradi, vlasništvu i vrsti vozila te baznoj potrošnji. Za svaku godinu ažuriraju se cijene, potrošnja i energetski izdaci, čime se mogu identificirati heterogeni učinci koji nisu vidljivi iz agregiranih prosjeka. Financijski dio modela povezuje dodatne energetske troškove s poslovnom dobiti i procijenjenim troškom investicije potrebne za prilagodbu. Poduzeće se u skladu s konceptom Socijalnog fonda smatra ranjivim ako njegova neto dobit nije dovoljna da pokrije kombinirano opterećenje dodatnog troška energije i godišnjeg dijela potrebne investicije u obnovu ili prometnu tranziciju. Istodobno se primjenjuje sektorski filter kako se ranjivima ne bi automatski proglasila poduzeća u djelatnostima u kojima energija predstavlja zanemariv dio ukupnih troškova. Model je primijenjen na Belgiju, Češku, Dansku i Hrvatsku. Rezultati pokazuju da ETS2 povećava energetske rashode mikro-poduzeća u svim promatranim državama, ali učinak ovisi o vrsti potrošnje i poslovnom profilu. Energija koja se koristi u zgradama predstavlja dominantan kanal izloženosti za mnoga mikro-poduzeća koja koriste fosilna goriva. Relativni rast troška iznosi približno šest do osam posto u 2027. godini te s rastom cijene ugljika doseže približno 14–15 % do 2030. godine, nakon čega se stabilizira. Kod standardnih mikro-poduzeća prometni je učinak relativno manji, ali heterogeniji. Dodatni izdaci povezani s gorivom rastu s približno tri do četiri posto u 2027. na sedam do devet posto do 2030. Poduzeća koja manje koriste vozila nalaze se na donjem dijelu raspona, dok su ona koja ovise o cestovnom prometu znatno više izložena. Transportno intenzivna mikro-poduzeća imaju posebno visoke apsolutne iznose dodatnog troška. U nekim sektorima, poput teretnog i putničkog prijevoza, godišnji dodatni izdaci mogu premašiti 4.000 eura po

poduzeću. Takav iznos može biti vrlo značajan u odnosu na prethodno utvrđene razine dobiti tipičnih mikro-poduzeća. Poduzeća, naravno, mogu pokušati dio povećanja troška prenijeti na kupce. Međutim, mogućnost prijenosa ovisi o konkurenciji, elastičnosti potražnje, poslovnoj marži i tržišnom položaju. Mikro-poduzeća u izrazito konkurentnim djelatnostima imaju manju pregovaračku moć i ograničen prostor za povećanje cijena. Kada prijenos nije potpun, povećani energetski trošak smanjuje profit. Slabija profitabilnost zatim može smanjiti mogućnost reinvestiranja, odgoditi energetsku obnovu ili zamjenu vozila i povećati potrebu za vanjskim financiranjem. Time može nastati negativna povratna sprega: poduzeću je potrebna investicija kako bi se smanjila njegova izloženost fosilnom gorivu, ali upravo veći energetski trošak smanjuje sredstva kojima bi tu investiciju moglo financirati. Procjena udjela ranjivih mikro-poduzeća potvrđuje znatne razlike među državama. Rezultati petog rada imaju nekoliko neposrednih implikacija za provedbu ETS2 i Socijalnog fonda za klimatsku politiku. Prvo, nedostatak podataka nije samo istraživačko ograničenje nego rizik upravljanja javnim sredstvima. Ako se bazna potrošnja i financijska sposobnost poduzeća procjenjuju na temelju nepouzdanih agregata, povećava se mogućnost pogrešnog određivanja ciljnih skupina. Drugo, potrebna je sektorska diferencijacija. Mikro-poduzeće čiji je glavni izvor izloženosti grijanje poslovnog prostora treba drukčiju vrstu potpore od prijevoznika čiji je glavni problem vozni park. Treće, konkurentnost i ograničena mogućnost prijenosa troška treba promatrati kao dodatne čimbenike ranjivosti. Četvrto, administrativna jednostavnost mora biti dio dizajna mjere jer složeni postupci prijave i dokazivanja mogu praktično isključiti upravo najmanja poduzeća s najmanjim administrativnim kapacitetom. Posebno važan zaključak odnosi se na vremenski slijed mjera. Ako ETS2 značajno poveća trošak prije nego što poduzeća dobiju realnu mogućnost financiranja obnove, nabave niskoemisijskog vozila ili korištenja održive alternative, cjenovni signal može samo smanjiti dobit bez pokretanja dekarbonizacije. Nasuprot tome, ako se prije pune materijalizacije cjenovnog učinka osiguraju dostupni krediti, jamstva, leasing, standardizirani paketi obnove, pojednostavljene procedure i druge investicijske mogućnosti, poduzeće dobiva izlaznu putanju iz fosilne izloženosti. U tom smislu rezultati podupiru redoslijed temeljen na načelu energetske učinkovitosti na prvom mjestu: najprije stvoriti realnu mogućnost prilagodbe, a zatim dopustiti da cjenovni signal ubrza prijelaz.

Promatranjem svih pet istraživanja zajedno potvrđuje se temeljna hipoteza disertacije. Dekarbonizacijske mjere mogu smanjivati energetsku ranjivost, ali njihov učinak ovisi o strukturnim uvjetima, redoslijedu provedbe i dostupnosti pouzdanih podataka. Ni kućanstva ni mikro-poduzeća ne reagiraju na energetske cijene kao homogeni reprezentativni potrošači. Njihove reakcije određene su stvarnim mogućnostima prilagodbe. Kućanstvo s niskim dohotkom može na povećanje cijene odgovoriti smanjenjem

temperature u domu. Financijski stabilnije kućanstvo može investirati u energetsku obnovu. Mikro-poduzeće s dovoljno dobiti i vlastitim poslovnim prostorom može zamijeniti opremu ili obnoviti zgradu. Poduzeće s niskom dobiti, unajmljenim prostorom i starim vozilom može reagirati samo smanjenjem poslovnog viška ili odgodom investicija. Zbog toga jednaka relativna promjena energetskih cijena ima različite ekonomske i socijalne posljedice. Važan zajednički nalaz jest da smanjenje energetske potrošnje nije samo po sebi dovoljno za procjenu uspješnosti dekarbonizacijske politike. Ako je smanjenje posljedica energetske učinkovitosti, promjene tehnologije ili zamjene fosilnog energenta, ono može istodobno smanjiti emisije, trošak i ranjivost. Ako je posljedica nemogućnosti plaćanja, ista brojčana promjena potrošnje može značiti gubitak toplinske ugode kod kućanstva ili smanjenje poslovne aktivnosti kod poduzeća. Stoga je pri evaluaciji politike nužno razlikovati strukturne uštede od prisilnog smanjenja potrošnje.

Drugi zajednički nalaz odnosi se na važnost financijske sposobnosti. U oba promatrana sektora početni investicijski trošak predstavlja jednu od glavnih prepreka. Kućanstvo s niskim prihodima može imati najveću korist od energetske obnove, ali najmanju sposobnost njezina financiranja. Mikro-poduzeće s visokom energetskom izloženošću također može ostvariti velik relativni povrat od učinkovitije opreme, ali mu niska dobit i ograničen pristup financiranju mogu onemogućiti investiciju. U oba slučaja postoji opasnost energetskog paradoksa u kojem najranjiviji potrošači, koji bi najviše dobili smanjenjem energetskih potreba, imaju najmanju sposobnost poduzeti potrebne mjere.

Treći zajednički nalaz jest važnost vlasništva i kontrole nad imovinom. Kod hrvatskih mikro-poduzeća vlasništvo prostora pokazalo se najsnažnijim pojedinačnim čimbenikom povezanim s prethodnim energetskim ulaganjima. Sličan problem postoji kod kućanstava koja ne mogu samostalno odlučivati o dubinskim zahvatima u zgradi. Politike stoga ne mogu pretpostaviti da je ekonomski poticaj dovoljan ako korisnik nema pravnu ili praktičnu mogućnost djelovanja.

Četvrti zajednički nalaz odnosi se na podatke. Kvalitetno ciljanje zahtijeva razlikovanje nominalne izloženosti od stvarne ranjivosti. Visok energetski račun nije dovoljan kriterij ako ne znamo prihod, dobit, strukturu potrošnje, sektor, dostupnost alternative ili investicijski kapacitet. Problem je posebno izražen kod mikro-poduzeća jer se velik dio poslovne energije nalazi unutar kućanskih statistika. Rezultati hrvatske ankete o zajedničkim računima i vozilima pokazuju da ta statistička nevidljivost nije hipotetska. Ona može izravno utjecati na procjenu potrošnje, energetskog siromaštva, energetskog intenziteta poduzeća i ciljanja kompenzacijskih mjera.

Peti zajednički nalaz jest potreba za razlikovanjem kratkoročnih i dugoročnih mjera. Kompenzacija energetskog troška može biti opravdana kao privremena zaštita od šoka, ali

dugoročno ne uklanja izvor ranjivosti. Trajno smanjenje ranjivosti zahtijeva promjenu zgrade, tehnologije, vozila, energenta ili poslovnog procesa. Međutim, strukturna promjena zahtijeva vrijeme i kapital. Optimalan redoslijed zato podrazumijeva pravodobno osiguravanje investicijske potpore, nakon čega cjenovni instrument može djelovati kao poticaj, a ne samo kao dodatno financijsko opterećenje.

Disertacija doprinosi znanstvenoj literaturi na nekoliko međusobno povezanih razina. Konceptualni doprinos proizlazi iz proširenja pojma energetske ranjivosti s dominantno kućanskog konteksta na mikro-poduzeća. Razvijeni okvir pokazuje da postoje zajedničke dimenzije, poput pristupa energiji, cjenovne izloženosti i ograničenog adaptacijskog kapaciteta, ali i specifično poslovne dimenzije poput profitabilnosti, konkurentnosti, mogućnosti prijenosa troška, vlasništva poslovne imovine i reinvesticijskog kapaciteta. Time se mikro-poduzeća ne tretiraju kao smanjena verzija većih poduzeća niti jednostavno kao kućanstva, nego kao zasebna skupina s elementima oba sustava.

Metodološki doprinos uključuje razvoj MEVI indeksa kojim se po prvi put na sustavan način uspoređuju strukturni uvjeti energetske ranjivosti mikro-poduzeća među državama članicama Europske unije. Kombinacija statističkih pokazatelja, ekspertnih pondera i normalizacije omogućuje procjenu u uvjetima u kojima harmonizirani mikropodatci ne postoje. Indeks ne zamjenjuje individualne podatke, ali predstavlja probirni instrument kojim se mogu identificirati zemlje i područja u kojima je potrebno detaljnije istraživanje.

Drugi metodološki doprinos proizlazi iz empirijskog povezivanja poslovnih i kućanskih energetskih statistika. Analiza hrvatskih mikro-poduzeća pokazuje da statističke kategorije ne odgovaraju nužno stvarnoj potrošnji te uvodi problem sustavne pogrešne atribucije kao relevantno pitanje energetske ekonomike i evaluacije politika. Time se otvara potreba za preispitivanjem nekih standardnih determinanti kućanske i poslovne potrošnje energije, jer poslovna aktivnost u domu može predstavljati skriveni čimbenik koji nije sadržan u postojećim modelima.

Treći metodološki doprinos predstavlja razvoj i primjena vlastitog statičkog energetskog modela i mikrosimulacijskog okvira koji omogućuju povezivanje cjenovnih promjena s potrošnjom, dobrobiti kućanstava, profitabilnošću i financijskom stabilnošću mikro-poduzeća. U kućanskom dijelu korištenje kompenzacijske varijacije omogućuje procjenu welfare učinka izvan jednostavne promjene računa. U poslovnom dijelu mikrosimulacija omogućuje procjenu heterogenih profila i povezuje dodatni energetski trošak s investicijskom sposobnošću, što je izravno relevantno za regulatornu definiciju ranjivog mikro-poduzeća u kontekstu Socijalnog fonda za klimatsku politiku.

Empirijski doprinos posebno proizlazi iz primarnog istraživanja na 470 hrvatskih mikro-poduzeća. Ono identificira konkretne determinante ranjivosti i prilagodbe, potvrđuje

važnost dobiti i energetskih rashoda, utvrđuje povezanost vlasništva, veličine i starosti poduzeća s investicijskim ponašanjem te pokazuje snažnu povezanost poslovne energetske ranjivosti s financijama kućanstva. Isto istraživanje pruža jedno od prvih empirijskih mjerenja razmjera preklapanja kućanske i poslovne potrošnje energije i vozila među mikro-poduzećima.

Praktični doprinos rada odnosi se na mogućnost primjene rezultata u oblikovanju klimatskih, energetskih i gospodarskih politika. MEVI može pomoći u određivanju dominantnih strukturnih izvora ranjivosti. Identificirane mikro-determinante mogu biti temelj preciznijih kriterija za potpore. Rezultati vezani uz nedostatak podataka upućuju na konkretne promjene statističkih sustava. Modeliranje kućanstava pokazuje potrebu kombiniranja ETS2 sa strukturnim mjerama energetske učinkovitosti i visokim stopama potpore niskodohodovnim skupinama. Modeliranje mikro-poduzeća daje alat kojim je moguće procijeniti profil i broj potencijalno ranjivih korisnika Socijalnog fonda te usmjeriti potporu prema zgradama, vozilima ili drugim potrebama.

Istraživanje ima i ograničenja. Najvažnije je povezano s nedostatkom harmoniziranih podataka o potrošnji energije mikro-poduzeća. MEVI se stoga oslanja na makroindikatore i dostupne poslovne pokazatelje, a ne na stvarnu individualnu potrošnju. Hrvatska anketa predstavlja velik korak prema mikrorazini.

Modeli dekarbonizacijskih politika također zahtijevaju niz pretpostavki. Projekcije budućih cijena energije i ugljika inherentno su neizvjesne. Cjenovne elastičnosti ranjivih kućanstava i mikro-poduzeća nisu dovoljno empirijski poznate. U modelu kućanstava korištene su prosječne vrijednosti koje mogu precijeniti sposobnost određenih ranjivih skupina da smanje potrošnju bez gubitka dobrobiti. U modelu mikro-poduzeća korišten je hibridni pristup temeljen na komercijalnim i kućanskim elastičnostima. *Bottom-up* reprezentativni profili ne mogu obuhvatiti punu heterogenost milijuna europskih mikro-poduzeća. Mikrosimulacija se usredotočuje na relativno kratko razdoblje pa ne uključuje sve dugoročne strukturne promjene, poput preseljenja poslovanja, promjene poslovnog modela ili endogene tehnološke transformacije. Dodatno, učinak ETS2 izoliran je od drugih istodobnih politika kako bi se mogao zasebno procijeniti, iako će u stvarnosti konačni učinak ovisiti upravo o interakciji s drugim instrumentima. Ta ograničenja istodobno upućuju na smjerove budućih istraživanja. Potrebno je razvijati harmonizirano prikupljanje podataka o energiji mikro-poduzeća, uključujući sektor, broj zaposlenih, prostor u kojem posluju, stvarnu uporabu energije i vozila, financijsku stabilnost i investicijsko ponašanje. Posebno bi korisno bilo u statistike kućanstava uključiti podatak o tome odvija li se u stambenom prostoru poslovna aktivnost. Time bi se dio trenutno skrivene poslovne potrošnje mogao pravilnije atribuirati. Buduća istraživanja trebala bi obuhvatiti više država i sektora kako bi

se provjerilo u kojoj su mjeri obrasci uočeni u Hrvatskoj prisutni u različitim institucionalnim i gospodarskim kontekstima.

Potrebna su i detaljnija istraživanja cjenovnih elastičnosti mikro-poduzeća i kućanstava s niskim prihodima. Posebno je važno razlikovati kratkoročnu i dugoročnu elastičnost te utvrditi koji dio odgovora proizlazi iz promjene ponašanja, koji iz smanjenja potrebnih energetskih usluga, a koji iz ulaganja u energetsku učinkovitost ili promjene tehnologije. Bez tog razlikovanja smanjena potrošnja može se pogrešno interpretirati kao uspješna dekarbonizacija. Dinamički modeli mogli bi dodatno obuhvatiti promjene u investicijama, cijenama proizvoda, zapošljavanju, konkurentnosti i tehnološkoj strukturi tijekom duljeg razdoblja.

U konačnici rezultati disertacije pokazuju da se distribucijski učinci dekarbonizacije ne mogu odvojiti od pitanja tko ima mogućnost odgovoriti na uvedenu mjeru. Klimatska politika najuspješnija je kada cjenovni, regulatorni i investicijski instrumenti djeluju komplementarno. Cjenovni signal može potaknuti promjenu, ali samo ako postoji dostupna alternativa. Regulacija može ubrzati energetsku obnovu ili zamjenu tehnologije, ali mora biti praćena financijskim i tehničkim instrumentima za one koji sami ne mogu financirati zahtijevanu prilagodbu. Privremena kompenzacija može zaštititi potrošača od naglog šoka, ali ne smije zamijeniti strukturno rješenje koje dugoročno smanjuje izloženost.

Kod kućanstava to znači da se cilj ne bi trebao svesti na smanjenje računa ili privremeno subvencioniranje energije. Dugoročni cilj mora biti smanjenje količine energije potrebne za ostvarivanje primjerene razine toplinske ugode i drugih energetskih usluga. Kod mikro-poduzeća cilj nije samo kompenzirati dodatni trošak goriva, nego omogućiti ulaganje kojim poduzeće može prijeći na učinkovitiju zgradu, opremu, vozilo ili drugi poslovni model. Praćenje provedbe politike stoga bi uz iznose dodijeljenih sredstava trebalo mjeriti koliko je stvarnih investicija omogućeno i koliko je korisnika trajno smanjilo svoju izloženost.

Rezultati također pokazuju da kategorije ranjivosti ne bi trebalo promatrati izolirano. Kod vlasnika mikro-poduzeća kućanstvo i poduzeće često su jedan financijski sustav. Povećanje poslovnih troškova utječe na kućanski dohodak, a nedostatak kućanskih sredstava ograničava poslovne investicije. Ista zgrada može biti dom i poslovni prostor, a isto vozilo privatno i poslovno sredstvo. Energetske politike koje strogo razdvajaju kućanstva i poduzeća mogu zato propustiti skupinu kod koje se rizici akumuliraju. To je posebno relevantno u području Socijalnog fonda za klimatsku politiku, gdje se različiti oblici ranjivosti susreću unutar istog regulatornog instrumenta.

Glavna hipoteza istraživanja stoga se potvrđuje kroz različite razine analize. U nepovoljnim strukturnim uvjetima i bez odgovarajućih pratećih mjera dekarbonizacijski instrumenti mogu kratkoročno povećati ranjivost. Kod niskodohodovnih kućanstava ETS2 samostalno

može dovesti do smanjenja potrošnje uz pad toplinske ugode i realne dobrobiti. Kod mikro-poduzeća veći troškovi mogu smanjiti profit i upravo time onemogućiti investiciju potrebnu za dekarbonizaciju. Nasuprot tome, kada je cjenovni instrument kombiniran s energetskom obnovom, dostupnim čistim tehnologijama, visokim stopama financiranja za ranjive skupine, administrativno izvedivim programima i pravodobnom potporom, isti proces može dugoročno smanjiti energetsku potrošnju, trošak, ovisnost o fosilnim gorivima i ranjivost.

Time se potvrđuje da je vremensko usklađivanje jedna od ključnih dimenzija pravedne energetske tranzicije. Trošak i mogućnost prilagodbe ne bi smjeli biti promatrani odvojeno. Ako se nova cijena ili obveza uvede prije nego što su alternativa i financiranje dostupni, ona može povećati ranjivost čak i kada je njezin dugoročni klimatski učinak pozitivan. Ako se najprije izgradi mogućnost prilagodbe, ista mjera može ubrzati transformaciju uz znatno manji distribucijski teret.

Druga ključna dimenzija jest ciljanost. Univerzalne mjere mogu biti jednostavne, ali ne uzimaju u obzir različitu sposobnost potrošača da snose trošak. Istodobno previše složeno ciljanje može proizvesti visoke administrativne troškove i isključiti najmanje korisnike. Razvijeni pokazatelji i modeli pružaju mogućnost kombiniranja nekoliko ključnih kriterija, uključujući energetsku izloženost, profit ili dohodak, investicijski kapacitet, sektorsku relevantnost i dostupnost alternative. Takav pristup omogućuje preciznije usmjeravanje potpore bez nužnog prikupljanja neograničenog broja podataka.

Treća ključna dimenzija jest statistička vidljivost. Potrošač koji nije prepoznat u podatcima teško može biti pravilno uključen u politiku. Mikro-poduzeća predstavljaju posebno jasan primjer tog problema. Njihova brojnost i gospodarska važnost nisu praćene odgovarajućom energetskom statistikom. Podatci o njihovoj energiji mogu završiti u sektoru kućanstava, usluga, industrije ili prometa, a agregirane statistike MSP-ova prikrivaju razlike među veličinskim razredima. Poboljšanje podataka nije stoga samo znanstvena potreba, nego preduvjet kvalitetnog upravljanja energetskom tranzicijom.

Disertacija u konačnici zagovara pomak od analize prosječnog potrošača prema analizi sposobnosti prilagodbe različitih skupina. U tradicionalnoj analizi dovoljno je procijeniti promjenu prosječne cijene i potrošnje. U distribucijskoj analizi potrebno je dodatno utvrditi tko troši energiju, za koju svrhu, iz kojeg izvora prihoda plaća taj trošak, kakvu alternativu ima, može li financirati investiciju i što se događa s njegovom dobrobiti ili poslovnom održivošću ako to ne može. Takav pristup ne dovodi u pitanje potrebu za dekarbonizacijom. Naprotiv, omogućuje njezinu uspješniju i društveno održiviju provedbu.

Dugoročno, smanjenje ovisnosti o fosilnim gorivima, energetska učinkovitost i prelazak na obnovljive izvore mogu biti snažni mehanizmi smanjenja energetske ranjivosti. Energetski učinkovita zgrada manje je osjetljiva na promjenu cijene energenta; elektrificirani i

diversificirani sustav smanjuje ovisnost o pojedinom fosilnom gorivu; poduzeće s manjom energetskom intenzivnošću otpornije je na energetske šokove; kućanstvo koje koristi manju količinu energije za istu razinu ugode ima niži rizik energetskog siromaštva. Međutim, prelazak iz početnog u takvo dugoročno stanje nije automatski i zahtijeva investicije koje najranjiviji potrošači najteže financiraju.

Stoga pravedna tranzicija ne podrazumijeva zaštitu svakog potrošača od svakog povećanja cijene energije niti trajno subvencioniranje postojeće fosilne potrošnje. Takav bi pristup mogao čak odgoditi strukturnu prilagodbu i povećati buduću ranjivost. Pravednost podrazumijeva osiguravanje stvarne mogućnosti prilagodbe i sprječavanje situacije u kojoj trošak tranzicije nerazmjerno snose oni koji imaju najmanje sredstava da promijene tehnologiju, zgradu, vozilo ili obrazac potrošnje.

Na temelju svih provedenih analiza može se zaključiti da energetska ranjivost mikro-poduzeća predstavlja zasebno i relevantno područje istraživanja koje zahtijeva sustavnije uključivanje u energetsku ekonomiku i klimatsku politiku. Mikro-poduzeća nisu homogena skupina niti su samo umanjeni oblik većih poduzeća. Njihova ranjivost proizlazi iz specifične kombinacije malih financijskih rezervi, ograničenog investicijskog i administrativnog kapaciteta, heterogene energetske potrošnje, tržišne izloženosti i čestog preklapanja s kućanstvom vlasnika.

MEVI indeks pokazuje da se strukturni uvjeti te ranjivosti značajno razlikuju među državama i da različite zemlje zahtijevaju različite kombinacije politika. Hrvatska studija pokazuje koji se čimbenici mogu identificirati kada postoje primarni mikropodatci te potvrđuje ključnu ulogu dobiti, energetskih troškova, vlasništva i veličine. Analiza statističke nevidljivosti pokazuje zašto takvi podatci u redovitim sustavima uglavnom ne postoje i kako miješana kućanska i poslovna uporaba energije može iskriviti oba sektora. Modeliranje kućanstava pokazuje da kombiniranje strukturnih i cjenovnih mjera daje bolje rezultate od izoliranog oslanjanja na cijenu, dok mikrosimulacija mikro-poduzeća potvrđuje da će ETS2 imati izrazito heterogene učinke i da se ranjivost koncentrira kod poduzeća s velikom energetskom izloženošću i nedostatnim financijskim kapacitetom.

Znanstvena i praktična vrijednost disertacije stoga proizlazi upravo iz povezivanja tih razina. Problem energetske ranjivosti najprije se konceptualizira, zatim mjeri dostupnim kompozitnim pokazateljima, empirijski ispituje primarnim podatcima, povezuje s nedostatcima statističkog sustava te se na kraju uključuje u model distribucijskih učinaka konkretnih dekarbonizacijskih politika. Time se stvara cjelovit okvir od identifikacije ranjivosti do procjene učinka i preporuke za oblikovanje politike.

Zaključno, dekarbonizacijske politike imaju potencijal dugoročno smanjiti energetsku ranjivost, povećati otpornost potrošača i poboljšati energetsku sigurnost, ali samo ako su

oblikovane u skladu sa stvarnim mogućnostima prilagodbe. Njihov uspjeh ne ovisi samo o ambicioznosti klimatskog cilja ili visini cjenovnog signala, nego i o tome postoje li dostupne alternative, može li ih ranjivi potrošač financirati, jesu li mjere potpore uvedene pravodobno i raspolaže li donositelj odluka podatcima potrebnima da prepozna kome je potpora potrebna. Rezultati disertacije potvrđuju potrebu za diferenciranim, pravodobnim i podatkovno utemeljenim politikama koje istodobno uzimaju u obzir okolišnu učinkovitost, ekonomsku održivost i distribucijsku pravednost. Takav pristup omogućuje da tranzicija prema klimatskoj neutralnosti ne bude samo proces smanjenja emisija, nego i proces povećanja otpornosti i dobrobiti društva u cjelini.

CURICCULUM VITAE

Ivana Rogulj, born in 1983 in Split, completed her secondary education at a language gymnasium in Omiš. In 2007, she graduated from the Faculty of Electrical Engineering and Computing (FER), University of Zagreb, with a Master's degree in Power Engineering - Energy Systems. She completed a postgraduate interdisciplinary study in Eco-engineering (univ. spec. oecoing) at the University of Zagreb, as well as a postgraduate study (MBA, univ. spec. oec.) in Energy Economics at the Faculty of Economics and Business, University of Rijeka. In 2021, she started this PhD.

She has nearly 20 years of professional experience in the energy sector, in both expert and managerial roles. Since 2020, she has been working at the international research Institute for European Energy and Climate Policy (the Netherlands), where she leads a team conducting research and supporting the implementation of European Union climate and energy policies, with a particular focus on energy efficiency in industry and SMEs. She has also worked as an external lecturer in the MBA.

Ivana has coordinated and contributed to more than 40 European and national research and expert projects, as well as numerous studies, analyses, policy documents and technical assistance assignments. In addition, she has organised conferences and lectures and developed educational materials (including those for children).

Ivana has completed training in CBA, energy audits, M&V, and one-year education in project management. She was the President of the Management Board of DOOR and a member of national and international advisory boards in her field.

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IZJAVA

kojom ja, Ivana Rogulj, broj indeksa: _____ doktorandica Ekonomskog fakulteta Sveučilišta u Rijeci, kao autor/ica doktorske disertacije s naslovom: *Utjecaj dekarbonizacijskih politika u energetskom sektoru na ugrožene potrošače energije*

1. Izjavljujem da sam doktorsku disertaciju izradila samostalno pod mentorstvom prof. dr. sc. Pavla Jakovca, a pri izradi doktorske disertacije pomagao mi je i prof.dr.sc. Saša Žiković. U radu sam primijenila metodologiju znanstvenoistraživačkog rada i koristila literaturu koja je navedena na kraju rada. Tuđe spoznaje, stavove, zaključke, teorije i zakonitosti koje sam izravno ili parafrazirajući navela u radu citirala sam i povezala s korištenim bibliografskim jedinicama sukladno odredbama Pravilnika o izradi i opremanju doktorskih radova Sveučilišta u Rijeci, Ekonomskog fakulteta u Rijeci. Rad je pisan u duhu engleskog jezika.

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Ivana Rogulj