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National diversity in European energy policy: Analyzing dependencies of changes in energy prices, climate regulations, and technological innovations on economic implications

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A R T I C L E I N F O

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A B S T R A C T

This study analyzes how national diversity in energy policies influences key economic outcomes across European countries, with particular emphasis on the interdependencies between energy prices, climate regulations, and technological innovations. Addressing a gap in existing literature, the study adopts a cross-country perspective that integrates policy, innovation, and macroeconomic dimensions. A two-step methodological framework is applied: (1) expert-based causal mapping using the DEMATEL method to identify bidirectional cause-effect relationships and (2) panel data econometric modeling to empirically validate the impact of selected indicators -electricity prices, greenhouse gas emissions, and R&D expenditure - on inflation, unemployment, and economic growth from 2012 to 2022.

DEMATEL results identify energy prices and climate regulations as primary causal drivers exerting strong directional influence on technological innovation and macroeconomic variables. Innovation acts mainly as an effect shaped by regulatory and market forces. Panel data estimates show that current energy price hikes reduce R&D spending, while past increases encourage innovation. Climate regulations exhibit delayed but positive effects on innovation. Inflation mediates these relationships, with both immediate and lagged impacts on energy prices and R&D.

The findings underscore the need for strategic planning and investment in innovation to effectively manage energy prices and climate policies. This research provides a novel framework for evaluating the economic implications of energy policy diversity and supports more coordinated EU-level policymaking. Further research should incorporate more granular, sector-specific indicators with longer time series to enhance robustness and policy relevance.

1. Introduction

Energy systems are fundamental to modern economies [1]. Challenges such as climate change, increasing energy demand, resource limitations, and the need for sustainable development underscore the importance of energy economics [2–4]. Developing effective energy policies is crucial, particularly in Europe, where diverse national strategies reflect varied socioeconomic contexts [5]. Recent shifts in energy prices, stricter climate regulations, and rapid technological advancements have transformed the European energy landscape [6,7]. However, a comprehensive understanding of how these diverse policies affect economic outcomes across the EU remains limited.

To provide conceptual clarity and ensure terminological consistency throughout this study, interrelated concepts such as "economic implications," "economic performance," and "economic outcomes" are here contextualized using academic literature in the context of energy policy and macroeconomic analysis. The context-specific definitions reflect their operationalization in this research. In this study "economic implications" refer to the set of consequences, both positive and negative, that diverse national approaches to energy prices, climate regulation, and technological innovation within member states [8,9]. These may include changes in energy supply costs, industrial competitiveness, labor market dynamics, and GDP fluctuations [10,11].

Economic performance denotes the measurable outcomes of

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economic activities that are directly or indirectly shaped by energy policy. It includes metrics such as GDP growth, return on investment, productivity, or operational efficiency [9,12,13]. This concept is often operationalized through comparative cross-country metrics. Economic outcomes refer to the specific socio-economic results achieved through the implementation of energy policies. These may include both positive and negative effects on growth, employment, inequality, and ecological sustainability [14].

Grounded in these definitions, the following sections explore how climate changes in regulations and technological innovations present both challenges and opportunities for economic and energy market stability (Tang, 2006; [15]; Alessandria et al., 2023).

While previous studies have examined individual countries or specific aspects of the energy sector [16–18], there is a lack of holistic research on the broader economic influences on national energy policy diversity.

In Central and Eastern European Countries (CEECs), energy prices are closely linked to inflation [19], and energy import dependency varies significantly across the region. While Estonia has successfully reduced its dependence by increasing renewable energy production, other countries have experienced a rising reliance on imported energy. Additionally, fluctuations in CO_2 emission allowances and energy resource prices (2010–2021) have led to substantial changes in electricity prices, with household prices in Hungary decreasing by 41 %, in contrast to other CEE nations, where prices have surged [139]. These disparities underscore the need for a more comprehensive assessment of national energy policy effects.

While CEECs exemplify the varied national impacts of energy policy, such patterns extend across the EU and warrant broader investigation. Despite extensive research on energy economics, a systematic, comparative analysis of how energy policies, energy prices, climate regulations, and technological innovations interact across EU economies remains lacking [17]. Existing literature predominantly focuses on single-country analyses or renewable-energy-driven economies [20,21]. However, national energy strategies are deeply interconnected with broader economic indicators, policy uncertainty, and market stability, requiring an integrated approach.

This study addresses the aforementioned gap by conducting a rigorous, cross-national analysis of European energy policy diversity and its economic impacts. Using DEMATEL and panel econometric models, including autoregressive dynamic models, the study examines key relationships among energy prices, climate policies, technological innovation (R&D), and macroeconomic indicators such as inflation, unemployment, and GDP growth. Unlike previous studies that focus on energy consumption trends, this research explores the complex interactions shaping national policy responses and economic outcomes. Key challenges include.

- Policy Diversity: Different regulatory frameworks and policy instruments complicate comparative studies.
- Dynamic Interactions: Complex interactions between energy prices, regulations, and technological advancements require advanced analysis.
- Economic Disparities: Varying economic structures and energy dependencies across Europe affect the generalizability of findings.
- Data Heterogeneity: Variations in data availability and quality across countries hinder unified analysis.

The novelty of this study lies in an in-depth analysis of the relationships between key energy policy factors in EU countries, integrating economic, regulatory, and technological perspectives. Previous research has focused on selected or individual aspects of the energy sector, overlooking a broad approach to the diversity of national strategies and their impact on EU economies. Existing analyses have primarily examined climate regulations [22] and their role in economic decarbonization [23], the limited effectiveness of EU governance mechanisms in achieving RES targets [24], or the impact of renewable energy on employment [24], as well as the growth of renewable energy consumption and its positive effects on the economy, environment, and conventional energy use [20]. However, there remains a lack of studies that systematically examine the interactions between energy policy, energy prices, climate regulations, and technological innovations across the EU and their impact on national economies and economic sectors, particularly in the context of economic policy uncertainty affecting long-term energy planning and investment strategies.

The energy transition in the EU is primarily driven by environmental concerns, energy independence, and technological advancements [20]. While previous research has highlighted the increasing role of renewable energy in industry and households, a systemic analysis of how energy policies influence the interactions between energy prices, climate regulations, and technological innovations across countries and economic sectors is still missing.

This study employs a unique combination of the DEMATEL methodology and econometric panel models, enabling the identification of cause-and-effect relationships between key energy policy factors across different countries. DEMATEL enables the determination of the hierarchy of influences and interactions within the energy system, identifying which elements - energy prices, climate regulations, or innovations - are most significant for the economy. Meanwhile, econometric panel models provide a quantitative assessment of their impact on key indicators such as inflation, R&D expenditures, and the competitiveness of the energy sector.

Another innovative aspect of this study is the analysis of ten European countries, which vary in their dependence on energy imports, the intensity of climate regulations, and their level of innovation. Unlike previous research, which has shown a significant increase in renewable energy consumption in the EU and its beneficial effects on economic growth, greenhouse gas reduction, and decreased reliance on conventional energy [20], this study focuses on regional differences in how countries respond to changes in energy policy and their long-term economic consequences in the face of economic policy uncertainty [21]. Furthermore, the study also reveals how energy price fluctuations and inflation influence investments in research and development as well as how climate regulations shape technological advancements in the energy sector - aspects that have not yet been comprehensively examined from an international perspective. The use of panel data from 2012 to 2022 enables the identification of long-term trends and an assessment of energy policy effectiveness, particularly in an environment where economic policy uncertainty can create barriers to stable and predictable energy transitions.

To address the outlined knowledge gaps and advance understanding of the economic implications (e.g., impact on inflation and unemployment or technological investment responses) of national energy policy diversity, this study is guided by the following literature research questions.

RQ1. How do energy prices, climate regulations, and technological innovations interact within national energy policy frameworks across the EU?

RQ2. Which of these factors act as primary causal drivers influencing macroeconomic indicators such as inflation, R&D intensity, and economic growth?

RQ3. How do these relationships differ between countries with varying levels of energy import dependency, regulatory stringency, and innovation capacity?

To answer these questions, a two-stage methodological approach is applied. First, the DEMATEL method is used to capture the causal structure among energy policy factors, identifying which elements act as dominant influencers within the energy system. Second, panel econometric models, including dynamic autoregressive approaches, quantify the impact of these factors on macroeconomic indicators across ten EU countries over the period 2012–2022. This integrated design enables both structural insight and empirical validation, contributing to a deeper understanding of the interactions shaping the European energy-economic landscape.

The rationale for this study stems from the need to better understand the complexity and asymmetric effect of national energy policies within the EU and its economic effects in the context of dynamic market and regulatory changes. In the face of rising energy prices and climate change, providing empirical evidence on the consequences for economic performance is essential to inform more effective policy coordination.

The main research objectives of this study are as follows.

(1) To identify the directional relationships among selected energy, innovation, and economic indicators using the DEMATEL method;
(2) To quantify the strength and statistical significance of these relationships using panel data econometric models.

This two-stage approach enables both the identification of potential cause-effect relationships and the estimation of their economic impact in the context of European energy policy.

The research objectives are operationalized through a two-stage methodological design: DEMATEL is applied to identify the causal structure and relative importance of variables, while panel econometric models test the robustness and statistical significance of these relationships across countries and over time. This integration ensures that the study's objectives are methodologically actionable.

The article consists of five main sections. The introduction outlines the research objective to examine how energy prices, climate regulations, and innovation relate to economic outcomes in the EU. The Literature review identifies a gap in integrating qualitative and quantitative methods. The Methods section describes variable selection and the two-stage approach: DEMATEL for causal mapping and panel econometrics for estimating relationships. Results present findings from both methods, while the discussion reflects on national policy diversity, methodological limitations, and future research directions.

2. Literature review

This section reviews the existing literature on the interdependencies between energy prices, climate regulations, technological innovations, and their economic indicators (inflation, unemployment, economic growth) in the European Union. Recent studies [25–28] have examined the multifaceted impacts of these developments. Some studies highlighted that integrating EU energy markets could enhance competitiveness against global rivals by reducing energy costs and improving energy security. Similarly, research by [29] emphasized the importance of cross-border electricity trade and market integration in optimizing renewable energy utilization and reducing supply costs. The shift towards renewable energy sources has also been a focal point. In the first half of 2024, wind and solar energy accounted for 30 % of the EU's electricity generation, surpassing fossil fuels for the first time. This transition underscores the EU's commitment to decarbonization and the effectiveness of policies promoting the deployment of renewable energy. However, the interplay between energy policy and economic factors remains a complex issue. Studies have shown [30,31] that economic policy uncertainty can adversely affect renewable energy investments, as firms may delay or reduce their investments amid unclear policy environments. Conversely, geopolitical risks have been identified as potential drivers of innovation in renewable energy technologies, suggesting that external shocks can catalyze energy transitions.

The review is structured under three thematic sub-sections as recommended: energy price dynamics, technological innovation and climate policy, and integrated policy diversity in the EU.

2.1. Energy prices and macroeconomic indicators

Global attention is increasingly focused on the impact of energy use on international trade and economic growth. Energy prices are crucial for many industries' cost structures, impacting inflation, production costs, competitiveness, and household budgets. Rising energy prices lead to increased transportation and production costs, fueling inflation and potentially reducing consumer demand [32–34]. The relations between economic growth and energy are well-established, with each influencing the other [35,36]. The relationship between energy prices and economic indicators such as economic growth (GDP, GNP, NNP), unemployment (unemployment rate, economic activity rate), inflation (HCPI, CPI), and investment has been extensively studied in the literature, highlighting the diverse impacts of energy price fluctuations on different countries' economies [37].

Recent studies have further explored these dynamics in light of the EU's energy crises and policy shifts. For instance, Banna et al. [38] and Brucal and Dechezleprêtre [39] show that energy price volatility affects inflation and firm-level investment, particularly in energy-importing countries. However, most of these studies adopt traditional econometric or regression approaches without explicitly integrating EU climate policy frameworks such as EC [40].

While studies such as Bigerna [41] provide valuable information into the links between oil prices, exchange rates, and inflation, they focus mainly on static analysis and do not consider the broader context of EU energy and climate policies. Similarly, studies [42] offer useful evidence on the inflation co-movement across European countries in response to exchange rate shocks, but they neither integrate EU energy or fiscal policy frameworks nor apply causal inference methods. In contrast, this study adopts a policy-informed and causally structured approach to analyzing the interdependencies between energy prices, innovation, and macroeconomic indicators across EU member states. Although [43] contribute to understanding the long-term relationships between energy consumption and economic growth, their analysis remains purely quantitative and does not consider the multidimensional impact of EU energy and climate policies.

To provide additional context selected seminal papers on the correlation between energy prices, climate regulations, and technological innovation's influence on economic growth are outlined in Table 1.

These studies collectively enhance understanding of the complex interplay between energy prices and macroeconomic indicators. However, many focus on specific aspects or regions, and there remains a need for comprehensive analyses that integrate various macroeconomic factors across multiple EU countries.

Some European countries are actively pursuing sustainable energy solutions and reducing carbon emissions through their national energy policies. Germany faces rising energy prices due to its shift toward renewable energy sources and carbon pricing, while Norway experiences moderate fluctuations driven by its involvement in the oil and gas

Table 1
Representative papers focusing on the energy prices - economic growth relations.

Authors	Year	Topic
[44]	2014	Energy prices, economic growth
[45]	2015	Energy prices, growth channels
[46]	2020	Economic growth, carbon emission, renewable and nonrenewable energy consumption
[47]	2021	Energy prices, economic growth, renewable energy consumption
[48]	2022	Energy prices, economic growth
[49]	2023	Urbanization, renewable energy, investments
[50]	2023	Sustainability, economic growth
[51]	2023	Renewable energy, energy efficiency
[52]	2023	Energy prices, economic performance
[53]	2024	Alternative energy sources, economic and environmental analysis
[54]	2024	Clean energy, sustainable energy growth

market and carbon pricing mechanisms. France focuses on nuclear energy within its global climate commitments, while Denmark targets ambitious reductions in emissions. These examples illustrate how shifts in energy prices directly influence national economic and investment priorities.

2.2. Technological innovation and climate policy

Technological innovations are widely recognized as key drivers of economic growth, productivity improvements, and enhanced quality of life [55–58]. The reviewed studies highlight the dual role of innovation: as a response to environmental regulations and as an endogenous factor shaping systemic transformation [59]. However, while this literature convincingly outlines the macro-level benefits of innovation, such as job creation [60], investment stimulation [55,61,62], and sectoral shifts [63], it often overlooks distributional impacts, particularly at the microeconomic and regional levels. For instance, many contributions [60] emphasize employment creation through new technology sectors but lack sectoral disaggregation, leaving it unclear how innovation affects employment across traditional, emerging, and carbon-intensive industries. Moreover, the evidence for innovation-induced growth tends to be aggregated at the national level, without differentiating across sectors or firm sizes, which limits its applicability for tailored policymaking.

The literature also frequently underscores the positive feedback loops between environmental regulations and innovation [61,64], a view aligned with the Porter Hypothesis. However, many studies approach this relationship from a linear and deterministic perspective, overlooking important contextual moderators such as institutional quality [65], cross-country heterogeneity in innovation systems [66], or regulatory uncertainty and its dampening effects on long-term investment in green R&D [67,68]. These omissions may limit the explanatory power of existing models and their policy relevance in diverse regional contexts.

Notably, the role of R&D as a proxy for innovation is commonly accepted (e.g.,[56,69]), but this measure does not always capture intangible or non-R&D-based innovation—particularly relevant to service sectors or digital transitions. Additionally, sectoral disaggregation of R&D efforts remains scarce in these analyses, despite clear indications that innovation dynamics differ significantly across industries [62].

While climate regulations are acknowledged as pivotal policy tools influencing the environment and impacting economic outcomes, imposing compliance costs, and shaping business and consumer behavior [67,70], the reviewed works offer limited insight into their effectiveness under different governance regimes or institutional settings. The reliance on quantitative efficiency metrics (e.g., green economic efficiency) [66,71] may also obscure important qualitative factors, such as public trust, political feasibility, or administrative capacity.

Finally, the global dimension of regulatory divergence is rightly identified as a challenge to competitiveness [65], but the interaction between national and supranational frameworks, particularly within the EU, remains underexplored.

2.3. Policy integration and national diversity in the EU

Energy policies across EU members reveal a significant heterogeneity, shaped by diverse resource endowments, political priorities, and historical energy choices. While the overarching EU frameworks such as the European Energy Union, the Paris Agreement (2015) and the European Green Deal (2019), seek to achieve policy integration and understand the interplay between national energy policies and economic outcomes [72].

Most existing studies focus on single countries or specific policy aspects (e.g. renewable energy targets or fiscal tools), thus underestimating the complexity of cross-national interdependencies and overlooking macroeconomic consequences such as inflation or unemployment. This study presents a comparative synthesis of ten energy-importing countries (Germany, France, Sweden, Poland, the Netherlands, Spain, Denmark, Belgium, Italy, and Norway) with a focus on how national energy policies interact with inflationary pressures, climate ambitions, and technological innovation capacity (Tables 2–4). The countries were selected based on a set of justified criteria, including rising energy costs, robust climate regulations, and the development of innovative energy technologies, and consistent time series data (2012–2022) were drawn from EUROSTAT (Table 2). This selection was dictated by the desire to account for significant variation in three dimensions crucial to the energy transition: (1) dependence on energy imports (from heavily importing countries to exporting ones, such as Norway), (2) the intensity and instrumentation of climate and energy policies (countries with ambitious national strategies and varying approaches to regulation), and (3) the level of innovation and the capacity to absorb new technologies (from innovation leaders to economies with medium or rising innovation performance). This geographic and systemic diversity enables a comparative analysis of the impact of energy availability, public policies, and innovation potential on the transition to low-emission solutions and allows for the use of rich sources of statistical data [73–75] and previous comparative analyses [76,77].

The comparative overview (Table 3) and country-specific summaries (Table 4) highlight the spectrum of energy strategies, from France's nuclear dependency to Denmark's wind leadership to Poland's coal-based challenges. Table 4 further maps how energy prices, climate regulations, and innovation outcomes interact within each national context [99–103]. However, while such mapping reveals structural diversity, it remains largely descriptive and insufficiently linked to causal mechanisms.

Recent studies [104] have examined the EU's response to energy price volatility, particularly. For instance, the European Union's REPowerEU Plan (reuters.com), adopted in 2022, aimed to enhance energy resilience and reduce dependency on external sources by accelerating the deployment of renewable energy and streamlining permitting processes. Additionally, the European Commission's decision to soften gas consumption curbs in early 2024 indicates a shift towards more flexible energy policies as the crisis eased. The interplay between climate policies and technological advancements has been a key focus of recent research [105–107].

To distinguish the paper from other research, the authors underline that, unlike studies focusing solely on individual aspects, this research concurrently analyzes energy prices, climate regulations, and technological innovations, providing a holistic view of their interdependencies. Moreover, the research investigates explicitly the economic consequences of energy policy decisions, a perspective less explored in recent empirical studies, and offers insights into how national contexts influence energy policy outcomes. In addition, despite these insights, a gap remains in the literature regarding the causal relationships between energy prices, climate regulations, technological innovation, economic growth, and unemployment across EU member states. Most existing

Table 2
Diversities across the analyzed countries.

Factor	Variation across countries
Energy Source	From nuclear-heavy (France) to coal-dependent (Poland) to hydro (Norway)
Policy Ambition	High (Denmark, Sweden) vs. transitional/lagging (Poland, Belgium)
Climate Regulation	Aggressive (Netherlands, Germany) vs. slower uptake (Italy, Poland)
Innovation Focus	Aggressive (Netherlands, Germany) vs. slower uptake (Italy, Poland)
Energy Prices	High and volatile (Germany, Italy), subsidized (France), rising (Poland)
Dependency on Imports	Low (Norway, France), high (Italy, post – Russia Germany)

Table 3
Comparative analysis of energy policies across selected countries.

Country	Approach to energy policy	Economic implications
Germany	Focused on renewable energy (wind, solar, biomass, and bioenergy) and grid modernization; carbon emission reduction [78,79]	High investment costs in renewables, reduced fossil fuel dependence [80,81]
France	Significant reliance on nuclear energy; development of electro mobility.	Low CO_2 emissions due to nuclear energy, high electricity share in energy consumption [81].
Sweden	Strong support for renewable energy and high energy efficiency standards.	Low greenhouse gas emissions and development of the clean energy technology industry.
Poland	Transition from coal as the main energy source; development of nuclear energy and renewable energy, improving efficiency; ensuring energy security; diversifying energy supply sources	High coal dependence and challenges in reducing greenhouse gas emissions [82].
The Netherlands	Support for energy efficiency focusing on creating market demand for renewable energy (demand-driven policies); investments in specific renewable energy technologies (supply-driven policy) [83].	Growth in renewable technology, reduced CO_2 emissions from transportation [84,85].
Spain	Diversification and increased share of renewables; development of photovoltaic, wind, solar, and hydropower	Innovation in the energy sector: reduced energy import dependence [86,87]
Denmark	Shift to low-carbon energy and smart grids; wind energy development [88,89]	Leadership in wind energy technology, reduced fossil fuel reliance, and wind technology exports.
Belgium	Phasing out nuclear; promoting renewables and energy efficiency [90,91]	Transition to cleaner energy, job creation in green energy, and reduced fossil fuel imports [91]
Italy	Diversification of energy sources; support for renewables (solar, wind, and geothermal) and efficiency, reducing carbon emission; and promoting green certificates [92,93].	Growth in renewables, investment in infrastructure, and reduced greenhouse gas emissions.
Norway	Focus on hydropower, exploration and export of oil and gas; sustainable economic growth [94,95].	High renewable energy production; shift to green jobs; economic benefits from oil/gas exports; decarbonization of energy systems [96–98]; investment in electric vehicle infrastructure

Table 4
Relations between energy prices, climate regulations, and technological innovations in separate countries based on relevant literature from Table 3.

Country	Changes in Energy Prices	Climate Regulations	Technological Innovations in the Energy Sector
Germany	Increasing energy prices due to the renewable energy transition and carbon pricing.	Stringent climate regulations promote renewable energy and energy efficiency.	Innovations in solar and wind energy technologies and smart grid development.
France	Moderate changes in energy prices with a focus on nuclear and renewable energy mixes.	Active participation in global climate agreements and emphasis on nuclear energy and emission reduction targets.	Technological advancements in nuclear energy and research in carbon capture and storage (CCS) technology.
Sweden	Moderate energy price changes with investments in renewable energy and energy efficiency.	Ambitious climate regulations with targets for emissions reduction and renewable energy adoption.	Leadership in bioenergy and district heating technologies, investment in smart grid infrastructure.
Poland	Gradual increase in energy prices due to transition from coal to renewable energy sources.	Developing climate regulations focusing on emissions reduction and adaptation measures.	Emerging innovation in carbon capture technologies and investment in renewable energy sources.
The Netherlands	Increasing energy prices driven by renewable energy investments and carbon pricing.	Strong climate regulations promoting renewable energy adoption and emissions reduction.	Development and investment in specific renewable energy technologies.
Spain	Moderate changes in energy prices with a focus on renewable energy subsidies and carbon pricing.	Supportive climate regulations promoting renewable energy growth and emissions reduction.	Innovations in concentrated solar power (CSP) technology and research in energy storage solutions.
Denmark	Moderate to high energy prices due to heavy reliance on renewable energy and carbon pricing.	Ambitious climate regulations with aggressive emissions targets and incentives for renewable energy.	Pioneering in wind energy technology, investment in district heating, and energy efficiency measures.
Belgium	Moderate energy price changes with emphasis on energy efficiency and carbon pricing.	Active participant in climate agreements with measures for emissions reduction and renewable energy promotion.	Research in offshore wind energy and implementation of smart grid technology.
Italy	Moderate energy price changes with investments in renewable energy and energy efficiency.	Climate regulations focus on emissions reduction, renewable energy adoption, and energy efficiency measures.	Advances in solar energy technology and investment in energy storage solutions.
Norway	Moderate energy price changes are influenced by oil and gas market fluctuations and carbon pricing.	Climate regulations with a focus on emissions reduction, renewable energy adoption, and carbon capture initiatives.	Technological innovations in hydropower efficiency and investment in electric vehicle infrastructure.

studies employ econometric models or focus on individual policy aspects without integrating expert judgments or providing a comprehensive causal mapping. This study addresses this gap by utilising the DEMATEL method to elucidate the complex interdependencies among these critical factors, offering a novel methodological synthesis that combines expert-based causal mapping with cross-country analysis. This integrated methodological approach enables the analysis to move beyond correlation toward understanding causality and policy leverage points—an aspect often underexplored in recent econometric or descriptive studies.

In summary, while national diversity remains a structural feature of EU energy policy, greater analytical integration, both conceptually and methodologically, is needed to understand its macroeconomic consequences. This study contributes to filling that gap by offering an empirically grounded, causally informed, and policy-relevant framework for analyzing European energy diversity.

3. Materials and methods

The study explores the interconnected dynamics between climate regulation, electricity prices, technological innovations, unemployment rates, economic growth, and inflation. The use of DEMATEL in this study is theoretically grounded in systems thinking and the concept of mutual causation, which is particularly relevant in the context of complex socio-economic and policy-driven systems such as energy and innovation. DEMATEL enables the identification of causal pathways and directional dependencies among variables where simultaneity and feedback loops are likely to occur (e.g., between innovation and energy prices, or energy prices and inflation). To complement this qualitative insight, panel data econometrics was applied to estimate the strength and statistical significance of the relationships identified through DEMATEL. This two-step approach allows for a better understanding of not only whether relationships exist, but also how robust and economically meaningful they are over time and across countries.

3.1. *Identifying key indicators*

Based on a comprehensive literature review, a set of six indicators was selected to capture the complex dynamics among energy, economic, and environmental dimensions: electric energy price (EP), unemployment rate (UE), economic growth (GDP), inflation (HICP), climate regulation (CR), and technological innovations (RD). The relations between various economic, environmental, and social indicators, including electric energy prices (EP), play a central role. The relations illustrate how changes in one indicator can cascade through to affect others, highlighting the complex interdependencies within the economic and environmental landscape.

3.2. *Data and metrics' selection*

The analysis is based on a panel dataset extracted from EUROSTAT, covering ten EU countries over the period 2012–2022. The selected timeframe ensures full availability and reliability of the data for all chosen indicators, with 2022 being the latest year for which complete and validated statistics were accessible at the time of analysis. The time series used consisted of data without gaps (full) and did not require additional estimation, so the sample was balanced. The variables included in the dataset comprise climate regulation (CR), measured by greenhouse gas emissions (GH), electric energy price represented by electricity prices for non-household consumers (EP), and technological innovations measured by research and development expenditure (RD) as well as unemployment rate represented by total unemployment rate (UE), economic growth measured by gross domestic product (GDP) and inflation represented by harmonized index of consumer prices (HICP).

The selection of variables reflects a policy-relevant and empirically grounded framework for analyzing the relationships among energy markets, environmental outcomes, and innovation across European countries. Each indicator was carefully chosen to represent a critical aspect of the energy–economy–environment nexus and to align with both theoretical constructs and EU policy priorities.

- Greenhouse gas emissions (GH) serve as a key indicator of environmental pressure and are directly aligned with the EU's Climate Law, the European Green Deal, and national decarbonization targets. Greenhouse gas data allow for direct measurement of climate policy outcomes. Greenhouse gas emissions were used as a proxy for climate regulation due to their direct link to the objectives of climate policies, which predominantly focus on reducing these emissions. GH data are extensively monitored and reported according to international standards, providing reliable and comparable information across the analyzed countries. This proxy is commonly employed in literature to assess the intensity and effectiveness of climate regulation. Despite the multifaceted nature of regulatory instruments, GH emissions serve as a practical and integrative measure reflecting the overall impact of climate policies.
- Electricity prices for non-household consumers (EP) are used as a proxy for energy price dynamics. This choice is motivated by the fact that industrial and commercial sectors are exposed to real-time fluctuations in energy markets and are less protected by state-regulated tariffs compared to household consumers. This metric captures trends relevant to economic performance and investment behavior and is consistent with recent EU energy competitiveness assessments (European Commission, 2023).
- The Harmonized Index of Consumer Prices (HICP) is employed to track inflationary pressures uniformly across countries, ensuring comparability and macroeconomic consistency in the assessment of economic stability.
- R&D expenditure as a share of GDP is used to approximate technological innovation efforts, particularly those linked to green technology development. This indicator aligns with the priorities outlined in the EU's Horizon Europe framework and Innovation Union Strategy, and it has been widely used in prior research to model the role of innovation in sustainable development, e.g., [108]. In this study, aggregate R&D expenditure was used as a proxy for technological innovation. This indicator is commonly employed in macroeconomic analyses, as it captures the overall investment intensity in research and development, which is closely linked to a country's innovation capacity. While this measure does not distinguish between sectors or the type of R&D (e.g., public vs. private), it offers reliable and comparable data across countries and time periods, making it suitable for panel data analysis.
- Economic growth, measured by gross domestic product (GDP), is a widely recognized macroeconomic indicator that reflects the overall value of goods and services produced in an economy. GDP is a standard metric in empirical economic research, allowing for cross-country comparability and consistent time-series analysis.
- Inflation is represented by the Harmonized Index of Consumer Prices (HICP), which ensures comparability across European countries by using a standardized methodology. It captures the overall change in consumer prices and serves as a key macroeconomic indicator influencing purchasing power, investment decisions, and cost structures. Its inclusion in the model allows for assessing the impact of price stability (or instability) on economic performance, innovation, and labor market dynamics.

These indicators are frequently cited in previous studies due to their critical roles in shaping energy prices, economic outcomes, and environmental policies. Their recurrent presence in the literature ensures analytical relevance and allows for a robust evaluation of interdependencies within the EU context.

Although this study relies solely on secondary data (Eurostat), the indicators were selected based on theoretical relevance and wide acceptance in EU energy policy assessments. The use of standardized data ensures replicability and cross-country comparability.

Together, these indicators capture essential dimensions of the policy-technology-market nexus. They provide analytical foundation for the methodological framework outlined in the following section, which integrates expert-based causal mapping with panel econometric modeling.

The causal logic linking innovation, energy prices, and macroeconomic indicators builds on established economic and policy frameworks. Higher energy prices can exert inflationary pressures [19] and alter industrial competitiveness [6], which in turn can affect R&D investment levels [12]. Conversely, technological innovation can reduce energy intensity, stabilizing prices and supporting economic growth [109]. These bidirectional relationships justify the use of causal mapping to capture the feedback loops between economic and energy system variables.*3.3 Methodological approach.*

This study applies a mixed-methods design combining the expert-based causal mapping (DEMATEL) method [110] with quantitative panel econometrics (ADL models). This dual approach enables a comprehensive understanding of the interplay between energy policy, macroeconomic performance, and innovation, balancing conceptual insights with empirical validation. The methodology workflow is presented in Fig. 1, which integrates the research objectives with each stage of the analytical process.

3.2.1. Expert-derived causal mapping (DEMATEL)

To identify the structure of causal relationships among the selected indicators, we applied the DEMATEL method which is widely used in energy policy and sustainability studies to uncover feedback loops and bidirectional influences [111–113].

In the context of our study, DEMATEL method was selected over other causal modelling approaches because the research questions required explicit mapping of bidirectional and feedback relationships between policy, economic performance, and technological innovation variables, which could not be adequately captured by unidirectional or latent-variable-based methods such as Structural Equation Modelling (SEM) or Analytic Hierarchy Process (AHP) [111]. Compared to other causal analysis methods (ANP, VIKOR) [12,113,114], which are more appropriate for large sample sizes and unidirectional latent constructs [115], DEMATEL offers greater interpretability and flexibility to construct a more comprehensive framework [116]. Its visual outputs, such as influence matrices and causal network diagrams, are directly applicable in strategic policy assessments [110,117,118].

To conduct the analysis, a panel of experts was assembled to evaluate cause–effect relationships between key indicators. The experts were intentionally selected to ensure diversity and balanced representation of academia, policy-making, and industry, reflecting the multidimensional nature of energy policy, innovation, and macroeconomic outcomes.

The analysis was implemented using DEMATEL software available at onlineoutput.com enabling structured expert input and generation of normalized direct-relation and total relation matrices. This tool enabled aggregation of expert judgement, reducing bias through collective evaluation [112], and generating interpretable graphical representations of causal interdependencies within the selected indicators. To strengthen methodological transparency and address potential concerns about analytical depth, the following methodological steps were implemented and structured accordingly:

(Step 0) Experts' elicitation and judgement.

Experts were selected based on their experience in energy policy analysis, macroeconomic assessment, and innovation systems. Their role was to provide pairwise influence ratings between indicators, which formed the foundation of the Direct Relation Matrix. Combining literature-derived variables with expert judgement ensured that the DEMATEL analysis was grounded in both theoretical evidence and practical insights.

(Step 1) Generating the direct relation matrix based on expert scoring: An n × n (1) the created matrix shows

$$X = \begin{bmatrix} 0 & \cdots & x_{n1} \\ \vdots & \ddots & \vdots \\ x_{1n} & \cdots & 0 \end{bmatrix} \tag{1}$$

how each element (factor) influences every other element. Opinions from multiple experts are aggregated using an arithmetic mean to create the direct relation matrix, which is the same as the pairwise comparison matrix of the experts.

(Step 2) Normalizing the matrix using the maximum sum of rows or

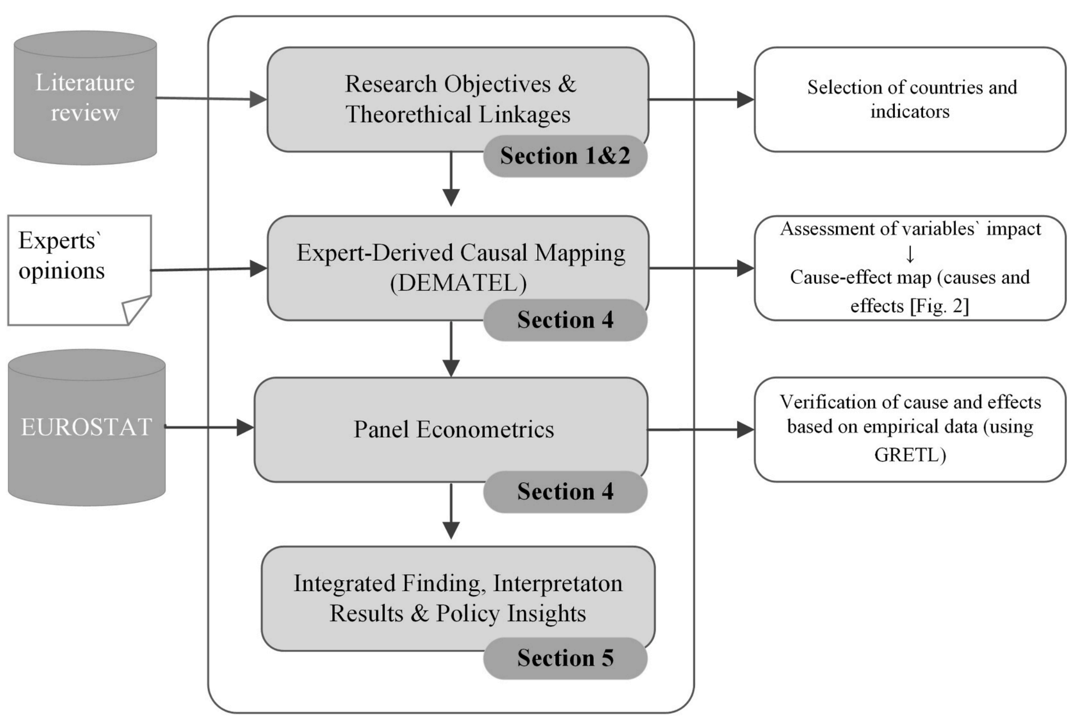

Fig. 1. Methodology workflow.

columns. The matrix is normalized by dividing each element by the maximum sum of rows and columns k, transforming it into a normalized direct-relation matrix (eqs. (2) and (3)).

$$k = max\left\{ max\sum_{j=1}^{n} x_{ij}, \sum_{i=1}^{n} x_{ij} \right\} \tag{2}$$

$$N = \frac{1}{k} {*} X \tag{3}$$

(Step 3) Calculating the total relation matrix accounting for both direct and indirect effects. Based on the normalized direct relation matrix, the fuzzy total relation matrix is calculated as (Eq. (4)), which accounts for both direct and indirect influences between factors.

$$\lim_{k \to +\infty} \left(N^1 + N^2 + \ldots + N^k\right) \tag{4}$$

The normalized matrix is multiplied by the resulting matrix to obtain the total relation matrix (eq. (5)).

$$\mathrm{T} = \mathrm{N} \times (I - N)^{-1} \tag{5}$$

(Step 4) Setting the threshold value and pruning insignificant relations. A threshold value is determined to identify significant relationships in the total relation matrix. To compute the threshold value for relations, it is sufficient to calculate the average values of the matrix. Relationships below this value are ignored, allowing for the visualization of significant connections in the model.

(Step 5) Calculating importance and net cause-effect results using D + R and D-R formulations. A summary of results shows the importance of each factor in the entire system (sum of rows and columns of the relation matrix from step 3) and their net effect (difference between the sums of rows and columns). The sum of rows (D), eq. (6), and columns (R), using eq. (7), can be calculated as follows:

$$D = \sum_{j=1}^{n} T_{ij} \tag{6}$$

$$R = \sum_{i=1}^{n} T_{ij} \tag{7}$$

Then, the values of D + R and D-R can be calculated by D and R, where D + R represents the degree of importance of the factor in the entire system and D-R represents the net effects that factor *i* contributes to the system.

Following standard DEMATEL procedure [113], we applied threshold filtering to the total relation matrix using the mean of all elements as the cut-off, ensuring that only the most relevant interactions were retained for visualization. This approach reduced noise from weak or incidental relationships and clarified the dominant causal pathways. In our study, this methodological choice was particularly important because DEMATEL's visual outputs such as threshold-filtered total relation matrices and heatmaps support interpretation directly by highlighting the strongest causal pathways and feedback loops. These visual tools form the empirical basis for the integrated cause–effect diagram (Fig. 5), which translates complex numerical outputs into actionable policy insights.

Despite the advantages, DEMATEL also has notable limitations. First, it relies on subjective expert judgment, which may introduce bias and variability. Second, the method is sensitive to small changes in expert ratings/scoring, which can significantly affect the resulting network structure. Third, DEMATEL captures a static view of relationships, limiting its applicability in dynamic policy environments. Finally, compared to SEM and other related modelling approaches, it lacks confidence intervals and formal statistical validation, which constrains the interpretation of uncertainty [119,120].

Table 5 summarizes these methodological constraints, as identified in recent literature.

Table 5
Key methodological limitations of the DEMATEL approach.

Limitation	Explanation	References
Subjectivity	Expert judgments introduce bias and variability in results.	- DEMATEL depends on expert judgments [120]. - Subjectivity in linguistic expressions (Gölcük and Baykasoğlu, 2016)
Sensitivity to input	Small changes in scores can substantially alter the network of causal relationships.	- Sensitive to input quality (Zhan et al., 2024) - Sensitivity analysis recommended [112]
Static nature	No modeling of temporal dynamics; captures only a one-time snapshot.	- Future work should consider dynamics ([112]; Qi et al., 2022). - Extensions include dynamic versions (Chaker et al., 2015; Qi et al., 2022).
Lack of error estimation	No mechanisms for assessing confidence or statistical significance.	- Does not include error margins or confidence [119]

In the context of this study, reliance on a few experts introduces potential subjectivity, but this was mitigated through diverse panel composition, spanning academia, policy-making, and industry, as well as by aggregating scores to balance individual differences. Sensitivity to input values was reduced by adopting a Delphi-inspired consensus process that smooths extreme ratings. The static nature of DEMATEL was complemented by the dynamic capabilities of our panel econometric models, which explicitly tested key causal links identified in the DEMATEL phase. The absence of formal statistical inference within DEMATEL was addressed by using econometric validation to provide independent, data-driven confirmation of expert-derived relationships.

Moreover, the causal structure revealed by DEMATEL aligns with findings in previous studies. For instance, energy prices emerged as a dominant driver, consistent with research highlighting their central role in shaping inflation, industrial competitiveness, and innovation investment [6,19]. Similarly, the role of innovation as an outcome influenced by policy and market conditions mirrors evidence from studies on R&D responsiveness to regulatory signals [12]. These insights informed the specification of the panel econometric model, ensuring that statistically tested relationships reflect conceptually validated interdependencies. Thus, DEMATEL not only guides the model specification in the econometric phase but also strengthens the study's triangulation between expert-based knowledge, statistical evidence, and existing theoretical work.

This dual-method approach ensures that DEMATEL results are not interpreted in isolation but are integrated within a broader mixed-methods framework, enhancing both conceptual insight and empirical robustness.

3.2.2. Building and verifying econometric models (panel econometrics)

To complement the conceptual after causal mapping, we implemented an econometric analysis using an Autoregressive Distributed Lag (ADL) panel model. This allowed the quantification of the influence of energy prices, innovation, and climate regulations on inflation, GDP growth, and unemployment.

The model incorporates Lagged Dependent Variables (LDV) to capture dynamic relationships over time. Parameters were estimated using Pooled Ordinary Least Squares (Pooled OLS) and Weighted Least Squares (WLS). Pooled OLS pools observations from different units and time periods without accounting for individual or time-specific effects, assuming all observations are equal. This approach is appropriate only when no significant heterogeneity exists.

WLS modifies OLS by applying weights inversely proportional to error variance to address heteroskedasticity. Observations with lower variance have greater influence, improving model accuracy. WLS is useful when error variance varies across units or time and helps reduce the impact of outliers.

Panel data econometric modelling was selected over cross-sectional or pure time-series approaches because the research questions required disentangling both temporal and cross-sectional variation in macroeconomic and policy indicators. Panel models allow controlling for unobserved heterogeneity across countries, mitigating omitted variable bias by capturing time-invariant effects specific to each entity [121]. This is essential in the context of our study, as differences in institutional frameworks, policy environments, and innovation capacities across countries may confound relationships of interest. Compared with time-series methods, panel models increase degrees of freedom and improve estimation efficiency, while enabling the simultaneous analysis of dynamic effects and structural differences [122–124]. We considered both fixed-effects and random-effects specifications, using the Hausman test to select the most appropriate structure for each dependent variable [125]. Robustness checks included alternative lag structures and exclusion of potential influential observations [126]. This approach is particularly suited to the present study because it enables empirical testing of hypotheses derived from the DEMATEL causal mapping, providing quantitative validation of expert-assessed cause–effect relationships.

The integration of DEMATEL with panel econometrics follows the mixed-methods tradition in policy evaluation, where qualitative causal structures guide the specification of econometric models, and statistical estimation provides empirical validation of expert-based hypotheses. As Greene [127] emphasizes, rigorous econometric analysis requires theoretically motivated model construction and critical assessment of underlying assumptions to ensure reliable inference. DEMATEL complements this process by uncovering complex causal structures and feedback loops through expert knowledge and systems thinking, which are often difficult to capture with standard econometric specifications alone. This mixed-method integration enhances the robustness of causal inferences and supports more nuanced evaluations of multifactorial energy systems.

4. Results

4.1. Causal mapping using the DEMATEL method

Due to experts' opinions, the DEMATEL method was applied to analyze the relationships between key indicators influencing unemployment rate, economic growth, and inflation within the context of energy policy. This approach enables the decomposition of direct and indirect effects between variables, highlighting both their magnitude and causal orientation.

Tables 6, 8 and 10 display the stepwise transformation of expert assessments in the DEMATEL procedure: starting from the raw direct relation matrix, the normalized matrix ensures convergence, followed by the total influence matrix, which aggregates direct and indirect effects, and finally the threshold-filtered matrix, retaining only significant relationships. This structure aligns with standard methodological practice documented in DEMATEL studies.

For clarity in Step 4, the threshold value of 1.806 was applied for the inflation subsystem, calculated as the average of all elements in the total relation matrix. Values below the threshold were set to zero, filtering out weaker relationships and retaining only the most influential causal links for further analysis. The final step involves calculating the sum of rows (D) and columns (R) to determine the importance (D + R) and net effect (D−R) of each factor (see Table 6).

To visually explore the interaction intensity among energy prices, climate regulations, and research and development concerning key macroeconomic indicators, a series of heatmaps was generated. Figs. 2–4 present the total relation matrices derived from the DEMATEL analysis for three dependent variables: inflation (HICP), unemployment (UE), and economic growth (GDP). Each matrix visualizes the intensity of direct and indirect influences between key energy policy indicators (EP, CR, RD) and the selected macroeconomic variable. The color gradient reflects the strength of the relationship, while black-bordered cells indicate values exceeding the predefined threshold, which were retained for further causal mapping.

Fig. 2 shows the dominance of EP→HICP (2.012) and RD → HICP

Table 6
DEMATEL relation matrices – inflation.

Step 1 - Direct Relation Matrix				
	EP	CR	RD	HICP
EP	0.0	3.0	2.5	3.0
CR	2.25	0.0	2.5	0.75
RD	3.5	1.0	0.0	3.5
HICP	3.0	1.75	3.5	0.0
Step 2. Normalized Relation Matrix				
	EP	CR	RD	HICP
EP	0.0	0.343	0.286	0.343
CR	0.257	0.0	0.286	0.086
RD	0.4	0.114	0.0	0.4
HICP	0.343	0.2	0.4	0.0
Step 3. Total Relation Matrix				
	EP	CR	RD	HICP
EP	1.969	1.663	2.128	2.012
CR	1.604	0.999	1.569	1.349
RD	2.269	1.526	1.914	2.075
HICP	2.246	1.581	2.209	1.789
Step 4. Threshold Value Relation Matrix				
	EP	CR	RD	HICP
EP	0.0	0.0	2.128	2.012
CR	0.0	0.0	0.0	0.0
RD	2.269	0.0	0.0	2.075
HICP	2.246	0.0	2.209	0.0

Table 7
The final output – inflation.

	R	D	D + R	D-R	Identity
EP	8.089	7.772	15.861	−0.317	effect
CR	5.769	5.522	11.291	−0.247	effect
RD	7.821	7.784	15.605	−0.036	effect
HICP	7.225	7.826	15.05	0.601	cause

Table 8
DEMATEL relation matrices – unemployment.

Step 1. Direct Relation Matrix				
	EP	CR	RD	UE
EP	0.0	2.0	2.0	3.5
CR	3.5	0.0	3.25	3.75
RD	2.0	1.5	0.0	2.5
UE	1.25	1.5	1.5	0.0
Step 2. Normalized Relation Matrix				
	EP	CR	RD	UE
EP	0.0	0.19	0.19	0.333
CR	0.333	0.0	0.31	0.375
RD	0.19	0.143	0.0	0.238
UE	0.119	0.143	0.143	0.0
Step 3. Total Relation Matrix				
	EP	CR	RD	UE
EP	0.315	0.42	0.481	0.703
CR	0.681	0.35	0.672	0.869
RD	0.423	0.342	0.267	0.565
UE	0.314	0.292	0.334	0.289
Step 4. Threshold Value Relation Matrix				
	EP	CR	RD	UE
EP	0.0	0.0	0.0	0.703
CR	0.681	0.0	0.672	0.869
RD	0.0	0.0	0.0	0.565
UE	0.0	0.0	0.0	0.0

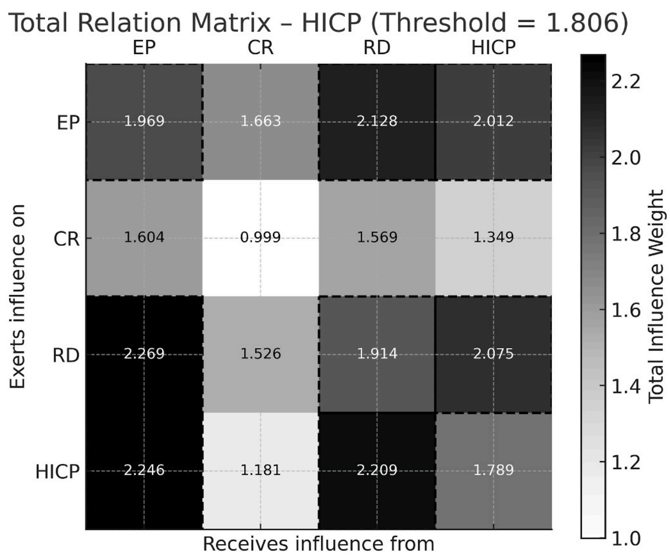

Fig. 2. Heatmap of total relation matrix for inflation-causal interactions among energy policy indicators in relation to inflation (HICP).

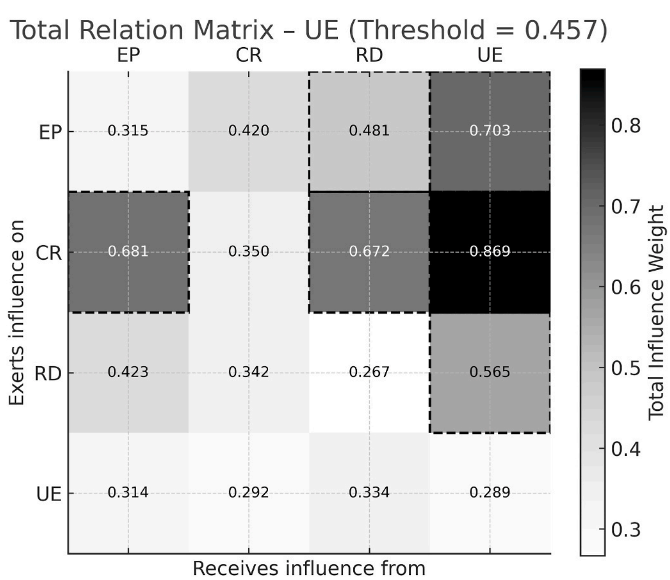

Fig. 3. Heatmap of total relation matrix for unemployment.

(2.075) interactions, marked by the deepest black shades. This indicates strong combined direct and indirect effects, meaning inflationary dynamics are tightly linked to both energy price volatility and technological innovation. The EP→RD link (2,128) and the RD→EP link (2.269) are also prominent, suggesting that technological changes and energy price movements are interdependent drivers of inflation. Additionally, HICP→EP (2.246) and HICP→RD (2.209) further highlight the bidirectional nature of inflation's role in the system.

These visual patterns are consistent with the D + R rankings in Table 7, where energy prices (EP) score the highest importance (15.861, D−R = −0.317), followed by technological innovation (RD) at 15.605 (D−R = −0.036) and inflation (HICP) at 15.050 (D−R = 0.601). Climate regulations (CR), while important (D + R = 11.291), play a more peripheral role with a negative D−R (−0.247), indicating they are more influenced by other factors than they influence themselves. This integrated evidence from both heatmap and causal metrics confirms that EP and RD are central drivers within the inflation subsystem. The relationships are further illustrated in the cause–effect diagram (Fig. A.1, Appendix A), emphasising that targeted interventions in energy price stabilisation and innovation incentives are likely to yield the most pronounced effects on inflation control.

A similar DEMATEL procedure was applied to variables affecting the unemployment rate (see Table 8). For this subsystem, a threshold value of 0.457 was determined. All causal links below this value were excluded. The filtered relations are shown in Table 9, while Fig. 3 presents the unemployment-related heatmap. The analysis reveals (Table 9) that climate regulations and energy prices are the primary causal factors, significantly influencing technological innovations and unemployment rates. Specifically, climate regulations hold the highest degree of importance (D + R = 3.976) and are the strongest causal factor (D-R = 1.169). Conversely, the unemployment rate is primarily an effect, with a negative net effect (D-R = −1.196), indicating it is influenced by other factors rather than acting as a cause (Fig. A.2, Appendix A).

In Fig. 3, climate regulations (CR) stand out as the dominant causal driver, exerting strong influences on EP (0.681), RD (0.672), and especially UE (0.869). These interactions, marked by intense colour gradients, represent the strongest causal channels in this subsystem and align with CR's highest net cause status (D−R = 1.169) and top D + R value (3.976) in Table 9.

Energy prices (EP) are highly important (D + R = 3.651) and act as a moderate cause (D-R = 0.185), with their strongest link towards UE (0.703) and indirect effects on RD via CR. Technological innovation (RD) plays a smaller causal role (D + R = 3.351, D−R = −0.157), mainly affecting UE (0.565), while the unemployment rate itself is primarily an effect variable (D + R = 3.654, D−R = −1.196), shaped by CR and EP.

This integrated evidence from causal metrics and visual patterns provides a clear framework for understanding the dynamics affecting unemployment, emphasising climate regulations and energy prices as key drivers, with RD acting as a secondary transmitter of effects. From a policy standpoint, this pattern suggests that regulatory frameworks - particularly those targeting environmental and energy standards - indirectly shape employment outcomes by influencing both technological innovation and energy prices. The relationships are further visualized in a cause-effect diagram (Fig. A.2, Appendix A), highlighting the critical roles of climate regulations and energy prices.

For economic growth, any causal relationship with a value below the threshold of 0.593 is not considered. Because the threshold value for economic growth is 0.593 (step 3), all the values in the matrix that are smaller than 0.593 are set to zero; that is, the causal relation mentioned above is not considered. The threshold-filtered matrix is presented in Table 10 (Step 4), and the final cause–and–effect outputs are displayed

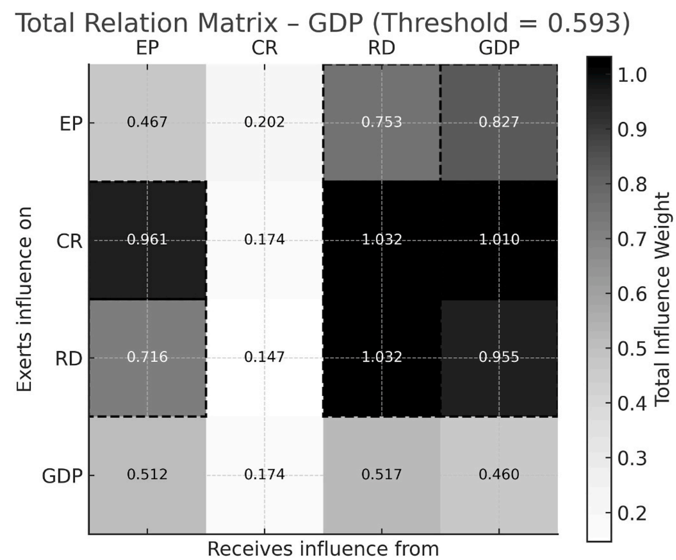

Fig. 4. Heatmap of total relation matrix for economic growth.

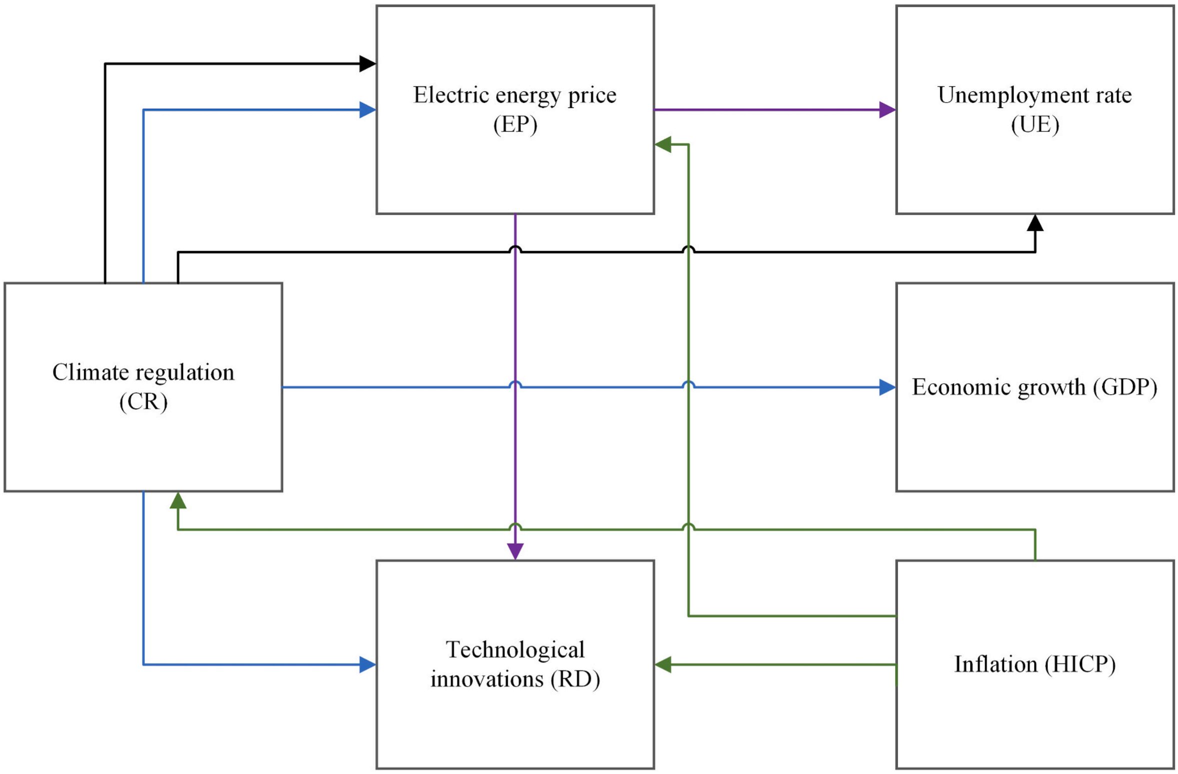

Fig. 5. Relationships between variables derived from Tables 7, 9 and 11.

Table 9
The final output - unemployment.

	R	D	D + R	D-R	identity
EP	1.733	1.918	3.651	0.185	cause
CR	1.403	2.572	3.976	1.169	cause
RD	1.754	1.597	3.351	−0.157	effect
UE	2.425	1.229	3.654	−1.196	effect

Table 10
DEMATEL relation matrices – economic growth.

Step 1. Direct Relation Matrix (GDP)				
	EP	CR	RD	GDP
EP	0.0	0.75	2.75	2.5
CR	3.25	0.0	3.5	1.75
RD	2.75	0.0	0.0	4.0
GDP	1.5	0.75	2.0	0.0
Step 2. Normalized Relation Matrix (GDP)				
	EP	CR	RD	GDP
EP	0.0	0.088	0.324	0.294
CR	0.382	0.0	0.412	0.206
RD	0.324	0.0	0.0	0.471
GDP	0.176	0.088	0.235	0.0
Step 3. Total Relation Matrix (GDP)				
	EP	CR	RD	GDP
EP	0.468	0.202	0.753	0.827
CR	0.961	0.174	1.032	1.01
RD	0.716	0.147	1.032	0.955
GDP	0.512	0.174	0.517	0.46
Step 4. Threshold Value Relation Matrix (GDP)				
	EP	CR	RD	GDP
EP	0.0	0.0	0.753	0.827
CR	0.961	0.0	1.032	1.01
RD	0.716	0.0	1.032	0.955
GDP	0.0	0.0	0.0	0.0

in Table 11.

In Fig. 4 climate regulations (CR) emerge as the dominant causal factor, exerting strong influences on EP (0.961), RD (1.032), and GDP (1.010). These interactions, shown in the darkest cells, correspond to CR's positive net cause status (D−R = 2.479) and its D + R score of 3.874 in Table 11, indicating that CR is the primary driver in this subsystem.

Technological innovation (RD) holds the highest overall importance (D + R = 5.216) but has a negative net effect (D−R = −0.548), meaning it is more often influenced by other variables than acting as a driver. RD's strongest outgoing link is to GDP (0.955), with additional influence on EP (0.716). Energy prices (EP) are also highly important (D + R = 4.904) but primarily act as an effect (D−R = −0.406), with their most notable outgoing link to GDP (0.827). GDP itself is the most effect-oriented variable (D + R = 4.978, D−R = −1.525), receiving its strongest influence from RD (0.955).

These relationships are visually represented in the cause-and-effect diagram (Fig. A.3, Appendix A), which confirms that both energy prices and economic growth are effect-oriented indicators within the system.

The individual subsystem results (Tables 7, 9 and 11) form the structural basis for the dependency graph in Fig. 5 (relationships between variables), which integrates causal pathways across inflation (HICP), unemployment (UE), and economic growth (GDP).

For HICP (threshold = 1.806), the strongest influences are observed between RD and EP (2.269) as well as between HICP and RD (2.209). For

Table 11
The final output is economic growth.

	R	D	D + R	D-R	Identity
EP	2.655	2.249	4.904	−0.406	effect
CR	0.698	3.177	3.874	2.479	cause
RD	2.882	2.334	5.216	−0.548	effect
GDP	3.251	1.726	4.978	−1.525	effect

UE (threshold = 0.457), the highest values correspond to CR→UE (0.869) and CR→EP (0.681). For GDP (threshold = 0.593), the dominant effects are CR→RD (1.032) and RD→GDP (0.955), highlighting the centrality of innovation in driving economic growth.

Synthesising these findings, Fig. 5 shows that.

- Inflation (HICP) acts as a primary driver, influencing EP, RD, and CR (green arrows, Table 7).
- Climate regulations (CR) affect EP, RD, and GDP (blue arrows, Table 11), as well as UE and EP (black arrows, Table 9).
- EP, in turn, impacts UE and RD (purple arrows, Table 9).
- GDP is directly influenced only by CR, while HICP is not affected by any other variable.

Using Fig. 5, we derived the dependencies structure for the econometric analysis: The results indicate that RD (dependent variable) is influenced by HICP, EP, and CR (independent variables). CR (dependent variable) is influenced by HICP (independent variable). Furthermore, EP (dependent variable) is affected by CR and HICP (independent variables), while UE (dependent variable) is influenced by EP and CR (independent variables). In the case of GDP (dependent variable), it is influenced by CR (independent variable). Finally, HICP is the only indicator that is not affected by any of the examined variables.

This mapping directly connects the qualitative causal structure obtained through the DEMATEL analysis with the subsequent econometric modelling phase, ensuring that the relationships identified through expert judgement are explicitly tested using quantitative methods. In this way, the DEMATEL outputs serve not only as conceptual insights but also as structured input for hypothesis formulation in the econometric stage, thereby addressing the reviewer's concern regarding the integration of DEMATEL findings with econometric analysis.

4.2. Verification of cause and effects based on empirical data (using GRETL)

After conducting a DEMATEL analysis to identify the factors influencing the relationship between Energy Prices, Climate Regulations, and Technological Innovations on Economic Outcomes in the European Union countries, econometric models for panel data were constructed. Focusing on the relationships shown in Fig. 5, only those involving multiple variables were selected (Equations (12)–(14)). Dynamic panel data models, which use lagged values as regressors, were employed for the econometric analysis, estimated using GRETL software. Following standard econometric decision-making procedures [121], the estimation began with a simple panel model using the classical method of least squares, followed by diagnostic tests.

Analysis using DEMATEL allowed for the construction of the following relationships:

$$RD = f(EP, GH, HICP) \tag{12}$$

$$UE = f(EP, GH) \tag{13}$$

$$EP = f(GH, HICP) \tag{14}$$

Before proceeding to model estimation, we conducted a series of panel data diagnostic tests to determine the appropriate specification (fixed vs. random effects). The results of the F-test, Breusch-Pagan Lagrange Multiplier test, and Hausman test are presented in Table 12.

The F-tests confirm the joint significance of individual-specific effects, supporting the use of fixed effects in all models. For the UE model, the Breusch–Pagan Lagrange Multiplier test does not support the random effects specification ($p = 0.630$), and the Hausman test fails to reject the null hypothesis in favour of fixed effects ($p = 0.150$). Nevertheless, for consistency across specifications and based on theoretical justification, fixed effects were retained for all models). Based on these outcomes and in accordance with econometric literature [121,128], we decided to estimate all models using the fixed effects specification.

Table 12
Diagnostic (panel) test values for the estimated models.

Test values	Models		
	RD	UE	EP
F	2.729	2.072	2805
p	0.008	0.041	0.006
LM	–	0.232	–
p	–	0.630	–
H	26.995	8.107	26.995
p	0.000	0.150	0.000

To capture the stochastic properties, the authors included the natural log of the variables and introduced lagged values to account for the model's dynamic nature. The resulting models are autoregressive dynamic econometric models. Based on the DEMATEL analysis, three econometric models were created using the GRETL software. The test results for each of these models are shown in Table 13. For each of the models, the pooled OLS and WLS methods were carried out. Tests performed for the models were presented in Table 14.

The model uses several zero-one variables. The zero-one variables have been defined in a way that identifies their location. For example, the variable z807 indicates the occurrence of "1″ in the seventh period for the eighth object (country). They concern the correction resulting from an incidental (incomprehensible) deviation of the GH variable data for Norway and Poland in selected periods.

Due to the heteroscedasticity of the models and doubts about normality, the WLS panel method was used. Assessments of the structural parameters of the models were mostly convergent regardless of the method used. In addition, for all models estimated with WLS, the correspondence of the random component with the normal distribution was confirmed.

The Model derived from equation (12) MRD is detailed in Table 13. The first model examines the relationship between technological innovations, measured by research and development expenditure (RD), and three parameters: climate regulation (CR), measured by greenhouse gas emissions (GH); electricity prices for non-household consumers (EP); and inflation, measured by the harmonized index of consumer prices (HICP).

Using WLS estimation, Model MRD demonstrated strong results, with all explanatory variables statistically significant and tests confirming the model's validity. GRETL analysis identified this as the best model, suitable for further research.

In the model derived from equation (13), MUE, as presented in Table 13, the method WLS also proved to be the correct analysis. This model examines the relationship between the unemployment rate, represented by the total unemployment rate (UE), and climate regulation, measured by greenhouse gas emissions (GH), as well as the electricity price, represented by electricity prices for non-household consumers (EP). Earlier analysis of the models properties confirmed the presence of heteroscedasticity in the random component. To address this issue, WLS was used to estimate the model parameters, thereby mitigating the identified heteroscedasticity.

To the estimation of Model MEP based on Eq. (14), the method WLS proved to be the correct analysis. Model MEP examines the relationship between electricity prices for non-household consumers (EP), and second parameters: climate regulation (measured by greenhouse gas emissions (GH)) and inflation (measured by the harmonized index of consumer prices (HICP)).

The influence of the explanatory variables on dependent variables was statistically significant at a significance level of 1 % or 5 % for all models.

Model MRD examined the relationship between technological innovations (measured by R&D expenditure) and factors like climate regulation, electricity prices, and inflation. The model revealed that all

Table 13
Verification of the model from equations 12–14 using two methods: Pooled OLS and WLS (prepared based on [129].

Dependent variable	Model RD	Model UE	Model EP			
EP	−0.137***(-0.024)	−0.144***(0.023)	−0.168***(0.042)	−0.137***(-0.040)		
EP_1	0.145***((-0.033)	0.152***(0.030)	0.250***(0.083)	0.174**(-0.079)	0.947***(0.074)	
GH	−0.207**(-0.079)	−0.213***(0.059)	−0.470**(0.207)	−0.432**(-0.172)		
GH_1	0.203**(-0.079)	0.211***(0.059)	0.448**(0.207)	0.423**(-0.173)		0.072***(-0.015)
HICP	0.917***(-0.239)	0.933***(0.222)			7.161***(0,770)	9.289***(-0.937)
HICP_1	−1.003***(-0.316)	−0.973***(0.0276)			−6.522***(1.114)	−9.569***(-1.378)
RD_1	0.987***(-0.011)	0.991***(0.009)				
UE_1			0.974***(0.023)	0.981***(-0.021)		
z711	−0.156***(-0.038)	−0.153***(0.041)				0.499**(-0.230)
z807	0.132***(-0.035)	0.136***(0.043)				
z811					−0.493***(0.153)	−0.732***(-0.242)
const	0.470(-0.570)	0.235(0.472)	0.488*(0.284)	0.200 (−0.256)	−3.173***(2.099)	−2.278(-2.689)
No. of observations	100		100		100	
No. of countries	10		10		10	
Method	Pooled OLS	WLS	Pooled OLS	WLS	Pooled OLS	WLS

Notes: 1) ***, **, and * denote significance at the 1 %, 5 %, and 10 % levels, respectively; 2) standard errors are given in parentheses.

Table 14
Tests for three models from equations 12–14 were performed for Pooled OLS.

Dependent variable	RD		UE		EP	
Test	Test statistic:	p-value	Test statistic:	p-value	Test statistic:	p-value
Pesaran CD test for cross-sectional dependence	z = 0.928	0.353	z = 8.972	<0.000	z = 0.530	0.596
Wooldridge test for autocorrelation in panel data	t(9) = 1.061	0.316	$t_{(9)} = 3.860$	0.004	$t_{(9)} = 1.205$	0.259
White's test for heteroskedasticity	LM = 36.489	0.493	LM = 21.461	0.370	LM = 36.489	0.493
Wald's test for heteroskedasticity	$\chi^2_{(10)} = 423.941$	<0.000	$\chi^2_{(10)} = 42.080$	<0.000	$\chi^2_{(10)} = 606.569$	<0.000
Test for normality of residual	$\chi^2_{(2)} = 5.310$	0.070	$\chi^2_{(2)} = 1.052$	0.591	$\chi^2_{(2)} = 80.926$	<0.000
Total significance of group mean inequalities	$F_{(9, 81)} = 1.841$	0.073	$F_{(9, 85)} = 2.072$	0.041	$F_{(9, 86)} = 1.902$	0.062

factors are statistically significant. The return on current electricity prices negatively impacted R&D expenditure (EP: −0.144), while lagged prices had a positive effect (EP_1: 0.152). Similarly, climate regulation showed both direct (GH: −0.211) and lagged impacts (GH_1: 0.211). Inflation also significantly influenced R&D expenditure, whereby immediate inflation increased (HICP: 0.933) and lagged inflation decreased (HICP_1: −0.973). An additional statistically significant impact is the lagged technological innovation (RD_1:0.991).

When electricity prices rise in the current period, firms reduce their R&D spending. Likely this is because higher operational costs limit available funds for innovation. However, when prices were higher in the previous period, firms increased their R&D investments now. This suggests that firms may respond with a delay by investing in energy-efficient technologies.

Newly introduced climate regulations may initially decrease R&D spending, possibly due to added compliance costs or uncertainty, but over time, these same regulations increase innovation spending, for example, by encouraging the development of low-emission technologies.

In the case of inflation, when inflation rises now, companies increase R&D spending, possibly as a way to improve efficiency and counter rising costs; however, if inflation was high in the previous period, firms tend to cut back on innovation spending now, likely due to the lingering effects of increased prices.

Model MUE indicated that energy prices and climate policies significantly affect employment rates. Current energy prices negatively impacted the unemployment rate (EP: −0.137), while lagged prices had a positive effect (EP_1: 0.174). Climate regulation also influenced unemployment, both directly (GH: −0.432) and with a lag, but the impact is negative (GH_1: 0.423). The lagged total unemployment rate (UE_1: 0.981) was highly significant.

In Model MUE we can see that higher current energy prices are associated with lower unemployment. This may suggest a short-term stimulating effect, possibly due to increased investment or structural shifts in the labor market. However, lagged energy prices have a positive effect on unemployment. In the longer term, higher energy prices are linked to rising unemployment, possibly due to reduced competitiveness of firms or increased operational costs.

Lower emissions (i.e., stricter climate policies) are associated with lower unemployment in the short run. This may reflect the effects of innovation, green investments, or energy transition efforts. But in the long term, stricter climate policies may lead to higher unemployment, potentially due to industrial restructuring or regulatory pressure on traditional sectors.

The Model also shows that unemployment in the previous period strongly determines current unemployment, which is typical of macroeconomic phenomena resulting from labor market inertia.

Model MEP was finalized and estimated using the WLS method (Table 13). This model showed a significant impact of late energy prices on current energy prices (EP_1: 0.947). Return on current inflation positively impacted electricity prices (HIPC: 7.161), while lagged inflation had a negative effect (HICP_1: −6.522). In this MEP, it was found that electricity prices from the previous period have a very strong influence on current prices. This suggests high persistence – if energy was expensive before, it's likely to remain expensive now. However, a rise in current inflation causes a sharp increase in electricity prices. Likely due to producers passing increased costs onto consumers, the effect size is large and immediate. Inflation from the previous period has a negative impact on current energy prices. This could indicate delayed regulatory responses, subsidies, or market adjustments that suppress price growth following prior inflation.

In order to better understand country-specific baseline effects in the estimated models, we analyzed the decomposed intercept terms for each country and model specification. This analysis of decomposed intercept terms was conducted to identify baseline structural differences between countries that are not explained by the model's independent variables. By isolating the country-specific fixed effects, we gained insight into how national contexts influence the dependent variable independently of measurable inputs. This helps to better understand the role of unobserved heterogeneity in shaping cross-country variation in innovation, employment, or energy outcomes. Table 15 presents the intercept values for each country across the three models: RD, UE, and EP.

Table 15
Decomposed intercept values for individual models.

Country	Model		
	RD	UE	EP
Belgium	1.98	77.21	8985.50
Denmark	1.90	59.01	4636.71
France	1.90	125.99	25 833.57
Germany	1.90	144.49	42 770.33
Italy	1.90	124.11	27 599.42
Netherlands	1.90	87.82	12 361.71
Norway	1.90	59.01	4636.71
Poland	1.90	104.03	21 319.55
Spain	1.90	111.49	21 528.87
Sweden	1.90	59.01	4636.71

While in the MRD model only free expression for Belgium indicated a statistically significant difference compared to others, in subsequent models it was much more frequent. The decomposed intercept in the estimated models, due to their powerful character, has a multiplicative effect. The difference in the case of the MRD model is, despite its significance, insignificant in plus for Belgium. This is in line with the overall results, with the differences between the WLS and OLS models not significant. In subsequent models, the tested chips for Denmark, Norway, and Sweden behaved in a "typical" way for the model. For other countries, we observed an increase in effects with the same input data, and a significant one. For example, in the MEU model, with the same input data, the effect for France or Italy would be twice as strong as in the above-mentioned countries (125.99/59.01 and 124.11/59.01, respectively). In the EP model, the individual impact is even stronger and amounts to up to 9 times the "typical" value (42770.33/4636.71). The lowest marks of decomposed intercepts are recorded for the Nordic countries. However, it should be remembered that these countries are leaders in the field of climate care, rational energy management, and in the area of modern technologies. In practice, the indicated free word does not weaken them, because the levels of expenditure described by the variables used in these countries are definitely high compared to others.

From Table 16 it turns out that the obtained estimates for the studied models are consistent with the study of the convergence of endogenous variables. In the panel used, only for the RD variable (which has an undifferentiated intercept) was the existence of convergence confirmed. In contrast, unemployment and energy prices remain divergent, likely due to persistent structural differences and heterogeneous national policies.

5. Discussion

This paper contributes to the growing body of literature examining the economic impacts on national diversity in energy policies, particularly within the context of dynamic variables such as changing energy prices, climate regulations, and technological innovation [25,27,43]. Employing both DEMATEL and panel data econometric models, the study identifies and disentangles complex interrelationships between these key factors, providing valuable insights into how macroeconomic outcomes, especially inflation and research and development (R&D) expenditure, are shaped by energy policy landscapes across Europe.

Table 16
Values of convergence coefficients for 2012–2022 for selected variables in the panel of surveyed countries.

Measure	Variable		
	RD	UE	EP
θ	−3.333	−1.237	−1.181
β	0.020	0.026	0.038
p	0.010	0.251	0.272

All the research questions were examined during the research process. Energy prices, climate regulations, and technological innovations interact within national energy policy frameworks across the EU (RQ1) in a highly complex manner. The interaction between these factors is complex and multi-layered. These three elements influence each other in feedback loops that shape the direction, efficiency, and outcomes of European energy policy [37,63,80]. Concerning the second research question (RQ2), the main issue is that energy prices are strong short-term causal drivers of inflation and economic performance, climate regulations are medium-to long-term causal drivers, particularly for R&D intensity and green-sector growth, and technological innovation is a fundamental long-term driver of economic growth and productivity, with indirect effects on inflation and R&D policy. Concerning research question (RQ3), the interplays between energy prices, climate regulations, technological innovations, and macroeconomic indicators differ significantly across European countries depending on three structural dimensions: energy import dependency, regulatory stringency, and innovation capacity.

The DEMATEL method incorporated structured expert input from academia, policy, and the energy industry, aggregated using arithmetic means. This qualitative approach was then validated through panel data econometric analysis, strengthening causal inference (Section 3). While a larger set of variables was initially considered, the model was constrained to a manageable number of high-impact factors to avoid matrix sparsity and ensure interpretability. The selected indicators, such as energy prices, climate regulations, and research and development (R&D), serve as proxies for innovation and reflect the core dimensions of the energy–economy–environment interface.

While DEMATEL is inherently based on expert judgment, its reliability in this study was enhanced through structured input collection from professionals with documented expertise in energy policy, macroeconomics, and EU regulatory frameworks. Experts were selected to reflect interdisciplinary knowledge relevant to the energy–economy–environment nexus. Although the number of experts was limited, their backgrounds ensured contextual accuracy.

The rationale for selecting these variables is well grounded in EU policy documents, including the European Green Deal [130] and REPowerEU [40], which consistently emphasize energy affordability, regulatory intervention, and innovation as essential for achieving sustainability and energy resilience. In line with these strategic imperatives, existing literature supports this triad: energy prices correlate with economic growth [35], climate regulations must be linked with economic metrics to avoid policy fragmentation [103], and innovation - particularly in response to sustainability challenges - is both a reactive and proactive force in energy systems transition [59].

Energy prices, climate regulations, and technological innovations are deeply interconnected, influencing production costs, market dynamics, investment, and overall economic growth. Climate regulations reduce environmental harm, but also introduce compliance costs, drive innovation, and investment uncertainties [70,131,132]. Technological innovations, in turn, mitigate these effects by boosting productivity and enhancing economic resilience [59]. Understanding and managing these interactions is essential for shaping a competitive and sustainable economy.

Although the DEMATEL model suggests bidirectional relationships between technological innovation and macroeconomic variables, R&D expenditure was included as an explanatory variable in the panel model to quantitatively assess the predominant direction of influence.

Given the data limitations, the study does not claim strict causality but rather explores directional associations that can inform future empirical and policy-focused inquiries. To mitigate endogeneity arising from reverse causality between innovation and economic outcomes, the panel regression model may use lagged values of R&D. Furthermore, System-GMM estimation might be applied to account for both dynamic feedback and unobserved heterogeneity across countries. This approach may strengthen the reliability of the results and address biases that standard panel estimators may not capture [87,133,134]. It is also important to acknowledge that the use of R&D expenditure as a proxy for technological innovation is constrained by the lack of sectoral-level data. As a result, the model does not capture intra-country variations in innovation intensity across industries, particularly in energy-intensive or high-tech sectors, which may affect the precision of policy implications.

Summing up the results of the econometric models analyzed, it can be concluded that current increases in energy prices reduce firms' innovation spending, while higher prices from the previous period boost it, indicating a delayed response. Stricter climate regulations initially suppress innovation but stimulate it over time. In the short term, higher energy prices and lower emissions reduce unemployment, but in the long term, they lead to higher unemployment. Energy prices show strong persistence (prices from the previous period have a strong influence on current prices), and current inflation immediately raises prices, whereas past inflation may curb price growth due to delayed market and regulatory mechanisms.

Building upon this body of research, our study offers a comprehensive analysis of the interactions between energy prices, climate regulations, and technological innovation across European countries. By employing DEMATEL and panel data econometric models, we identify significant relationships and causal pathways that have not been fully explored in previous studies.

5.1. Limitations

The study's geographical scope is limited to ten countries due to the availability of harmonized time series. This limits external validity. Moreover, while secondary data allow for macro-level insights, they cannot substitute for localized, firm-level, or institutional data, which would enhance contextual interpretation.

Despite its contributions, this study faces several limitations. First, the use of R&D expenditure as a proxy for innovation is based on aggregated national-level data and does not capture sector-specific dynamics. This limits the ability to fully understand how innovation dynamics work across different industries, especially in energy-intensive sectors. Additionally, electricity prices for non-household users may not accurately reflect total energy cost burdens, especially for households and transport sectors.

Although the DEMATEL method effectively identifies causal relationships, it relies on expert judgment and may be sensitive to subjective bias. Furthermore, while the panel data model captures only macro-level interactions, it may overlook important institutional and contextual variables. For example, although structural differences between countries such as energy dependency, innovation capacity, and regulatory intensity were considered, the model does not explicitly account for institutional quality or governance effectiveness, which may influence policy implementation and innovation performance. Additionally, factors such as energy import dependency or energy mix composition were not included, which could affect the robustness of the findings and generalizability of the findings. Finally, while standard panel estimators were employed, the potential endogeneity among explanatory variables, particularly the bidirectional interactions between inflation and energy prices, remains a concern. Although the use of lagged variables and dynamic specification partially addresses this issue, future studies could benefit from the use of advanced econometric methods such as System-GMM [63,134] or instrumental variable approaches to enhance causal inference. Furthermore, while R&D expenditure is used as a dependent variable in the panel model consistent with its classification as an effect variable in the DEMATEL analysis, further exploration of potential feedback effects could provide a more complete understanding of the system's dynamics.

A key limitation related to data selection in this study is the use of proxy variables for climate policy and innovation. Greenhouse gas emissions, while commonly employed as an indicator of environmental regulation outcomes, may not fully capture the complexity of policy instruments, enforcement mechanisms, or sectoral differences [135]. Similarly, R&D expenditures represent innovation inputs rather than direct technological outcomes, potentially overlooking aspects of efficiency and commercialization (https://doi.org/10.1016/j.techfore.2021.120659). However, the choice of these indicators aligns with established empirical practice and ensures comparability across countries and over time. Furthermore, the inclusion of lagged variables partially mitigates the timing mismatch risk between policy implementation, innovation activities, and observed economic effects. Future research could employ more complex climate policy indices and innovation outcome measures (e.g., patents, technology adoption rates) to provide a more multidimensional assessment.

5.2. Future research

Future research should expand upon these findings by incorporating sectoral analyses and examining the role of institutional capacity in shaping effective and resilient energy policies. Additionally, it is recommended to apply advanced econometric approaches such as System-GMM or instrumental variable models to strengthen causal inference. Including institutional quality indicators like the World Bank Governance Index or Environmental Policy Stringency Index may also enhance the robustness and policy relevance of future analyses. It is also proposed to create multi-dimensional indices for regulatory stringency and innovation ecosystem quality that would allow for more precise measurement and cross-country comparison. Moreover, future studies should distinguish between general and energy-specific R&D to enhance the precision of innovation analyses. Additionally, expanding the set of macroeconomic indicators such as trade balances and consumer prices emphasized by [38] would support a more comprehensive approach to energy policy planning. Finally, broadening the country sample to include Central, Eastern, and Southeastern Europe would offer a more comprehensive EU-wide perspective and better capture regional heterogeneity.

Future studies could also enhance robustness by applying alternative panel specifications (e.g., dynamic System-GMM models) and incorporating different indicator sets (e.g., climate finance, patent-level data). Scenario testing on country subsamples may also validate the sensitivity of the findings.

6. Conclusions

This study fills the research gap by offering empirically grounded analysis of national diversity in European energy policies and their economic consequences. The analysis focused on climate regulations (GH emissions), electricity prices (EP), and technological innovations (R&D expenditures) as key variables, with economic impacts assessed through unemployment (EU), economic growth (GDP), and inflation (HICP). Unlike previous studies limited to specific countries [21] or high-RES nations [20], this study integrates both expert-based causal mapping (DEMATEL) and dynamic econometric modelling to analyze the interplay between climate regulations, electricity prices, and innovation, with economic outcomes such as GDP, inflation, and unemployment.It provides a comprehensive and comparative analysis.

Using DEMATEL and panel data econometric models, including dynamic models, the study disentangled complex causal pathways between policy variables and macroeconomic outcomes. The findings from Model 1 (OLS estimation) confirm that energy prices, climate change regulations, and inflation significantly influence R&D investments, highlighting the centrality of innovation for economic growth and sustainability [136].

The results emphasize the need for more coherent and coordinated energy policies across EU member states. While EU policies like ecodesign promote energy efficiency [137], energy-saving efforts have not yet reduced consumption or dependence [138], indicating the need for more effective instruments. Energy prices directly influence economic performance [136], highlighting the necessity of adaptive policies. Specific recommendations include implementing minimum tax levels and standardized pricing frameworks for electricity and gas across the EU. Member states should also align national climate instruments with EU-wide frameworks. Furthermore, introducing a benchmarking tool to monitor alignment with EU energy and climate objectives would enhance transparency and potentially condition access to funds.

In sum, this paper offers a comprehensive and empirically grounded perspective on the strategic management of energy policy, innovation, and economic stability. It underscores the necessity of aligning short-term economic responses with long-term innovation objectives.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.esr.2025.101886.

Data availability

No data was used for the research described in the article.

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