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Comprehensive analysis of factors influencing EU-countries household energy consumption (2000–2022): Trends and vulnerability to COVID-19 and the Russia-Ukraine war

Behnam Ata [a], János Pénzes [a,*], Parisa Pakrooh [b], Aynaz Lotfata [c], Safwan Mohammed [d,e]

[a] Department of Social Geography and Regional Development Planning, University of Debrecen, Debrecen, 4032, Hungary
[b] Marie Sklodowska-Curie Postdoctoral Research Fellow, Fondazione Eni Enrico Mattei (FEEM), Milan, Italy
[c] Department of Pathology, Microbiology, and Immunology, School of Veterinary Medicine, University of California, Davis, USA
[d] Earth Science Institute, Slovak Academy of Sciences, Dúbravská cesta 9, Bratislava 840 05, Slovakia
[e] Institutes for Agricultural Research and Educational Farm, University of Debrecen, Böszörményi 138, 4032, Debrecen, Hungary

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ABSTRACT

Recent global crises, such as COVID-19 and the Russia-Ukraine War, have accelerated efforts to reduce dependency to fossil fuels due to soaring prices. This research aims to identify the key factors such as climate, electricity and gas price, GDP, renewable energy use, population and COVID-19 influencing household energy consumption in EU countries, particularly in the context of recent crises such as COVID-19 and the Russia-Ukraine war. Research starts with trend analysis using the Mann-Kendall (MK) test and Sen's Slope estimator, then Tukey test, followed by the examination of household panel data from EU countries spanning 2000 to 2022 using static and dynamic panel models including Feasible Generalized Least Squares (FGLS) and System Generalized Method of Moments (GMM). The MK test reveals a significant upward trend in gas prices, while gas usage shows mixed trends in natural gas consumption and electricity usage generally increases across EU countries. The Tukey test reveals substantial shifts in pricing of gas and electricity trends influenced by external factors such as the COVID-19 pandemic and the Russia-Ukraine war. Moreover, renewable energy consumption emerged as significant, indicating a noteworthy increase in renewable energy utilization among EU-24 countries. Static FGLS model findings indicate significant effects of various factors on gas consumption, such as Heating Degree Days (HDD), Cooling Degree Days (CDD), Renewables use, Electricity price, Population, and GDP lead to corresponding increases in gas consumption. On the contrary, electricity consumption and gas prices lead to decreases in gas consumption. Similarly, HDD, CDD, gas price, population, and GDP have positive effects on electricity consumption. Meanwhile, increase in gas consumption and electricity price lead to decreases in electricity consumption. Dynamic model results differ slightly, HDD, CDD, GDP, and the dummy variable (COVID-19) contribute to an increase in gas consumption in the EU household sector. Meanwhile, according to the system GMM, electricity prices and gas prices lead to a decrease in gas consumption. However, CDD, gas consumption, and the dummy variable tend to increase electricity consumption. In the dynamic model, only gas prices contribute to a decrease in electricity consumption. In summary, the research offers valuable insights into factors influencing energy consumption in EU countries, suggesting implications for policy and future research directions in energy economics and sustainability.

1. Introduction

Due to the economic rebound post-COVID, there was a notable surge in worldwide natural gas demand in 2021. However, various geopolitical, environmental, and economic factors led to a decrease in the supply [1]. European governments have reacted differently to energy price shocks. Some are emphasizing renewable energy sources, while others are increasing domestic fossil fuel production and diversifying their supplier base [2]. The situation degraded significantly after the Russia-Ukraine conflict erupted in late February 2022, adding to a

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* Corresponding author.

E-mail addresses: Behnam.ata@science.unideb.hu (B. Ata), penzes.janos@science.unideb.hu (J. Pénzes), parisa.pakrooh@feem.it (P. Pakrooh), alotfata@ucdavis.edu (A. Lotfata), safwan@agr.unideb.hu (S. Mohammed).

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worldwide energy crisis [3]. A surge in global energy prices results from multiple factors such as ongoing geopolitical conflicts, swift post-pandemic economic rebound, sustained heavy dependence on fossil fuels, and significant disparities between energy demand and supply [3,4]. In 2023, some tensions in energy markets eased the post-global energy crisis, yet the situation remains delicate. The imperative shift to renewable energy faces challenges amidst uncertain supply chain resilience and transition risks. Despite growing opportunities in clean energy, uncertainties persist regarding climate change impacts and the pace of transition [5].

Following the Russian invasion, the EU introduced its REPowerEU strategy, with the goal of swiftly reducing reliance on Russian fossil fuels and achieving complete energy independence from Russia by 2027 [6]. This initiative includes gas storage mandates [7] and endeavors to hasten the adoption of renewable energy and enhance energy efficiency [8]. Energy security encompasses various aspects due to numerous threats to the reliability and affordability of energy. One aspect is intermittency, where renewable sources like sunlight and wind may not always be available, unlike fossil fuels which can be reliably generated on demand. Conversely, fossil fuels such as oil, natural gas, and coal face a different energy security challenge, susceptible to disruptions or price fluctuations due to international geopolitics [9–11] such as wars, embargoes, or sanctions.

The correlation relating to energy usage and economic growth is influenced by multiple factors, notably the cost of energy resources, for example gas and electricity. Additionally, events like conflicts and sanctions play significant roles in the cost of energy. Price stands out as a key determinant in shaping energy demand and consumption patterns [12]. The EU's energy policy has focused on increasing the proportion of renewable energy sources (RES) [13] to bolster energy security and lower end-user energy costs in the Union.

Since Russia's invasion, fossil fuel prices have notably risen, exacerbating significant price hikes since mid-late 2021. This surge in energy costs will impact households through the EU, posing a principally heavy financial burden on low-income households. The increased expenses hold significant political importance, as they have previously sparked public protests, such as the "yellow vest movement" in France or the "Petrol revolt" in Sweden. However, the impact of higher prices is expected to vary among European countries, influenced by their dependence on explicit fossil fuels. For instance, natural gas forms a substantial portion of the gross primary energy supply in Italy (40.5 %), the Netherlands (37.6 %), and Hungary (33.5 %), whereas it plays a slight role in Sweden (2.7 %), Finland (6.5 %), and Estonia (7.7 %) [14]. The disparity in cost burdens varies significantly among countries, ranging from median (average) effects of 25 % (31 %) in Hungary to less than 6 % (9 %) in France. Within countries, differences are substantial as well; for instance, over 5 % of households in Czech Republic, Hungary, Italy, Romania, and Slovakia would need over 60 % of their existing total expenses to afford the same goods and services as before, while 5 % would need less than 9 % of total expenditures. In Hungary, one-quarter of the population would need more than forty-four percent of their present total expenses. In contrast, the majority of households in Bulgaria, Denmark, Estonia, Finland, and Sweden that is, at least 95 % of them would have to pay an additional 20 % or less in expenditures. In the "embargo scenario," the median burden rises by a factor of at least 1.5 or doubles for many nations. For more than 5 % of households in Hungary, Italy, Romania, the Czech Republic, Croatia, and Slovakia, the new expenses would be greater than their present total outlays. [14]. An examination of the differences in energy usage must be carried out from a regional standpoint in order to formulate practical policy suggestions [15]. Shifting from fossil fuel-based systems to variable renewable energy (VRE) like wind and solar photovoltaic (PV) poses intricate effects on electricity markets, notably evident in the influence of VRE on price fluctuations [16]. Renewable energies seem more stable in the face of such political events [17,18]. The main objective of research is determining drives in household energy consumption by considering the most important variables on energy consumption, particularly price of energy. There are some important questions that should be addressed in terms of energy consumption, First, does a shock in electricity and natural gas prices lead to a decrease in households energy consumption across EU countries. Second, do dynamic and static econometric models representing different results in analyzing the determinants of energy consumption in EU households? Third, what drives leading EU countries into increasing energy security?

The significant contributions of the study are the followings: this study explores the impact of key factors such as the prices of natural gas and electricity, renewable energy use, GDP, population, climate factors (HDD, CDD), and COVID-19 on energy consumption (natural gas and electricity) in EU households. Therefore the study encompasses a wide range of socio-economic factors, which has not been addressed yet. It identifies the upward and downward trends in variables to assess the effects of the Russia-Ukraine war and COVID-19 on energy prices, GDP, renewable energy use, and energy consumption. Furthermore, the research compares two periods 2000–2018 and 2019–2022, to understand the short-, long-, and instant-term impacts of the crises on energy consumption patterns. This study's contribution lies in its dynamic analysis of how rising energy prices affect energy consumption patterns, providing valuable insights into the burden of these crises on EU households. The results are underpinned by the latest data and a robust methodological framework, ensuring the reliability of our findings.

By scrutinizing energy, climate factors, prices, GDP and population in relation to both COVID-19 and the Russia-Ukraine war, the study provides a clearer understanding of how these factors interplay and affect energy usage within households. In addition, the research endeavors to provide regional perspectives for each of the EU-24 countries which have completed data concerning the energy crisis. By offering insights tailored to the specific circumstances of each country, policymakers are empowered to formulate targeted plans and strategies. This approach acknowledges the unique challenges and dynamics present within individual nations, thereby facilitating more effective decision-making and policy implementation to address energy-related issues and energy security amidst the backdrop of COVID-19 and the Russia-Ukraine conflict. Based on prior literature and theoretical frameworks, the following hypotheses have been formulated:

1. An increase in the price of natural gas and electricity, driven by the ongoing Russia-Ukraine war, leads to a reduction in household energy consumption among EU countries. Price is a key determinant of energy consumption, and external factors such as economic crises and geopolitical conflicts significantly influence energy prices. Rising energy costs financially strain households, particularly those with lower incomes, potentially leading to reduced energy consumption as families adjust their usage to cope with higher expenses.
2. The COVID-19 pandemic has increased household energy consumption in EU countries, driven by higher home occupancy rates and changes in energy usage patterns. Crises such as the COVID-19 pandemic alter household behavior and consumption patterns. Lockdowns and extended periods spent at home led to increased energy usage, as households required more electricity and heating for remote work, online education, and daily activities. These shifts highlight the impact of behavioral changes on energy consumption during prolonged crises.
3. The impact of the war on household energy consumption varies across EU countries, depending on differences in energy dependency, economic structure, and government policies. The ongoing Russia-Ukraine war has had significant repercussions on energy prices, given the EU's reliance on Russian gas and oil imports. However, not all EU countries have been affected in the same way, as their responses depend on factors such as energy diversification, economic resilience, and national policy measures. Understanding these variations is crucial to comprehending the broader dynamics of energy consumption across the EU.

This study follows these steps: Section 1 provides a literature review of related work. Section 2 covers the materials and methods, including data collection and the methodologies used. Section 3 presents the results, including trend and econometric analysis. Section 4 contains the discussion and policy implications. Section 5 includes limitation and future research and finally, section 6 concludes the study.

1.1. Literature review

Many recent studies have been published on the energy crisis and geopolitical issues in Europe, particularly focusing on the household sector, especially in light of recent geopolitical issues, the price of gas. Ali et al. (2023) [19], studied the correlation between oil, coal, and gas prices, economic growth, and coal consumption in top European importers of Russian gas. Their study findings show that higher oil and gas prices increase coal consumption, negatively impacting the environment. War has differing effects on coal usage across nations, leading to ecological imbalances in Poland and Germany. The study emphasizes the need for a shift towards renewable energy sources to mitigate environmental impact. Governments and stakeholders must develop long-term strategies to reduce reliance on fossil fuels. Rasheed et al. (2022) [20], studied the connection between energy use, oil prices, and CO_2 emissions in 30 European countries from 1997 to 2017, aiming to understand their impact on environmental quality. It suggests that as oil prices rise, there's a shift towards cleaner energy sources, reducing CO_2 emissions. This underscores the importance for European nations to prioritize renewable energy adoption, promoting sustainability and mitigating environmental degradation. Guan et al. (2023) [21], analyzed the global input-output data and household expenditure patterns, they find that energy costs could surge by 62.6 %–112.9 %, resulting in a 2.7 %–4.8 % rise in overall household expenditures. These increased costs disproportionately affect different household groups, potentially pushing an additional 78 million to 141 million people into extreme poverty around the world. Szymańska et al. (2023) [22], studied factors influencing households' energy transition and the barriers hindering this process. Findings reveal a dominance of fossil fuels in Poland's energy production, with renewable sources accounting for 16.1 % in 2020, primarily driven by photovoltaic installations. Rasheed et al. (2025) [23], employed panel ARDL-PMG, FGLS, and PCSE methods to examine the impact of semiconductors, AI, and geopolitical risk on renewable energy across 13 leading semiconductor-producing countries (1999–2019). Findings reveal that semiconductors and AI significantly boost renewable energy, while geopolitical risk disrupts progress. Moreover, geopolitical uncertainty weakens the positive effects of both technologies. These insights provide a data-driven foundation for policymakers shaping sustainable energy strategies.

Zakeri et al. (2022) [24], studied the impacts of the COVID-19 pandemic and the Russia-Ukraine war on the global energy sector, including shifts in demand, disruptions in supply chains, and challenges to energy security. Initial responses to these crises suggested opportunities for low-carbon energy transitions, highlighting lifestyle changes and the importance of renewable energy sources. However, there is a trend towards short-term solutions favoring incumbent fossil fuel industries and seeking new supply routes. Zakeri et al. (2023) [25], argued that the Recent events like the post-pandemic power price surge in 2021 and the 2022 Russia-Ukraine war have brought the European energy transition into sharp focus.

Li & Leung (2021) [26], reported that economic growth and non-renewable energy prices influence renewable energy consumption in the long run, with short-run causality also detected from fossil fuel prices to renewable energy consumption. However, there is no evidence of renewable energy consumption directly impacting economic output. These findings underscore the significance of economic factors and non-renewable energy prices in driving the transition towards renewable energy. Colgan et al. (2023) [27] results represented Energy security is a crucial point in the current European tendencies. A recent analysis delves into the value of energy security, highlighting how geopolitical events like Russia's invasion of Ukraine can significantly impact fossil fuel costs in Europe. By estimating excess market costs incurred during this period, it's found that Europe faced an additional €517–831 billion, with an estimated €643 billion. Additionally, European governments allocated €908 billion towards energy-related infrastructure and policies. These costs, totaling over €1 trillion, are compared to direct aid to Ukraine and the expenses of expediting Europe's energy decarbonization. On the other hand, Hille (2023) [2], whatsoever, geopolitical risks in some of the fossil fuel supplier countries accelerate renewable energy adoption in importing countries. By analysis of trade patterns and geopolitical risk data (from 1991 to 2021), such risks tend to promote renewable energy diffusion, especially for coal and natural gas imports. Rising electricity prices and high import dependence, particularly on coal, further enhance this effect. Despite import reliance, natural gas serves as a transitional energy source in the shift towards renewables. Rasheed et al., 2024 [28] applied panel NARDL and asymmetric panel causality methods to examine the nonlinear impact of competitive industrial performance and renewable energy on the carbon footprint in seven Asian developing nations (1990–2020). Findings reveal that both positive and negative shocks in industrial performance mitigate emissions, while industrialization worsens environmental quality. Renewable energy improves sustainability, whereas ICT intensifies environmental concerns. The study highlights the role of AI, robotics, and technological competitiveness in addressing carbon footprints. Rasheed et al., 2024 [29], this study employed panel NARDL and symmetric ARDL models to analyze the impact of AI on renewable energy production across 22 robotics-innovative countries (1991–2020). Findings confirm that AI significantly stimulates long-term renewable energy growth under both symmetric and asymmetric assumptions. Country-specific results highlight Austria, Germany, and New Zealand, where AI-driven shifts enhance clean energy in the short run. Additionally, natural resources, ICT, and economic growth further support renewable energy expansion.

Fig. 1 represents the search conducted in Web of Science (WOS) on the research topic, recognizing the complexity of the factors involved. However, many studies have highlighted the common goal of shifting towards renewables to achieve decarbonization and reduce dependencies on fossil fuels. While EU countries have made significant strides in renewable energy adoption, the potential for renewables varies across Europe. Consequently, some EU countries still rely on importing energy from Russia and other nations. Russia, boasting vast gas and oil reserves and its close proximity to Europe, facilitates the transportation of energy via pipelines. However, recent geopolitical tensions have led EU countries to impose sanctions on Russia's gas and oil, resulting in increased energy prices across Europe. Hence, few research were conducted to evaluate the impact of consecutive crises on the household sector across EU. Given that, the detailed goals were to: 1) Evaluate the trend analysis concerning the impact of crises on energy consumption among households in EU countries (2000–2022), and 2) Investigate the relationship between economic growth and energy consumption behaviors within the EU. The novelty of this work lies in its use of data from both before and after major crises (COVID-19 and the Russia-Ukraine war), highlighting their influence on energy usage and household expenditure across the EU. Thus, the findings hold significant implications for policymakers and stakeholders seeking to devise strategies that promote energy efficiency and resilience in the face of economic turbulence.

2. Materials and methods

2.1. Materials

In this study, we employed a comprehensive methodological approach to analyze energy demand dynamics across EU countries from 2000 to 2022, with a particular focus on recent crises such as COVID-19

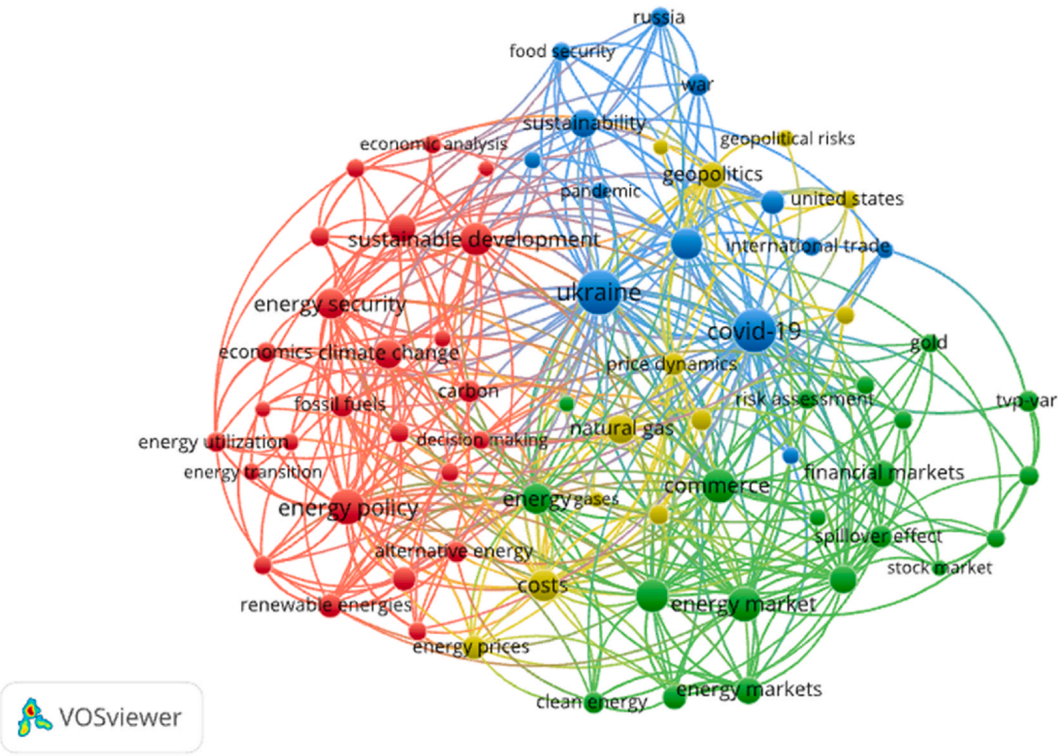

Fig. 1. The bibliometric analysis of the search conducted in Web of Science (WOS) on the research topic, using the equation (energy AND "energy sector" AND "energy price" AND Ukraine AND war AND "COVID-19″ AND pandemic AND gas) in Scopus (n = 399 documents). VOSviewer analysis identified 4 clusters.

and the Russia-Ukraine war. First, trend analysis is conducted to examine the evolution of key energy, economic, and climate variables over time. Next, the Tukey test is applied to assess differences in energy consumption before and after these crises across Europe. Finally, panel analysis is implemented to identify the factors influencing electricity and gas consumption among EU countries, providing a robust understanding of the drivers of energy demand in the region. However, there are other models could also identify drivers of energy demand in region, like machine learning, from a machine learning perspective, the goal is to maximize predictive accuracy [30], The goal of econometrics is to identify causal relationships within data [30]. In machine learning, linear relationships are rare. Econometrics, however, can uncover the fundamental underlying processes, providing valuable insights into the economic structure. However, since machine learning does not contribute to understanding these fundamentals, it may leave you unsatisfied [30]. Many machine learning models function as "black boxes," making it challenging to interpret the relationships between variables [31]. Computable General Equilibrium (CGE) is another Models offer a comprehensive framework for analyzing economy-wide policy impacts across sectors. They are particularly useful for evaluating trade liberalization and environmental policies. Meanwhile, CGE models are complex, demanding extensive data and computational resources. Their results heavily rely on assumptions about market structures and behaviors [32]. Panel data analysis offers distinct advantages over cross-sectional or time-series data. It enhances the accuracy of model parameter estimation by increasing degrees of freedom and sample variability [33]. By accommodating more complex behavioral hypotheses and controlling for omitted variable bias, it better captures the intricacies of human behavior [34,35]. Furthermore, panel data allows for the exploration of dynamic relationships and improves predictions for individual outcomes through data pooling [36,37]. It also simplifies computation and statistical inference in cases like nonstationary time series or measurement errors [38,39]. Overall, the ability of panel data to integrate inter-individual differences and intra-individual dynamics makes it a valuable tool in econometric analysis [40]. Electricity and Gas Consumption are the primary energy sources for households and industries in the EU, making them key indicators of overall energy demand. Numerous studies analyze electricity and gas consumption as dependent variables in energy demand models [41–44]. In more detail, to analyze the determinants of energy consumption in EU countries, various studies have employed a range of econometric methodologies [19,41,44–50]. The impacts of economic activity, population growth, and energy prices on energy demand have been widely examined using econometric frameworks, particularly panel data and cross-sectional analysis techniques [48–52]. These methods have been commonly utilized to assess the role of climate factors (HDD and CDD), renewable energy consumption [44,46], and geopolitical events such as the COVID-19 pandemic and the Russia-Ukraine war in shaping energy demand [19]. Additionally, studies have applied cointegration and error-correction models to capture both short- and long-term relationships in energy consumption [41]. In this study, static and dynamic panel regression models are applied [12] to comprehensively assess the effects of climate, economic, and policy-related variables on electricity and gas consumption across EU countries from 2000 to 2022. Compared to previous research, the incorporation of trend analysis, Tukey test and both static and dynamic models enhances the robustness of the findings, providing a more accurate estimation of energy consumption drivers in the region. Fig. 2 represents the whole process of methodology framework.

2.2. Data collection

Data were collected from Eurostat website. Data includes ten variables, namely: natural gas consumption, electricity consumption, Heating Degree Days (HDD) and Cooling Degree Days (CDD) are widely used climatic indicators that measure the demand for energy required for heating and cooling, respectively. HDD represents the cumulative number of degrees below a base temperature that necessitates heating, while CDD measures the excess degrees above a base temperature that requires cooling. Renewable energies, gas price, electricity price, GDP

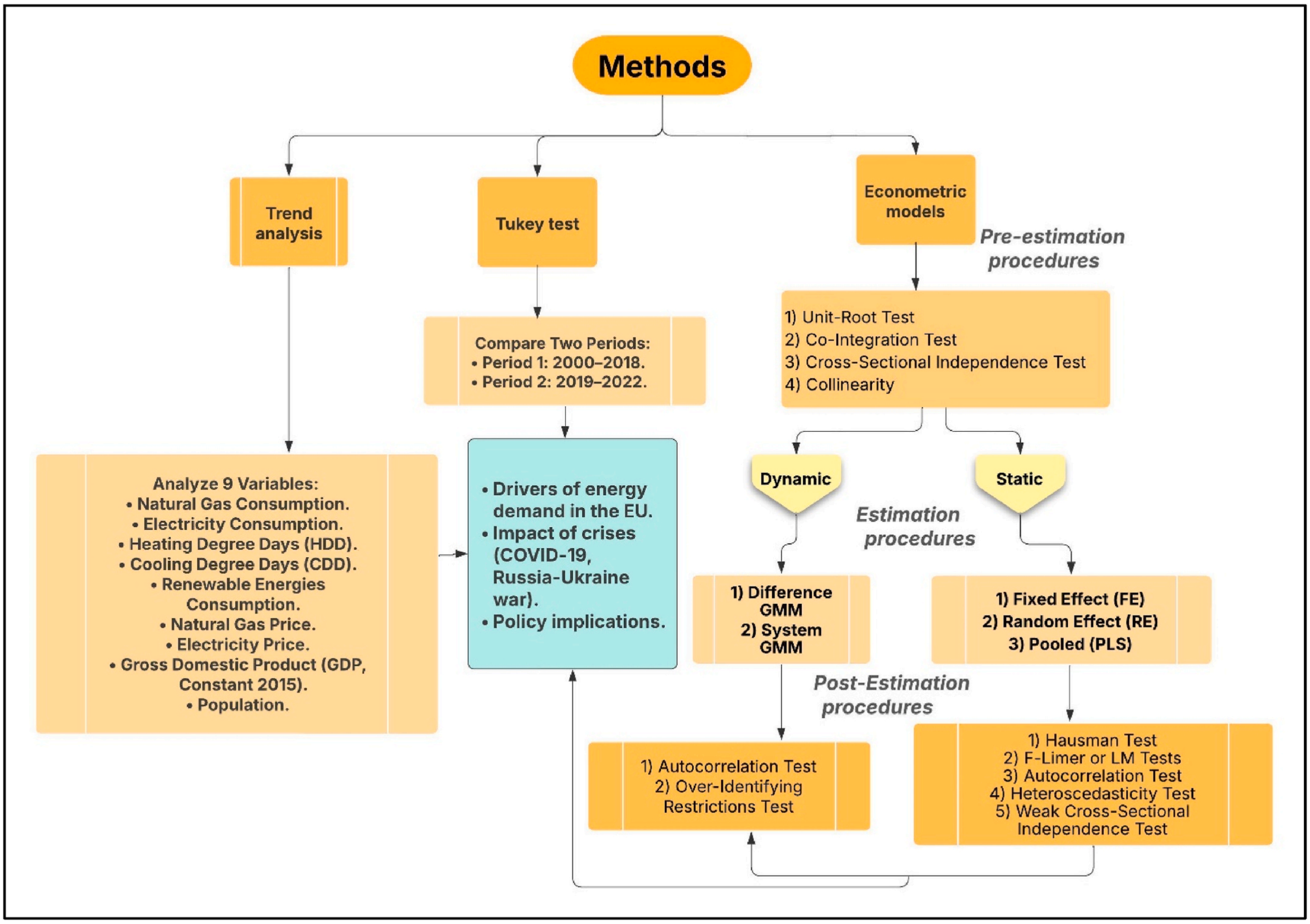

Fig. 2. Methodology framework.

and Population. We add a dummy variable for the COVID-19 with the value 1 for the years COVID-19 was pandemic, and zero for the rest of the period. All data is transformed to a logarithmic scale to control the variation of the data. More detailed information about the parameters was indicated in Table 1

2.3. Statistical analysis

For capturing the trend within the time series, the Mann-Kendall (MK) test, along with Sen's Slope estimator developed by Mann (1945) [53], were employed. The MK test, being nonparametric, is robust against outliers and can identify trends within data series. In this test, the null hypothesis (H0) states that there is no trend present in the series, while the alternative hypothesis (Ha) suggests the existence of a trend. The test statistics S could be calculated by the following:

$$S=\sum_{j=1}^{n-1}\sum_{k=j+1}^{n} Sign\,(yk-yi) \tag{1}$$

Where n = Total observations, yK and yJ represent the data point where k > j. To determine whether there are significant differences between the data before the crisis and after, the Tukey test was employed. The Tukey developed the Honestly Significant Difference (HSD) test to facilitate straightforward pairwise comparisons. It determines the significant differences between means by employing the student's q distribution, which denotes the greatest distinction among a group of means from the identical population. All variations are assessed against this distribution, rendering the HSD approach cautious in its evaluations [54]. For this research, data were divided into two groups, the first one before crisis (2000–2018) and the second one after (2019–2022). The Tukey HSD statistic is calculated as follows:

$$HSD = q\alpha, v, N^{*}\sqrt{\frac{MSW}{n}} \tag{2}$$

While qα, v, N is the critical value from the studentized range distribution. MSW is the mean square within groups, calculated as the sum of squares within groups divided by the degrees of freedom within groups. *n* is the number of observations in each group.

This study employs a structured approach to analyze growth trends,

Table 1
[1]Data overview and sources.

Variables	Time span	Units	Sources
Dependent variables			
Natural Gas Consumption	2000–2022	GJ (Gigajoule)	Eurostat[1]
Electricity Consumption	2000–2022	GJ	Eurostat
Independent variables			
Heating Degree Days	2000–2022	C^0 (Celsius)	Eurostat
Cooling Degree Days	2000–2022	C^0	Eurostat
Renewable energies consumption	2000–2022	GJ	Eurostat
Natural Gas Price	2000–2022	GJ/Euro	Eurostat
Electricity Price	2000–2022	GJ/Euro	Eurostat
Gross Domestic Product (Constant 2015)	2000–2022	Million Euro	Eurostat
Population	2000–2022	Person	Eurostat
Dummy variable for COVID-19			

compare pre- and post-crisis periods, and examine the impact of independent variables on energy consumption. First, the Mann-Kendall (MK) test is used to determine whether the selected variables exhibit an upward or downward trend. Second, the Tukey test is applied to compare two periods 2000–2018 (before the crises) and 2019–2022 (after the COVID-19 pandemic and the Russia-Ukraine war) to assess the impact of these crises on various factors across EU countries. Finally, both static and dynamic econometric models are utilized to identify the key determinants influencing household energy consumption (natural gas and electricity) in the EU. A detailed summary of variables is provided in Table 1 to enhance clarity.

2.4. *The econometric model*

This study examines the effects of several independent variables including renewables, GDP, price of natural gas and electricity, population, COVID-19 and climate factors (HDD,CDD) on the dependent variable, Energy consumption (natural gas and electricity), static and dynamic panel models were used. The equations, both static and dynamic, have been precisely defined and formulated as follows in equations (3) and (4).

Models	Equations
Static	$log\,gas_{i,t} = \alpha_0 + \alpha_1\ log\,t_{1_{i,t}} + \alpha_2\ log\,t_{2_{i,t}} + \alpha_3\ log\,ren_{i,t} + \alpha_4\ log\,elec_{i,t} + \alpha_5\ log\,gp_{i,t} + \alpha_6\ log\,ep_{i,t} + \alpha_7\ log\,gdp_{i,t} + \alpha_8\ log\,pop_{i,t} + \alpha_9 Z_{i,t} + \varepsilon_{i,t}$ (3)
	$log\,elec_{i,t} = \beta_0 + \beta_1\ log\,t_{1_{i,t}} + \beta_2\ log\,t_{2_{i,t}} + \beta_3\ log\,ren_{i,t} + \beta_4\ log\,gas_{i,t} + \beta_5\ log\,gp_{i,t} + \beta_6\ log\,ep_{i,t} + \beta_7\ log\,gdp_{i,t} + \beta_8\ log\,pop_{i,t} + \beta_9 Z_{i,t} + \sigma_{i,t}$
Dynamic	$log\,gas_{i,t} = \gamma_0 + \gamma_1 l.log\,gas_{i-p,t} + \gamma_2\ log\,t_{1_{i,t}} + \gamma_3\ log\,t_{2_{i,t}} + \gamma_4\ log\,ren_{i,t} + \gamma_5\ log\,elec_{i,t} + \gamma_6\ log\,gp_{i,t} + \gamma_7\ log\,ep_{i,t} + \gamma_8\ log\,gdp_{i,t} + \gamma_9\ log\,pop_{i,t} + \upsilon_{i,t}$ (4)
	$log\,elec_{i,t} = \theta_0 + \theta_1 l.log\,gas_{i-p,t} + \theta_2\ log\,t_{1_{i,t}} + \theta_3\ log\,t_{2_{i,t}} + \theta_4\ log\,ren_{i,t} + \theta_5\ log\,gas_{i,t} + \theta_6\ log\,gp_{i,t} + \theta_7\ log\,ep_{i,t} + \theta_8\ log\,gdp_{i,t} + \theta_9\ log\,pop_{i,t} + \mu_{i,t}$

In this study, gas and electricity consumption are the primary dependent variables. The static panel model captures the relationship between energy consumption (natural gas and electricity) and various explanatory independent variables, including climate (HDD, CDD), price of gas and electricity, GDP, population, renewable energies use and COVID-19. Meanwhile, the dynamic model extends this analysis by incorporating lagged energy consumption as an additional explanatory variable to assess persistence effects. The coefficients (α, β, γ, θ), corresponding to different categories of variables. I and t represent country and time from 2000 to 2022. Z shows a single specific effect. ε, σ and ν, μ are error terms. L denotes the lag operator, while p indicates the lag order.

2.5. *Econometric methodology*

2.5.1. *Panel Stationarity test*

To assess whether unit roots exist in the panel data, a range of general and specific panel unit-root tests have been developed by researchers such as, [55–61]. The alternative hypothesis is up for case, but the goal of these tests is to assess the null hypothesis of a unit root in a panel. We run the Cross-Sectional Augmented Dickey-Fuller (CADF) panel unit-root test in the investigation. as proposed by Pesaran (2007) [57] to assess the existence of unit roots in the single panel data. The CADF regression is represented by Equation (5):

$$\Delta Y_{i,t} = \alpha_i + \theta_t^{\,*} Y_{it-1} + d_0 \overline{Y}_{t-1} + \sum_{j=0}^{p} d_{j+1} \Delta \overline{Y}_{t-j} + \sum_{j=1}^{p} \gamma_{ij} \Delta \overline{Y}_{it-j} + u_{it} \tag{5}$$

In this model, Y represents the response variable for the i-th cross-sectional unit at time t. $\overline{Y}$ denotes the cross-sectional mean of Y, and P indicates the lag order. The coefficients are α_i, θ_t, d_0, and γ_{ij}. The null and alternative hypotheses of the CADF unit-root test are defined as follows [57–62]:

H_0: $\theta_t = 0$	The null hypothesis implies that there is no evidence of stationarity in any of the series
H_a: $\theta_t < 0$	The alternative hypothesis states that all series demonstrate stationary processes.

2.5.2. *Panel Co-Integration analysis*

Toward examine the extended co-integration midst the variables in the model, various testing procedures have been developed by researchers such as Kao (1999) [63], Pedroni (2004) [64], and Westerlund (2007) [65], In the study, we utilized the Kao test to assess the prolonged co-integration among the series in both models. The Kao test involves specifying both cross-section capture and homogeneous coefficients in the first-stage regression. For a regression as Eqs (6) and (7), the ADF test is as follows.

$$A_{it} = \pi\beta_{it} + \mu C_{jt} + e_{jt} \tag{6}$$

$$ADF = \frac{t_{ADF} + \frac{\sqrt{6N.\widehat{\sigma_v}}}{2\widehat{\sigma_{0v}}}}{\sqrt{\frac{\widehat{\sigma}^2_{0v} + 3\widehat{\sigma}^2_v}{2\widehat{\sigma}^2_v + 10\widehat{\sigma}^2_{0v}}}} \tag{7}$$

A denotes the variable that is influenced by other factors, β represents the variable that influences A, C signifies the constant term in the model, and e stands for the discrepancy between the observed and predicted values of A. θ and β are coefficients. t_{ADF} is the t statistic of ρ (the pair-wise correlation of the residuals). Also, $\widehat{\sigma}^2_{0v}$ and $\widehat{\sigma}^2_v$ stand for the long-run and simple variance of error terms [37,40].

2.5.3. *Test of panel cross-sectional independence*

Toward examine the presence of cross-sectional dependence among the factors in the panel data, a Cross-Sectional Dependence (CSD) test is employed. A novel test for cross-sectional dependence introduced by Pesaran (2007) [57]; is utilized, which does not rely on a specific spatial weight matrix, making it suitable for both large and small samples. The CD statistics for the panel data model in Eq (3) can be measured as Eq (8).

$$CD = \sqrt{\frac{2T}{N(N-1)}}\left(\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\widehat{\rho}_{ij}\right) \tag{8}$$

where, ρ is the sample estimate of the pair-wise correlation of the residuals [62,66,67].

2.5.4. *Test for panel collinearity*

Multicollinearity is a statistical concept that refers to the correlation between independent variables in a model, which can undermine the reliability of statistical assessments. It is essential to address multicollinearity to determine fixed factors in the model accurately. High levels of multicollinearity can complicate the assessment of relationships between variables. VIF used for examining the multicollinearity connecting the variables as Eq (9) [68,69].

$$VIF = \frac{1}{1 - R^2} \tag{9}$$

2.6. *Estimation methods*

2.6.1. *Static estimation models*

Static and dynamic techniques are the two main methods of estimate used in panel data regression. The methods used in Fixed Effect (FE), Random Effect (RE), and Partial Least Squares regression (PLS) in static panel regression vary in how they address model heterogeneity. (PLS) is a simple model where each panel unit has a common intercept. FE and

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[1] Statistics | Eurostat.

RE models, on the other hand, use a random component along with individual-specific effects to account for heterogeneity. FE models enable the model's intercept to be correlated with the dependent variable and to vary between individuals or groups. For large sample sizes (N) and short time dimensions (T), FE models are preferable over RE models. RE models treat individual-specific effects as random variables, uncorrelated with the independent variables. The general forms of all three static panel estimation methods PLS, FE, and RE—are presented as Equations (10)–(12), respectively.

$$Y_{it} = \alpha + \beta X_{it} + \varepsilon_{it} \tag{10}$$

$$Y_{it} = \alpha_i + \beta X_{it} + \varepsilon_{it} \tag{11}$$

$$Y_{it} = \alpha + \beta X_{it} + \nu_i + \varepsilon_{it} \tag{12}$$

Where Y and X are dependent and independent variables. α and β refer to coefficients. ε, ν, i, and t stand for error terms, random factor, province, and time period, respectively [70–73].

2.6.2. *Post-estimations*

To ensure the accuracy of the estimated model, the Hausman (1978) [74] was initially conducted to determine whether to adopt the (FE) or (RE) approach. The Hausman test is represented by Equation (13), where β_1 and β_0 denote the vector of coefficients under the null and alternative hypotheses, respectively.

Then, to recognize involving the selected model in the previous step and PLS, we need to do the F-Limer or the LM (Breusch-Pagan) tests, Eq (14) and Eq (15), to indicate a correct model as a final determination. One statistical test that is frequently used for matching statistical models is the F-limer test, to detect the model that best matches the data experimented. In the test, R^2_{FE} and R^2_{RE} are R-squared of the FE and RE estimation models [71,72,75].

$$H = (\beta_1 - \beta_0)' \left[var(\beta_0) - var(\beta_1)\right]^{-1} (\beta_1 - \beta_0) \tag{13}$$

$$F = \frac{\left(R^2_{FE} - R^2_{RE}\right)(n-1)}{\left(1 - R^2_{FE}\right)(nt - n - k)} \tag{14}$$

$$LM = \frac{NT}{2(T-1)} \left[\frac{\sum_{i=1}^{N} \left(T\bar{e}_i\right)^2}{\sum_{i=1}^{N} \sum_{t=1}^{T} e^2_{it}} - 1 \right]^2 \tag{15}$$

Heteroscedasticity, weak cross-sectional independence, and serial autocorrelation present major problems for panel regression models' error terms. We performed the Lagrange test for heteroscedasticity, the Pesaran test for cross-sectional independence in error terms, and the Wooldridge test for serial autocorrelation in order to resolve these problems. The model's output could be skewed and ineffective if these tests reveal the existence of these issues. Hansen (2007) [76], presented Feasible Generalized Least Square (FGLS) estimation as a solution to these issues, and the approach takes into account each issue directly during the estimate process. In the error terms of a panel regression model, this approach recognizes estimates in the existence of heteroscedasticity, weak cross-sectional correlation, and first-order autocorrelation. This method involves a two-step procedure to estimate the covariance matrix of error terms. The OLS method is used in the first stage to obtain the predicted residuals, and subsequently the matrix is re-estimated to generate the new residuals using OLS [66,75,77–80].

2.6.3. *Dynamic estimation models*

In the realm of economics, dynamic panel data approach ranks among the most often used and beneficial tools, especially for energy and environmental studies. Compared to static models, dynamic panel data model estimators have a few improvements, such as the ability to handle individual heterogeneity and the utilization of many instrumental factors to address the endogeneity issue. In a dynamic setting with numerous missing values, performing multiple integration becomes computationally impractical. However, with panel data, the complexity can be reduced by concentrating only on the subsample where past observed values are available [81]. Dynamic panel data estimators have clear asymptotic properties that remain valid as both T and N grow indefinitely. This strengthens the foundation of inferential statistics, ensuring the reliability of statistical tests and results, ultimately leading to robust conclusions in empirical research [82]. It was introduced by the Difference Generalized Method of Moments (GMM), the first estimator of a dynamic model was Arellano & Bond (1991) [83], and later the second estimator, the System Generalized Method of Moments (GMM), was developed by Arellano & Bover (1995) [84]. Finding instruments that are strongly linked to the endogenous regressors but not influenced by the error term is key to obtaining reliable estimates, especially in dynamic models [85]. Distinction The System GMM estimator uses both levels and lags in difference as instruments, in contrast to the GMM estimator which uses lags in differences alone. The difference and system GMM estimators are intended for scenarios involving many units and brief time intervals, or big N and short T panels. Specifically, consider Eq (16) a general dynamic model.

$$Y_{it} = \alpha + \gamma Y_{it-p} + \beta X_{it} + u_{it} \tag{16}$$

Where, Y and X are dependent and independent variables. α, β, γ refer to coefficients. ε, i, t, and p are error terms, province, time dimension, and lag order [86–90].

2.7. *Post-estimations*

In the model, using a lot of instruments is a sign of overidentification. In relation to this issue, the Sargan and Hansen tests, which were first presented by Sargan (1958) [91], are employed to verify that there are enough instrumental factors and that overidentification is not occurring. The validity of the instruments used in the testing of the one-step estimations is verified by the Sargan test. However, the Hansen test is advised to verify overidentification in two-step calculations. The validity of all overidentification limitations is the null hypothesis in both the Sargan and Hansen tests. With invalid instruments, however, the alternative hypothesis remains valid. The Arellano and Bond test is recommended to verify the serial autocorrelation in the dynamic panel models. The model's null hypothesis states that autocorrelation does not exist. On the other hand, the autocorrelation problem supports the alternative explanation [86,88]. For our key empirical findings, the study performed a robustness test the Dumitrescu & Hurlin (2012) Granger non-causality test to determine the presence or absence of causal relationships within the panel data structure. This is important for concluding the dynamic interactions between variables and understanding how one may influence the other [92].

3. Results

3.1. *An overview of parameters studied across EU*

The study selected EU-27 countries, but data for three countries (Malta, Cyprus, Finland) were not available. Therefore, the study focused on the 24 EU countries that had complete data for the study period. Fig. 3 represents electricity consumption among EU countries for three periods. The first year is 2000, where the countries with the lowest energy use are Lithuania, Latvia, and Estonia, along with Austria, with amounts ranging from 53 thousand GJ to 10 million GJ. In 2010, the minimum amount increased from 2 million to 23 million GJ, including Latvia, Estonia, Austria, Slovakia, and Croatia. There is a significant change in Austria, which increased from 2000. The last period, 2022, represents the highest consumption, which belongs to Germany and France.

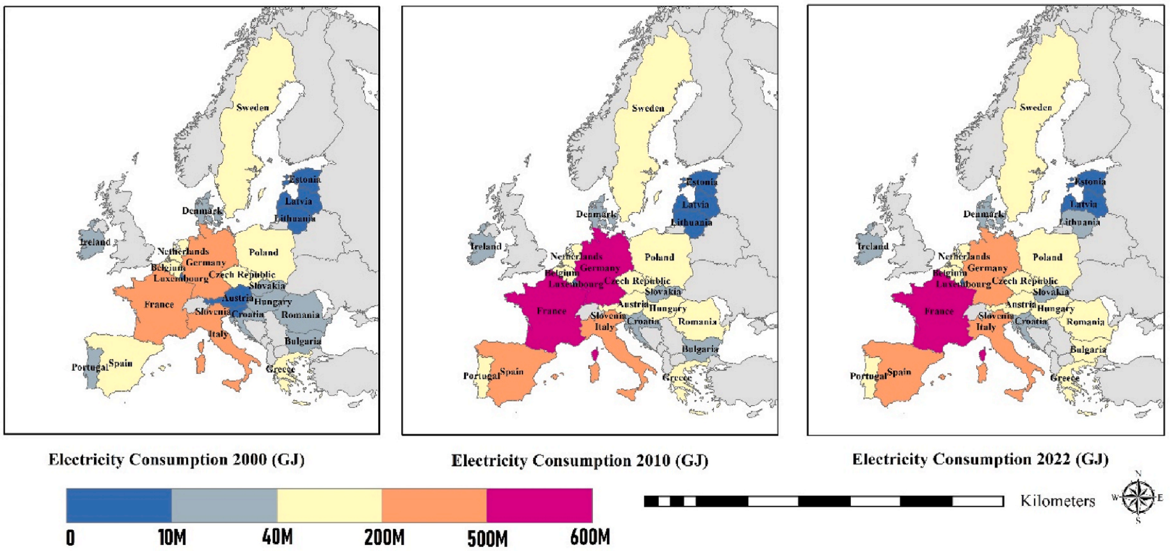
Electricity Consumption 2000 (GJ) Electricity Consumption 2010 (GJ) Electricity Consumption 2022 (GJ)

Fig. 3. Electricity Consumption in the household sector among EU-24 countries for three selected periods.

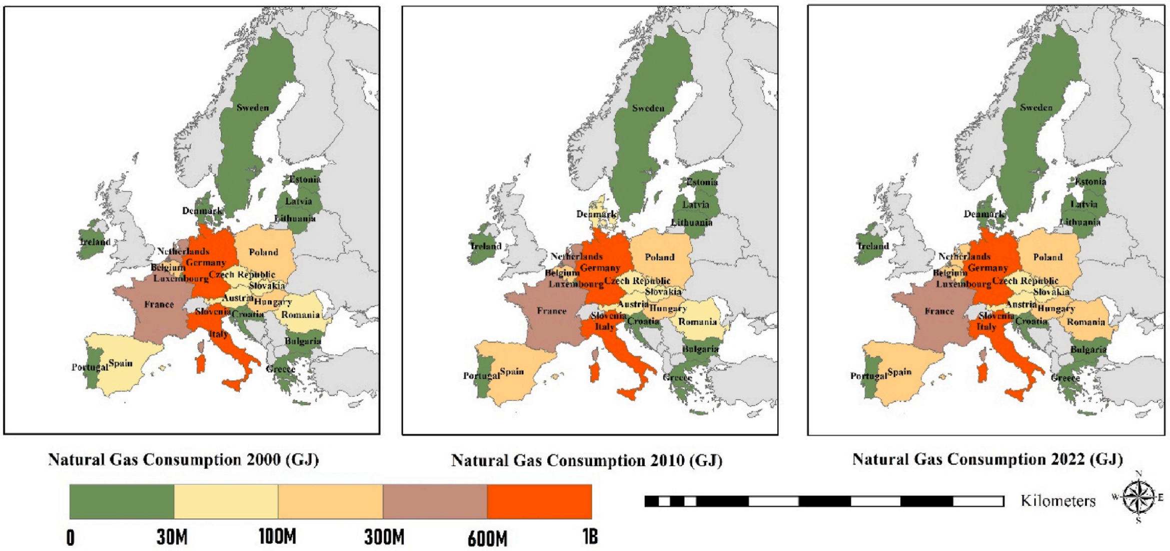
Natural Gas Consumption 2000 (GJ) Natural Gas Consumption 2010 (GJ) Natural Gas Consumption 2022 (GJ)

Fig. 4. Gas Consumption in the household sector among EU-24 countries for three selected periods.

In Fig. 4, gas consumption among EU-24 countries in 2000, shows that the majority of countries have consumption ranging between 8 thousand to 30 million GJ, with only Germany having the highest consumption. In 2010, around 10 countries had minimum consumption ranging from 2 to 30 million GJ, with Germany and Italy having the highest consumption. In 2022, the amount of gas consumption significantly decreased. Nevertheless, Germany and Italy remained the highest among EU-24 countries, albeit with decreased amounts.

In Fig. 5, renewables represent three countries with the lowest consumption: Slovakia, Belgium, and Ireland, ranging from 10 thousand to 6 million GJ. The highest consumption belongs to France. In 2010, the lowest consumption belongs solely to Ireland, while the highest consumption in 2010 is attributed to Germany, France, and Italy. In 2022, some countries experienced a slight increase, while the majority have decreased their renewables consumption.

In this context, the statistical overview of the examined variables under study in the natural logarithms is given in Table 2. For the years 2000–2022,. the dataset includes a balanced panel of 24 EU countries from 2000 to 2022, featuring annual observations. Since the dataset covers 23 years (2000–2022) and comprises 24 countries, the total number of observations is 552. The statistical mean is used to determine the center of the variable distributions, and the standard deviation and variance measures are presented to characterize the spread of the variables. Based on the findings, the majority of variables showed a limited standard deviation, suggesting a narrow dispersion. The subsequent section provides the maximum and minimum values for each variable. Skewness and kurtosis were computed to assess the distribution characteristics of the data. The final column presents the normality assessment of the variables, revealing that all variables strongly reject the null hypothesis of the Shapiro–Wilk test. However, it is important to emphasize that the chosen estimation methods do not rely on the assumption of normality in the data.

3.2. An outlook of energy and its related parameters changes across EU (2000–2022)

3.2.1. Trend analysis for studied parameters from 2000 to 2022

Results showed in appendix A that all countries experienced an

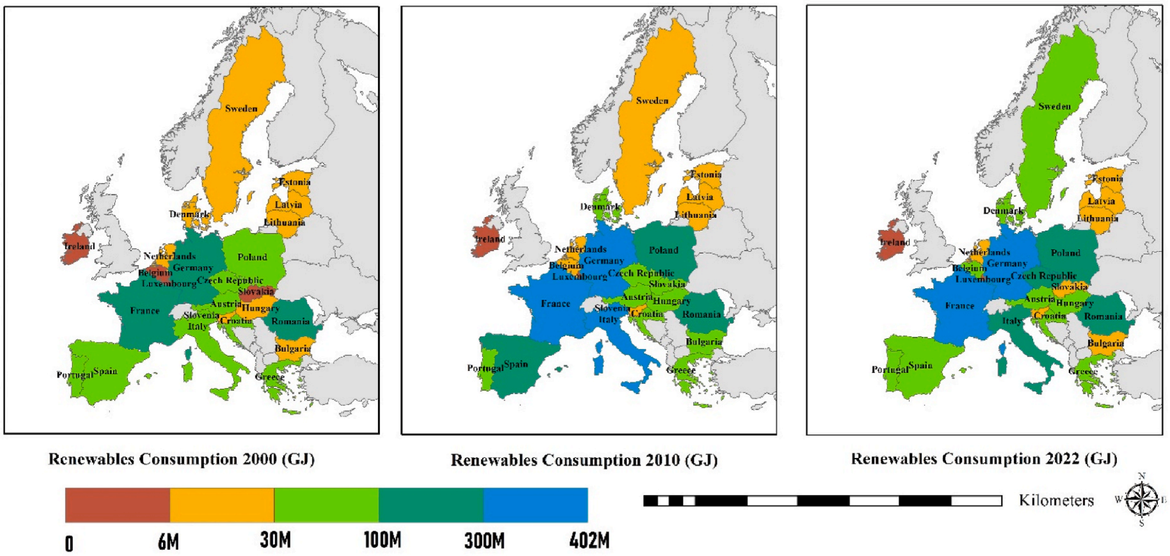

Fig. 5. Renewables and biofuels consumption in household sector among EU-24 countries for three selected periods.

Table 2

Statistical overview of the selected variables.

Variable	OBS	Mean	Std. Dev.	Max	Min	Skewness	Kurtosis	Variance	Shapiro-Wilk
Ln gas	552	17.29	2.01	20.77	8.99	−0.31	2.82	4.05	5.82 ***
Ln elec	552	17.61	1.31	20.23	14.84	−0.003	2.54	1.73	5.41***
Ln t1	552	7.91	0.32	8.69	6.87	−0.63	3.54	0.10	6.09***
Ln t2	552	3.15	2.10	6.10	−4.60	−1.16	4.55	4.42	8.31***
Ln ren	552	17.36	1.48	19.88	9.21	−1.15	5.38	2.19	8.76 ***
Ln gp	552	2.34	0.45	3.85	1.07	−0.42	3.44	0.20	5.19***
Ln ep	552	3.38	0.34	4.64	2.31	−0.06	3.87	0.11	3.75***
Ln GDP	552	12.13	1.41	15	9.43	0.20	2.15	2.01	6.14***
Ln Pop	552	16.01	1.24	18.24	12.98	−0.11	2.69	1.54	6.16***
D	552	0.086	0.028	1	0	2.93	9.59	0.079	

Note: * refers to 10 %, ** is 5 %, and *** is 1 % significance level.

increase in gas prices between 2000 and 2022, except for Denmark (DE). The highest increase was recorded in Sweden (SW), at 0.6806 GJ/Euro ($P < 0.0001$), followed by the Czech Republic (CZ) at 0.5278 GJ/Euro ($P < 0.0001$). The Mann-Kendall test results for natural gas usage (measured in Gigajoules) across EU-24 countries reveal a mixed trend in natural gas consumption. While some countries exhibit a significant decrease in gas usage, others show notable increases, reflecting diverse energy consumption patterns and possibly varying shifts towards alternative energy sources or changes in demand. Significant decreases are observed in countries like the Czech Republic (CZ) and Denmark (DE), in appendix A with Kendall's tau values of −0.5573 and −0.6126, respectively, and Sen's slopes indicating substantial declines in gas consumption (−1083444.4035 GJ for CZ and −260265.4440 GJ for DE). These trends suggest a significant reduction in natural gas demand in these countries. Conversely, Greece (GR) and Poland (PL) demonstrate strong increases in natural gas consumption, with GR's Kendall's tau at 0.8656 and PL's at 0.6759, and Sen's slopes showing substantial increases (938108.3640 GJ for GR and 1564348.9740 GJ for PL). This indicates a growing reliance on or increased demand for natural gas in these areas. An interesting case is Estonia (ES) and Luxembourg (LU), where tau values of 0.6680 and 0.6759 respectively, alongside positive Sen's slopes (34957.5764 GJ for ES and 152947.0246 GJ for LU), point towards an uptrend in gas usage, albeit at varying magnitudes. These findings highlight the diverse trends in natural gas consumption across the EU, suggesting the impact of factors such as economic growth, energy efficiency measures, and the transition towards renewable energy sources. The data emphasizes the necessity for customized energy policies that cater to the unique requirements and patterns observed in individual countries.

Some countries witnessed a significant reduction in electricity usage as shown in Figs. 6 and 7 and Appendix B. For example, Belgium (BG) observed a notable decrease, reaching −444915.5 GJ/year ($p < 0.05$). Also, Germany (GE) recorded a significant decrease, with Kendall's tau at −0.4071, and Sen's slope at −1,889,994.7890 GJ/year ($p < 0.05$). However, the largest increase in electricity usage was recorded in France (FR) and Italy (IT), reaching 5,590,801.5 ($p < 0.05$) and 346,370.9 GJ/year, respectively Figs. 6 and 7 and Appendix B.

The analysis of electricity price trends in the EU-24 (Study countries) using the Mann-Kendall (MK) test in Figs. 6 and 7 and Appendix B. reveals significant upward trends in most countries, as indicated by Kendall's tau values close to 1 and p-values below 0.05. Particularly notable are Belgium (BG) with a Kendall's tau of 0.8103 and a Sen's slope of 1.3455, and Ireland (IR) with a tau of 0.8317 and a Sen's slope of 1.9539, both showing strong positive trends in electricity prices. Italy (IT) and Hungary (HU) present exceptions, with increasing but not significant trend. The highest significant increase is observed in Ireland (IR), underlining the varying rates of electricity price inflation across the EU, with some countries experiencing sharp increases, while a few others show no significant trend.

The Mann-Kendall test results for GDP growth (measured in million Euros) across the EU-24 countries show in Figs. 6 and 7 and Appendix C a predominantly positive trend, with almost all countries demonstrating statistically significant growth (p-value <0.0001). This analysis underscores the economic vitality and growth momentum across the EU, with most countries experiencing significant increases in GDP. The results highlight the economic differences within the EU, from the high-

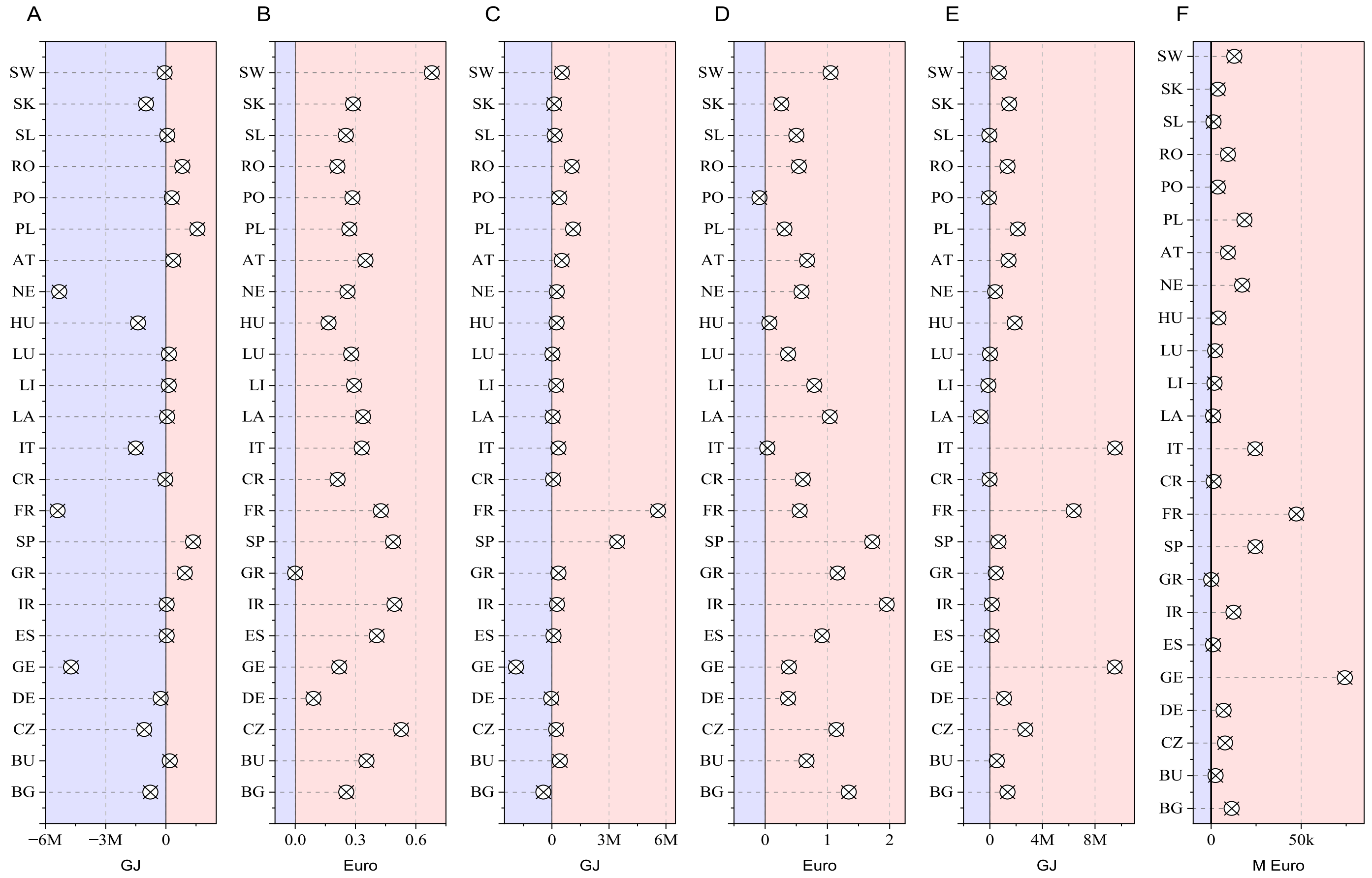

Fig. 6. Trend analysis of studied variables based on MK test and Sen slope across EU countries (2000–2022): A) Gas consumption GJ, B) Gas Price GJ/Euro, C) electricity use (GJ), D) electricity Price GJ/Euro, E) for Renewables GJ, F) GDP million Euro. Blue shadow is deemed a decreasing trend, while red shadow is an increasing one.

growth economies such as Bulgaria and Germany to the lowest growth in Greece, suggesting varied economic conditions and challenges within the Union.

Fig. 7 illustrates the time series evolution of various variables over the study period. Fig. 7 (a) depicts electricity usage among the EU-24 countries, showing a decrease after 2019, followed by a subsequent increase in 2021. However, there was a dramatic decrease following the onset of the war. Fig. 7 (b) displays cooling degree days, which exhibited significant fluctuations throughout the study period. Fig. 7 (c) represents electricity prices, indicating a significant increase after the war. Gas prices, as shown in Fig. 7 (d), also experienced an increase in the aftermath of the war. Fig. 7 (e) illustrates GDP trends, revealing a decrease after COVID-19, followed by recovery and subsequent growth. Fig. 7 (f) Heating degree days, similarly fluctuated during the study period. Fig. 7 (g) Natural gas usage, increased after COVID-19 but then sharply declined after the war. Fig. 7 (h), representing population trends, shows a consistent increase throughout the years 2000–2022. Lastly, Fig. 7 (i) illustrates renewables consumption among households in EU-24 countries, showcasing an increasing trend over the study period.

Further insights can be gleaned from Fig. 8, which highlights changes among energy and prices between the situation in 2000 and the situation in 2022. In terms of electricity usage, many countries experienced growth, except for Belgium, Sweden, and Denmark, which showed negative changes (i.e., 2000 vs 2022). Regarding electricity prices, all countries displayed growth, with minor changes observed in Hungary and Slovakia (i.e., 2000 vs 2022). Changes in natural gas usage predominantly showed minor growth or negative trends, with Sweden and the Netherlands exhibiting the highest negative changes, while Germany and Bulgaria showed the highest growth. Gas prices demonstrated growth across all countries, although Hungary, Poland, Slovakia, and Greece experienced relatively lower changes during the study period, while the Estonia and Romania experienced the highest increase. Renewable energy usage depicted predominantly positive changes, with some exceptions such as Latvia and Slovenia, which showed negative trends. Notably, Slovakia, Italy, Belgium, and Ireland exhibited the highest changes in renewable energy consumption.

The Tukey test was employed to compare the studied parameters before (2000–2018) and after crisis (2019–2020). Fig. 9 presents the results of the Tukey test conducted for all study variables. Among the variables assessed, energy usage and prices are particularly crucial. Results showed in Fig. 9 (a) that electricity usage did not reach a significant level in the Tukey test, suggesting no significant difference between the two distinct periods examined. Similarly, gas consumption also showed in Fig. 9 (g) non-significance, indicating stability in gas usage across the two periods. However, Fig. 9(c) and (d) reveal significant findings regarding electricity and gas prices. Both variables demonstrated a significant impact from the crises, implying discernible effects on electricity and gas pricing dynamics that depict plot charts displaying a notable increase in prices, emphasizing the substantial shifts in pricing trends influenced by external factors such as the COVID-19 pandemic and the Russia-Ukraine war. Fig. 9 (e) presents GDP data for two periods, analyzed using the Tukey test, which indicates a statistically significant difference. The results show an increase in GDP among EU-24 countries after 2019. Although there was a sharp decline during the COVID-19 pandemic, the economy rebounded strongly in the post-pandemic period. Fig. 9(f)–(b) and (h) shows a HDD, CDD and population. Moreover, renewable energy consumption in Fig. 9 (i)

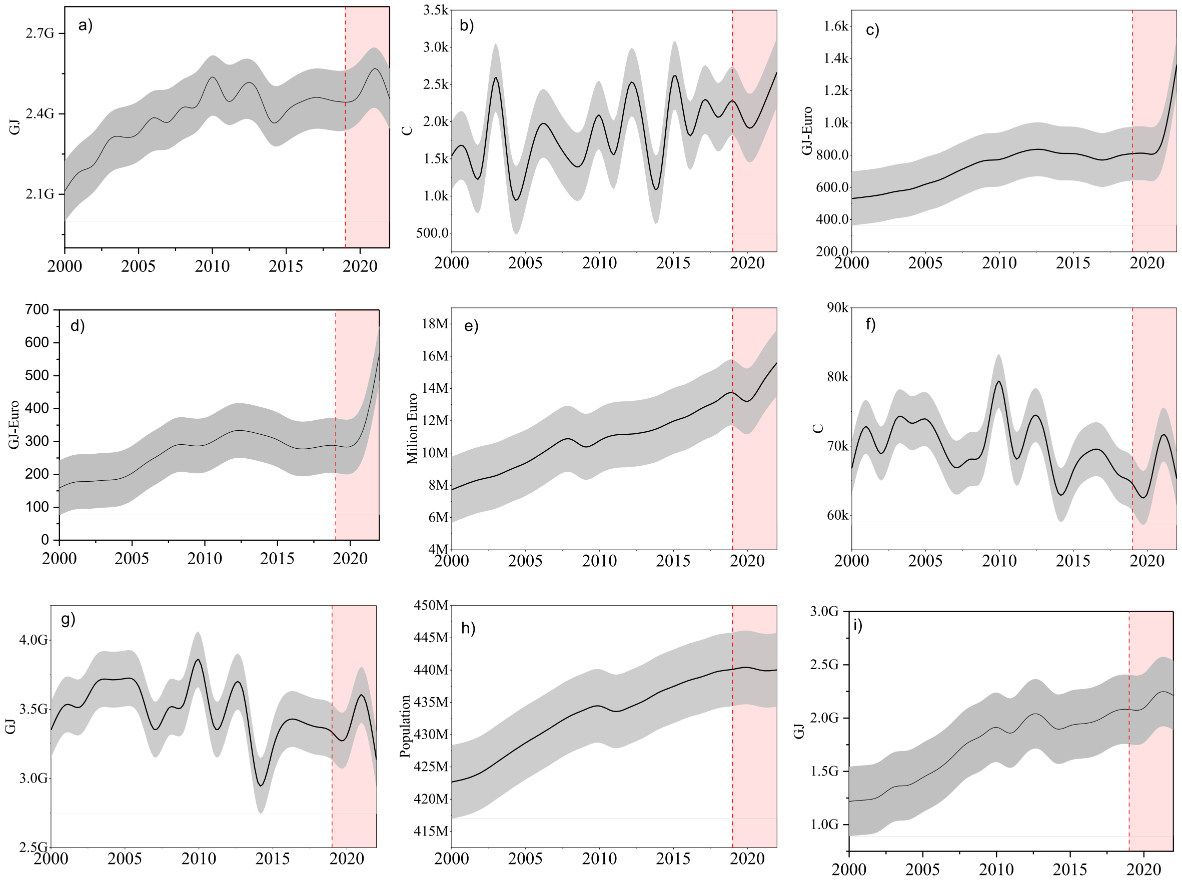

Fig. 7. Time series evolution of various studied variables within the EU from 2000 to 2022, with the red shadow indicating the onset of crises, starting with COVID-19 in 2019, followed by the Russian-Ukrainian war: (a) electricity use, (b) CDD, (c) Electricity Price, (d) Gas Price, (e) GDP, (f) HDD, (g) Natural gas use, (h) Population, (i) Renewables and biofuels.

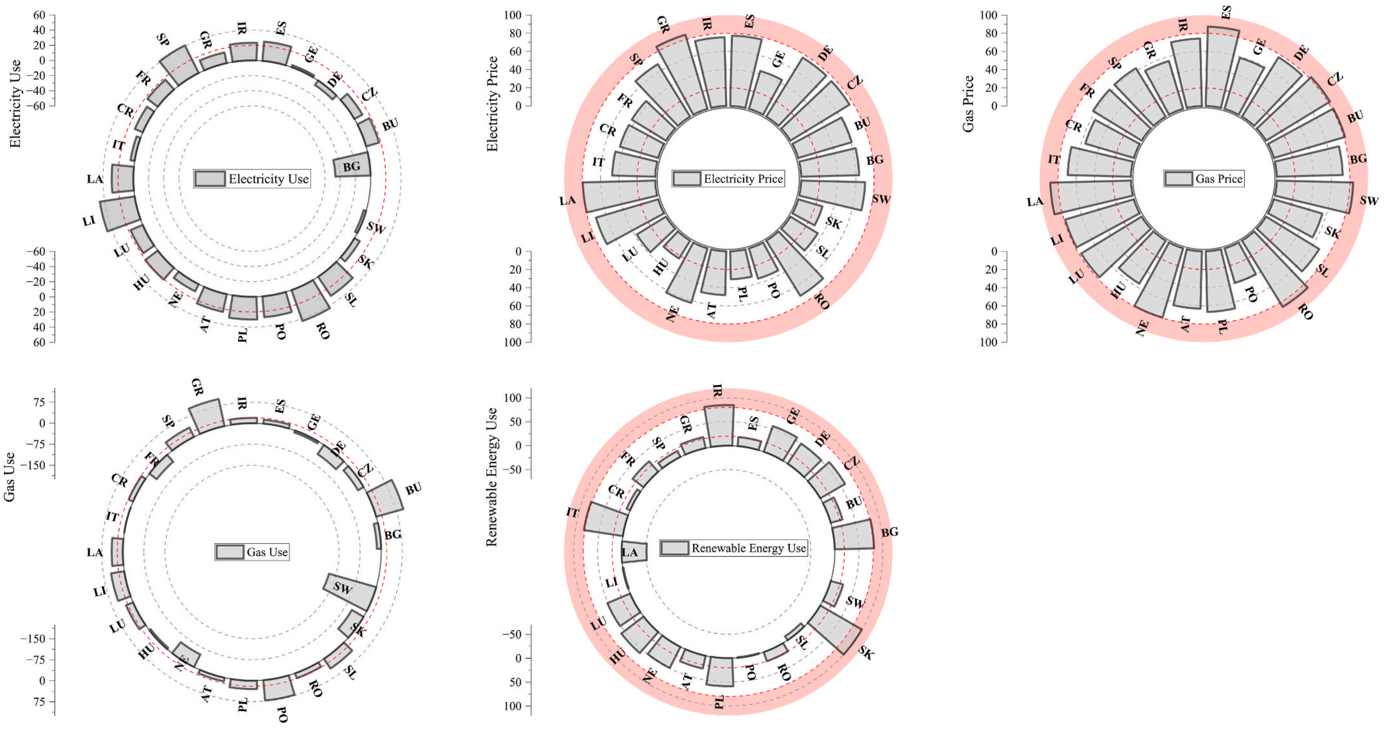

Fig. 8. Changes % between 2000 and 2022 of EU counties for some energy variables: Percentage Change= (Value in 2022−Value in 2000/Value in 2000) × 100.

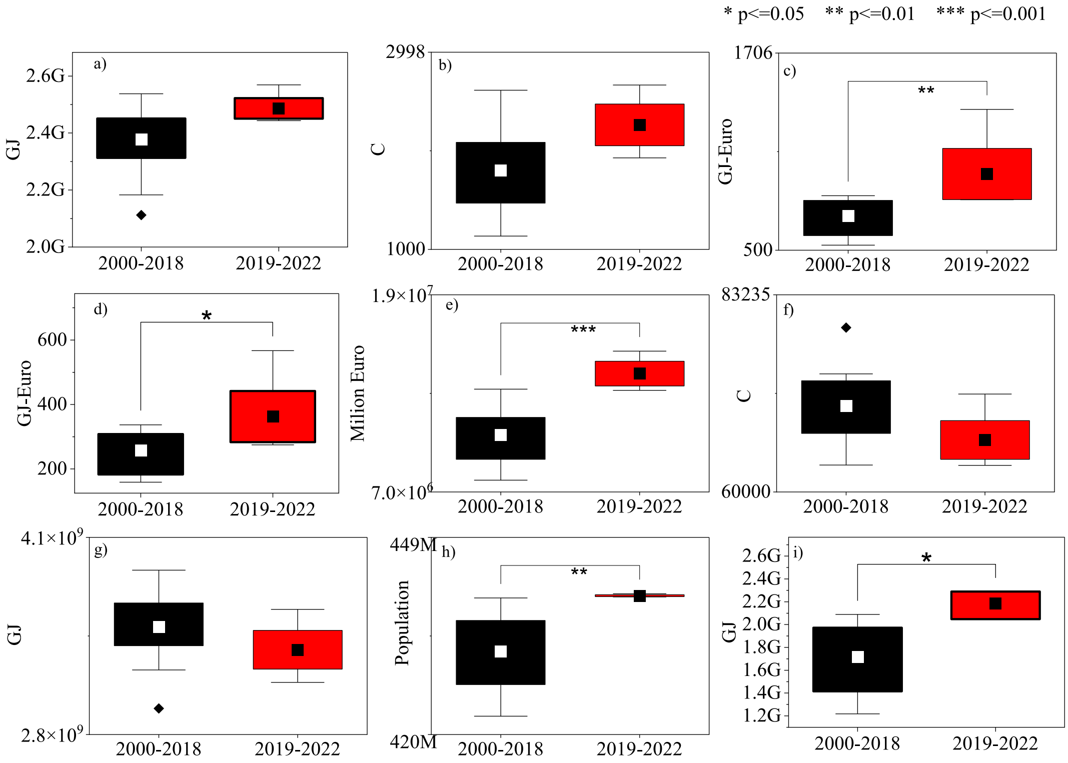

Fig. 9. Tukey statistical test for studied variables across two distinct periods, the first from 2000 to 2018 and the second from 2019 to 2022, for EU countries: (a) electricity use, (b) CDD, (c) Electricity Price, (d) Gas Price, (e) GDP, (f) HDD, (g) Natural gas use, (h) Population, (i) Renewables and biofuels.

emerged as significant at the 0.05 level, indicating a noteworthy increase in renewable energy utilization among EU-24 countries. This finding suggests an accelerated transition towards renewable energy sources amidst the crises. The significance of renewable energy consumption underscores the importance of energy diversification strategies and the increasing emphasis on sustainability in the face of global challenges.

3.3. Initial-estimation overview

The results of the estimation, including the Cross-Sectional Dependence Result, Multicollinearity Result, CIPS test for panel unit root test, and Kao Co-Integration Tests, are detailed in Appendices D to H. Based on the outcomes of these tests, there are no issues hindering the presentation and interpretation of the models' results.

3.4. Static estimation

We conducted analyses on the effects of GDP, climate (HDD,CDD), renewables, population, price of natural gas and electricity and the dummy variable (COVID-19) on energy consumption (natural gas and electricity) using various panel data regression techniques. Initially, we applied the Hausman test. The results in Appendices I and J strongly reject the null hypothesis, indicating that the (FE) model is suitable for our estimations. Subsequently, an F-test was conducted to choose between the FE and pooled least squares (PLS) models. This test, significant at the 1 % level, led to the selection of the FE model for further investigation (see Appendices I and J). We then employed the Wooldridge test to examine autocorrelation. The results indicate a clear rejection of the null hypothesis, suggesting autocorrelation in the estimated FE model. Furthermore, the Wald test was used to assess groupwise heteroscedasticity, revealing its presence in the estimated FE model (see Appendices I and J). Lastly, the Pesaran cross-sectional dependence test was employed to evaluate the correlation between panel units. The test results, found in Appendices I and J, reject the null hypothesis, indicating the existence of cross-sectional dependence in the estimated model. Given these test outcomes from Appendices I & J, the estimation results of the FE model may be misleading and biased. To address these issues, we applied the FGLS estimation method, which yields reliable and robust results (refer to Tables 3 and 4 below). All variables, with the exception of Renewables in electricity model, are statistically significant at 1 % and 5 % significance levels. According to the results in Table 3 for gas model as dependent variable, all variables in static model significant represent all variables effect on gas consumption among EU countries. Climate factors both HDD and CDD have positive impact on gas consumption with elasticities 0.29, 0.14 respectively, which shows 1 percent increase in HDD, CDD cause 0.29, 0.14 % increasing gas consumption. Therefore, Climate factors are among factors directly effect on gas consumption. Renewables and biofuels represent positive effects on gas consumption which represents 1 percent increase in renewables, which cause 0.12 increase in gas consumption. In contrast, electricity consumption among households in EU countries shows negative effect on gas consumption. In detail, 1 percent increase in electricity consumption cause −1.19 % decrease in gas consumption, which shows energy transition from gas to electricity in

Table 3
Results of FGLS estimation for Gas consumption.

Variables	Coefficients	Std. Dev.	P-value
Ln t1	0.291 ***	0.097	0.00
Ln t2	0.147***	0.024	0.00
Ln ren	0.122***	0.042	0.00
Ln ele	−1.197***	0.12	0.00
Ln ep	2.41***	0.19	0.00
Ln gp	−2.179 ***	0.14	0.00
Ln Pop	0.822 ***	0.12	0.00
Ln GDP	1.424***	0.091	0.00
d	−0.141	0.13	0.29
Wald Test	217471.58***		0.00

Note: * refers to 10 %, ** is 5 %, and *** is 1 % significance level.

Table 4

Results of FGLS estimation for electricity consumption.

Variables	Coefficients	Std. Dev.	P-value
Ln t1	0.366	0.025	0.00
Ln t2	0.023	0.007	0.00
Ln ren	0.009	0.013	0.47
Ln gas	−0.112	0.012	0.00
Ln ep	215	0.066	0.00
Ln gp	0.243	0.052	0.00
Ln Pop	0.664	0.283	0.00
Ln GDP	0.486	0.265	0.00
d	0.036	0.041	0.88
Wald Test	2391145 ***		0.00

Note: * refers to 10 %, ** is 5 %, and *** is 1 % significance level.

the household sector among EU countries. Electricity prices as a rivalry energy price has a positive effect on gas consumption which 1 percent increase in electricity price 2.41 % increase gas consumption. In terms of rivalry energy in EU countries the two most important energy have switching effect to each other which shows if EU countries are toward electrification, they might control electricity price to prevent increasing gas consumption. Gas price in the static model has a significantly negative effect on gas consumption which represents a 1 percent increase in gas price lead to decrease −2.17 % gas consumption in household sector in EU countries. Based on the results increasing gas prices cause reduce gas consumption that more effect vulnerable households in terms of energy poverty. Population and GDP both have positive effects on gas consumption with elasticities 0.82 and 1.42. The dummy variable (COVID-19) is not statistically significant in the static model.

According to results in Table 4 for electricity in static model all variables except renewables are significant. Firstly, climate factors (HDD and CDD) like gas model both have a positive effect on electricity consumption with elasticities 0.36, 0.023 respectively. Gas consumption has a negative effect on electricity consumption as a rivalry energy which 1 percent increase in gas consumption cause −0.112 % decrease in electricity consumption. Electricity prices have a negative effect on electricity consumption, 1 percent increase in electricity price cause −0.205 % decrease in electricity consumption in household sector among EU countries. Gas price as rivalry energy has a positive effect on electricity consumption which 1 percent increase in gas price lead to an increase of 0.243 % electricity consumption. In terms of electrification in the household sector, it is necessary to control gas consumption and find alternative for gas, however based on studies amount of renewables are leading to reduce based on dataset that represent importance of innovation and alternative energy sources. Population and GDP both have a positive impact on electricity consumption with elasticities 0.66 and 0.48 respectively. Also, the dummy variable (COVID-19) is not statistically significant in the static model for electricity consumption.

Table 5

Results of System GMM for Gas consumption.

Variables	Coefficients	Std. Dev.	P-value
Ln t1	0.232***	0.042	0.00
Ln t2	0.018***	0.004	0.00
Ln ren	0.020	0.019	0.27
Ln Elec	−0.071	0.224	0.74
Ln gp	−0.114***	0.027	0.00
Ln ep	−0.186**	0.092	0.04
Ln Pop	1.64	1.28	0.20
Ln GDP	0.191***	0.066	0.00
d	0.0387***	0.012	0.00
Sargan Test	17.82		1.00
Bond Test AR(1)	−2.53		0.01
Wald Test	12728.04***		0.00

Note: * refers to 10 %, ** is 5 %, and *** is 1 % significance level.

3.5. Dynamic estimation

According to dynamic models, system GMM selected as a model for analyzing the data, Table 5 represents system GMM for gas consumption as a dependent variable. The Sargan test results indicate that we do not reject the null hypothesis, suggesting that the instruments used in the model are valid and not correlated with the error terms. Similarly, the Arellano-Bond tests show that we do not reject the null hypothesis, indicating that there is no autocorrelation issue in the estimated model. Compared to the static model, the dynamic model offers more accurate results by accounting for changes over time, thereby providing a more nuanced understanding of the relationships between variables. The results show HDD, CDD, gas price, electricity price, GDP and dummy variable (COVID-19) are significant in levels of 1 and 5 percent. HDD and CDD both have positive effects on gas consumption with elasticities 0.23, 0.018 % respectively. Electricity price has a negative effect on gas consumption which 1 percent increase in electricity price caused −0.186 % decrease in gas consumption. In terms of transition, it is important to consider the price of rivalry energy. During the study period, it was observed that gas prices had a negative impact on gas consumption. Specifically, a 1 percent increase in gas prices resulted in a decrease of −0.11 % in gas consumption. This decrease can be attributed to factors such as the escalation of gas prices due to the Russian-Ukraine war. Consequently, these findings affirm that rising gas prices directly affect many households across EU countries, particularly vulnerable ones. GDP has a positive effect on gas consumption, that shows 1 percent increase in GDP leading to increase 0.191 % gas consumption. The dummy variable (COVID-19) indicates a positive effect on gas consumption, with an elasticity of 0.038 % among households. This suggests that the presence of COVID-19 and associated lockdown measures led to an increase in gas consumption among households in EU countries.

According to results for electricity model in Table 6, CDD, gas consumption, gas price and dummy variable are significant in dynamic model. CDD have a minor positive effect on electricity consumption which 1 percent increase in CDD cause 0.002 % increase in electricity consumption. Gas consumption also have a positive effect on electricity consumption which 1 percent increase in Gas consumption lead to increase 0.047 % electricity consumption. However, gas prices have a negative effect during the time on electricity consumption in household sector among EU countries. Which 1 percent increase in gas price cause −0.035 % decrease electricity consumption. The results clearly demonstrate a direct relationship between gas and electricity prices, indicating the need to consider both factors when analyzing energy consumption patterns. Moreover, this underscores the importance of evaluating the interplay between gas and electricity prices to effectively manage energy usage. Additionally, transitioning towards greater reliance on electricity has the potential to mitigate dependency on gas and potentially lower gas prices. The dummy variable (COVID-19) also demonstrates a positive effect on electricity consumption, with an elasticity of 0.033 %. COVID-19 directly impacted energy consumption

Table 6

Results of system GMM for electricity consumption.

Variables	Coefficients	Std. Dev.	P-value
Ln t1	0.011***	0.034	0.73
Ln t2	0.002	0.0007	0.00
Ln ren	0.008	0.012	0.50
Ln gas	0.047**	0.024	0.05
Ln gp	−0.035***	0.007	0.00
Ln ep	−0.013	0.021	0.52
Ln Pop	0.312	0.527	0.55
Ln GDP	0.052	0.042	0.21
d	0.033	0.003	0.00
Sargan Test	19.82		1.00
Bond Test AR(1)	−3.29		0.00
Wald Test	5319.77***		0.00

Note: * refers to 10 %, ** is 5 %, and *** is 1 % significance level.

among households in EU countries. Therefore, crises such as war and COVID-19 have a direct effect on energy consumption across EU countries.

For our key empirical findings, the study performed a robustness test (see Table 7). For the HDD as first variable both directions show significant levels, indicating rejection of the null hypothesis of non-causality, therefore, there is significant Granger causality between HDD and electricity consumption. Most of the variables show significant level except for CDD, electricity price, GDP and dummy variable, which represents most variables have bidirectional relationships with electricity consumption and significant granger causality among variables. Obviously, the results of granger non-causality test for most variables represent and confirm past value of variables provide useful information for forecasting other variables.

In other hand for gas consumption all variables except gas consumption on CDD, GDP and dummy variable, are significant. The direction for some variables is bidirectional and for some are unidirectional. Renewables has a direct granger on gas, meanwhile, gas has unidirectional on renewables. Upon analyzing Table 7 and it becomes evident that the null hypothesis of non-homogeneous causality is rejected for several series at the statistical significance levels of 1 % or 5 %. This rejection indicates the presence of lead-lag effects between our variables, signifying predictive relationships. Moreover, focusing on energy consumption as our variable of interest, the analysis reveals that gas price, electricity price, and other variables exhibit a causality effect on the dynamics of energy consumption. This inference aligns with the significant Granger causality relationships observed in Table 7.

Table 7

Dumitrescu & Hurlin (2012) Granger non-causality test results.

Hypothesis	Z-bar tilde	z-bar
lt1 does not Granger-cause lelec	8.6***	10.94***
lelec does not Granger-cause lt1	2.15***	3.04***
lt2 does not Granger-cause lelec	1.6	2.37***
lelec does not Granger-cause lt2	0.96	1.59
lren does not Granger-cause lelec	7.69***	5.95***
lelec does not Granger-cause lren	2.56***	3.55***
lgas does not Granger-cause lelec	3.22***	4.35***
lelec does not Granger-cause lgas	3.29***	4.44***
lgp does not Granger-cause lelec	4.97***	6.5***
lelec does not Granger-cause lgp	7.07***	9.06***
lep does not Granger-cause lelec	1.44	2.17***
lelec does not Granger-cause lep	5.99***	7.74***
lp does not Granger-cause lelec	7.9***	10***
lelec does not Granger-cause lp	16.64***	20.79***
lgdp does not Granger-cause lelec	8.81***	11.19***
lelec does not Granger-cause lgdp	1.06	1.71
lelec does not Granger-cause covid	−0.90	−0.70
covid does not Granger-cause lelec	−1.56	−1.50
Hypothesis		
lt1 does not Granger-cause lgas	10.47***	13.23***
lgas does not Granger-cause lt1	5.68***	7.36***
lt2 does not Granger-cause lgas	3.04***	4.13***
lgas does not Granger-cause lt2	1	1.63
lren does not Granger-cause lgas	12.46***	15.66***
lgas does not Granger-cause lren	2***	2.86***
lelec does not Granger-cause lgas	3.29***	4.44***
lgas does not Granger-cause lelec	3.22***	4.35***
lgp does not Granger-cause lgas	3.88***	5.16***
lgas does not Granger-cause lgp	4.84***	6.33***
lep does not Granger-cause lgas	5.52***	7.17***
lgas does not Granger-cause lep	5.96***	7.71***
lp does not Granger-cause lgas	6.48***	8.34***
lgas does not Granger-cause lp	12.90***	16.21***
lgdp does not Granger-cause lgas	7.31***	9.36***
lgas does not Granger-cause lgdp	−0.80	−0.57
Lgas does not Granger-cause covid	0.86	1.46
covid does not Granger-cause lgas	−0.42	−0.11

Note: * refers to 10 %, ** is 5 %, and *** is 1 % significance level.

4. Discussion and policy implications

Our findings offer a comprehensive perspective on household energy consumption across EU countries. We employed various methodologies, including trend analysis and panel analysis encompassing both static and dynamic models. These approaches yield crucial insights into the trends in household energy consumption and the significant factors influencing it. Based on trend analysis Mann-Kendall test results for gas prices highlight a significant increasing trend in gas prices in most of the EU-24 countries except for Denmark. The highest increase recorded in Sweden in this regard, Colgan et al. (2023) [27] found that Europe incurred additional market costs ranging from €517 to €831 billion because of elevated prices between October 1, 2021, and December 31, 2022, with an estimated total of €643 billion. Meanwhile, Brodny & Tutak (2023) [93] showed that the Scandinavian countries demonstrate a strong level of energy security. These findings are valuable for informing the development of a new EU energy and climate strategy, particularly given the emerging geopolitical dynamics in the region. Osička & Černoch (2022) [94], In the realm of energy affairs, the EU holds the essential resources, expertise, and determination needed to turn the crisis into an opportunity for advancement. However, without coordinated and effective management in the European response, there's a risk of worsening the situation, potentially triggering a political and legitimacy crisis.

Mann-Kendall test findings for gas usage across EU-24 countries reveal a mixed trend in natural gas consumption. Significant decreases are observed in countries like the Czech Republic (CZ) and Germany (GE) Which confirms the first hypothesis regarding the reduction in gas consumption. Conversely, Greece (GR) and Poland (PL) demonstrate strong increases in natural gas consumption that aligns with the third hypothesis that household energy consumption varies across different EU countries. The Mann-Kendall test analysis on electricity usage across EU-24 countries indicates a general increasing trend in usage, Sweden (SW) showing the most significant rise. Contrastingly, Bulgaria, Denmark and Germany experienced a decrease. However, the largest increase in electricity usage was recorded in France. The results are aligned with Hille (2023) [2] findings indicating that geopolitical uncertainties in supplier nations have contributed to the spread of renewable energy in Europe from 1991 to 2021. Meanwhile, Nikas et al. (2024) [8], reported that increasing domestic renewable energy production would necessitate significant investments, potentially placing financial strain on consumers. However, Prokhorov & Dreisbach (2022) [16] maintaining robust fiscal backing for renewables, auction design, and unchanged marginal cost bidding would progressively result in increased occurrences of negative prices in the foreseeable future.

In terms of panel analysis, in static model most of variables are significant which has effect on gas and electricity consumption among EU-24 countries, HDD and CDD both have positive effect on gas consumption, in more detail 1 percent increase in HDD and CDD are cause to 0.29 and 0.14 increase in gas consumption. Similarly, Borozan (2018) [46] and Iraganaboina & Eluru (2021) [95]. Electricity consumption as a rivalry energy has a negative effect on gas consumption. Meanwhile, electricity prices have a positive effect on gas consumption. Gas price has a most negative effect on gas consumption which is like findings of the Copiello & Gabrielli (2017) [49], Dilaver et al. (2014) [96] and Alberini & Gans (2011) [50]. The results also confirm the first hypothesis that rising gas and electricity prices significantly reduce household energy consumption in EU countries.

Population and GDP both have a positive effect on gas consumption which both cause increasing gas consumption. In terms of GDP results are different to Borozan (2018) [46]. In terms of electricity consumption, all variables except renewables are significant, HDD and CDD both have positive effects on electricity consumption. The results are like Fan et al. (2015) [97]. Gas consumption also has a negative effect on electricity consumption which represents both energies have a relationship with each other that align with Zakeri et al. (2022) [25], the energy transition has made natural gas the main electricity price setter in Europe. Electricity price also shows negative effect on electricity consumption among households in EU-24 countries like Borozan (2018) [46], Copiello & Gabrielli (2017) [49], Romero-Jordán & del Río (2022) [98] and Alberini et al. (2011) [50] Which result confirms the first hypothesis that rising prices lead to a decrease in household energy consumption in EU countries. Gas prices have a positive effect on electricity consumption. Population and GDP both have a positive effect on electricity consumption. In terms of GDP results are similar to Topolewski (2021) [99]. In order to population results are similar to Zaharia et al. (2019) [100]. Dynamic results for gas and electricity use, in terms of gas as a dependent variable, the results show HDD, CDD, gas price, electricity price, GDP and dummy variable (COVID-19) are significant in level of 1 and 5 percent. Meanwhile, in terms of electricity, CDD, gas consumption, gas price and dummy variable (COVID-19) are significant in dynamic models. Which COVID-19 result in the dynamic model confirms the second hypothesis that COVID-19 led to an increase in energy consumption (natural gas and electricity) in EU countries. According to our results both Electricity use and gas use after 2019 have decreased which is in line with previous studies Rokicki et al. (2023) [101] and Haxhimusa & Liebensteiner (2021) [47]. While, different to Rokicki et al. (2022) [102].

Contrary to previous research, which often focused on single crises or overlooked the regional context, our study addresses these gaps by incorporating the latest data up to 2022. Our research introduces several novel contributions and delivers comprehensive results. Our trend analysis presents a panoramic view for policymakers, spanning from 2000 to 2022, enabling a thorough understanding of energy consumption patterns and the impact of crises on these trends. Additionally, our panel analysis, utilizing both static and dynamic models, offer valuable insights into the factors influencing energy consumption across EU countries. By comparing the results of static and dynamic models, our study not only highlights the factors affecting energy consumption but also underscores the importance of considering temporal dynamics in policy formulation. These findings equip policymakers with valuable information to address energy security concerns at the regional level, facilitating informed decision-making and strategic interventions. Another key finding of our study is the interplay between gas consumption and electricity consumption, highlighting the significance of the transition to electrification. Our results underscore the role of natural gas prices in accelerating this shift, emphasizing the need to account for price dynamics in energy transition strategies. Regarding our results and studies have done since COVID-19 and geopolitical issues, some policies suggest based on crisis in different situation across world toward reduce dependency to fossil fuels and increase security in energy among EU-24 countries. Based on our results, innovation and energy efficiency plays a vital role in decreasing energy consumption. Ten years ago, amidst Japan's energy crisis, shopping malls opted to turn off escalators, factories reduced assembly line operations, and professional sports teams refrained from holding nighttime games to minimize the use of lighting [103]. Encouraging individuals to lower lighting levels and use stairs instead of elevators also contributed to reducing energy consumption [103]. Based on our findings, exploring various options for importing energy also plays a critical role in enhancing energy security among EU countries. The proportion of pipeline gas from Russia in EU imports declined from more than 40 % in 2021 to approximately 8 % in 2023. When considering both pipeline gas and LNG, Russia's share of total EU gas imports was below 15 %. In 2023, Norway and the United States emerged as the primary gas suppliers for Europe. Norway contributed nearly 30 % of all gas imports [104]. Speeding up to reach net zero emissions by 2030 also can accelerate regarding the crisis. The EU accelerated the adoption of renewable energy, achieving a record year for solar energy in 2022. With 41 GW of photovoltaic capacity installed, marking a 60 % increase from 2021's 26 GW. In May 2022, a milestone was reached as, for the first time, electricity generated from wind and solar power surpassed that from fossil fuels in the EU [105].

Collaborative efforts yielded positive results as gas prices in the EU significantly decreased by the end of 2022 and remained relatively steady throughout 2023. By December 2023, the cost of 1 MW/hour (MWh) of gas was €34, almost nine times lower than the peak crisis price of over €300/MWh. Furthermore, reduced reliance on Russia: The EU swiftly diversified its energy imports away from Russia, resulting in a decline in the overall share of Russian gas (including LNG and piped natural gas) in EU gas imports from 45 to 50 % in pre-crisis years to 15 %. Reduction in energy demand: EU nations collaborated to decrease energy demand, leading to an over 18 % decline in gas consumption in 2022 and 2023 compared to the previous five years. Enhanced security of supply: Gas storage facilities were filled to 95 % capacity before the winter of 2022–2023 and over 99 % capacity by October 2023, ensuring ample reserves ahead of each cold season [105]. Russia's invasion of Ukraine triggered a European energy crisis, prompting a study using various models to assess options for reducing reliance on Russian gas. The study highlights the trade-offs of replacing Russian gas with imports, boosting domestic energy production, and promoting energy efficiency. While importing gas from other sources may offer short-term cost benefits, it could hinder decarbonization efforts. Investing in renewable energy domestically requires significant financial input, while prioritizing energy efficiency offers potential for emission reduction at lower costs, albeit with risks of industry relocation [8].

According to our results, clean hydrogen is one of the key elements in reducing dependency on fossil fuels and increasing energy security among EU countries, which aligns with Saudi Arabia plans that renowned as the leading producer and exporter of clean hydrogen globally, is poised to spearhead the development of a novel sustainable energy resource, marking its third stride towards reducing CO_2 emissions. This substantial initiative is regarded as the most promising alternative to traditional fossil fuels [106]. However, Following the release of the REPowerEU plan in May 2022, the Commission reinforces the execution of the EU hydrogen strategy to bolster European aspirations for renewable hydrogen as a key energy transporter, aiming to reduce dependence on fossil fuel imports from Russia [107].

The implementation of the 5th PCI package by the European Commission, introduced in November 2021, is expected to significantly lower EU prices, particularly benefiting Eastern Member States reliant on a single external supplier. However, there's a risk of substantial investments becoming stranded assets in the long term due to stricter climate regulations. Additionally, uniform voluntary demand holds significant potential for price reduction, especially within Eastern Member States. Furthermore, while the establishment of European strategic gas reserves may offer temporary price alleviation, it may not be the most cost-effective solution. Nevertheless, security of supply concerns may outweigh potential negative economic outcomes [1].

5. Limitation and future research

This study is subject to a few limitations. Firstly, the availability of data for specific regional breakdowns is lacking. Moreover, the limitation of this study is the lack of complete data on household energy and gas consumption for all EU countries. Secondly, data on renewable energy prices and the distinction between different renewable energy sources were not accessible. Consequently, all renewable energy sources were grouped together as "renewables consumption". Another challenge in this study is the difficulty in isolating the individual effects of crises such as the COVID-19 pandemic and the Russia-Ukraine war on household energy consumption. Energy demand is influenced by multiple overlapping factors, including economic growth, policy interventions, climate conditions, and market fluctuations. While statistical methods help identify trends, attributing causality to specific events remains complex. Given these limitations, the study suggests avenues for further research. Future investigations could delve into specific renewable energy sources and their consumption patterns among households in EU countries, particularly in the context of energy security. Additionally, there is a need for more extensive work at the regional level within each EU country to gain deeper insights into energy consumption dynamics.

6. Conclusion

The study employed various methodologies, including trend analysis and panel analysis, to comprehend the effects of crises and factors affecting energy consumption in EU-24 countries. A comprehensive analysis including trends and economic analysis caused robust research findings that provide different perspectives in terms of energy consumption, regional planning and policy in the household sector among EU countries. The results highlighted the significant impact of energy prices as the most influential factor on gas and electricity consumption among EU countries. Additionally, COVID-19 as a dummy variable represents an increase in gas and electricity consumption during COVID time which is also observed in trend analysis. Other factors were found to have varying effects on energy consumption in the household sector across EU countries. The trends revealed considerable fluctuations in energy consumption and the factors influencing it among EU countries, despite common regulations in place. Referring to questions in the introduction section, the results represent the first question does a shock in electricity and natural gas prices lead to a decrease households energy consumption across EU countries? price shocks significantly impact energy consumption. The trend analysis shows a decrease in energy use after major crises, such as the COVID-19 pandemic and the Russia-Ukraine war, particularly in gas and electricity consumption. The static model confirms that gas prices reduce gas consumption (−2.17 %) and electricity prices lower electricity consumption (−0.205 %). These findings indicate that price shocks lead to decreased energy consumption in EU households. The second question is, do dynamic and static econometric models representing different results in analyzing the determinants of energy consumption in EU households? The static and dynamic models show differing results. While the static model highlights significant relationships, such as the negative effect of gas prices on consumption, the dynamic model accounts for time effects, offering a more nuanced understanding. For instance, the dynamic model reveals a smaller impact of gas prices (−0.11 %) on gas consumption over time compared to the static model (−2.17 %). Third question, what drives leading EU countries to increase energy security? Leading EU countries are driven to increase energy security by managing energy prices and diversifying energy sources. The results show that countries are focusing on balancing gas and electricity consumption, with investments in renewables and economic growth playing key roles. Price volatility, particularly due to crises, pushes countries to seek greater energy security by reducing dependency on imported energy and increasing renewable energy investments.

This suggests the necessity of implementing new regulations in the energy sector for households based on region-specific plans. It’s evident that while some countries possess a substantial potential for renewable energies, others lack access to such resources and are more dependent on energy imports. This underscores the importance of developing regulations that cannot solely rely on renewables and energy transition across Europe, as energy security issues persist. The EU regulations should be modified based on regional plans to address these disparities effectively. However, it’s worth noting that many countries have increased their investments in renewable energies following geopolitical issues. Nevertheless, the trends indicate a decrease in renewable energies in the majority of EU-24 countries, indicating the impact of climate change on energy production and consumption. This highlights the urgent need for comprehensive strategies to mitigate the effects of climate change and ensure sustainable energy practices across the European Union.

Author contributions

B.A. P.P and S.M; methodology. B.A, S.M and P.P; software. B.A., S. M, J.P and P.P; validation. B.A., S.M, P.P; formal analysis. B.A. SM, investigation, B.A and A.L; resources. B.A., S.M and J.P; Data curation. B.A and SM; writing original draft preparation. B.A, S.M, A.L and J.P; writing review and editing. B.A, S.M, J.P and A.L; visualization. B.A; supervision. B.A; project administration.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used [ChatGPT] in order to [English editing and grammar checks]. After using this tool/service, the author(s) reviewed and edited the content as needed and take full responsibility for the content of the publication.

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.

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Appendix A. Mann-Kendall’s test for Gas consumption GJ (Left) and Gas Price GJ (Right)

Series\Test	Kendall’s tau	p-value	Sen’s slope	Series\Test	Kendall’s tau	p-value	Sen’s slope
BG (Belgium)	−0.3597	0.0175	−773595.0360	BG	0.4466	0.0031	0.2550
BU (Bulgaria)	0.8893	<0.0001	190664.4092	BU	0.6522	<0.0001	0.3556
CZ (Czechia)	−0.5573	0.0002	−1083444.4035	CZ	0.6917	<0.0001	0.5278
DE (Denmark)	−0.6126	<0.0001	−260265.4440	DE	0.1383	0.3692	0.0919
GE (Germany)	−0.3248	0.0324	−4718911.5768	GE	0.4087	0.0070	0.2203
ES (Estonia)	0.6680	<0.0001	34957.5764	ES	0.6680	<0.0001	0.4066
IR (Ireland)	0.0593	0.7116	42423.7025	IR	0.7446	<0.0001	0.4951
GR (Greece)	0.8656	<0.0001	938108.3640	GR	0.0000	1.0000	0.0000
SP (Spain)	0.2964	0.0507	1351865.3850	SP	0.6917	<0.0001	0.4878
FR (France)	−0.4545	0.0026	−5385223.6509	FR	0.7233	<0.0001	0.4271
CR(Croatia)	−0.0435	0.7917	−37092.0574	CR	0.6495	<0.0001	0.2121
IT (Italy)	−0.0988	0.5262	−1494734.1200	IT	0.6733	<0.0001	0.3321
LA (Latvia)	0.4862	0.0013	56103.1200	LA	0.4308	0.0043	0.3380
LI (Lithuania)	0.6206	<0.0001	140078.0139	LI	0.4704	0.0018	0.2938
LU (Luxembourg)	0.6759	<0.0001	152947.0246	LU	0.4625	0.0022	0.2790
HU (Hungary)	−0.3755	0.0130	−1388775.5160	HU	0.1901	0.2142	0.1668

(*continued on next page*)

(*continued*)

Series\Test	Kendall's tau	p-value	Sen's slope	Series\Test	Kendall's tau	p-value	Sen's slope
NE (Netherlands)	−0.6126	<0.0001	−5306510.1796	NE	0.4071	0.0071	0.2611
AT (Austria)	0.2648	0.0813	367391.7000	AT	0.5889	<0.0001	0.3498
PL (Poland)	0.6759	<0.0001	1564348.9740	PL	0.5099	0.0007	0.2697
PO (Portugal)	0.7154	<0.0001	290699.9910	PO	0.3834	0.0112	0.2858
RO (Romania)	0.3439	0.0231	817380.5904	RO	0.6337	<0.0001	0.2111
SL (Slovenia)	0.4862	0.0013	71395.4070	SL	0.3992	0.0083	0.2525
SK (Slovakia)	−0.5573	0.0002	−987056.7080	SK	0.5178	0.0006	0.2882
SW (Sweden)	−0.5731	0.0001	−63761.7434	SW	0.8261	<0.0001	0.6806

Appendix B. Mann-Kendall's test for electricity use (Left) and electricity Price GJ (Right)

Series\Test	Kendall's tau	p-value	Sen's slope	Series\Test	Kendall's tau	p-value	Sen's slope
BG	−0.5652	0.0002	−444915.5355	BG	0.8103	<0.0001	1.3455
BU	0.7391	<0.0001	418581.0393	BU	0.9447	<0.0001	0.6655
CZ	0.5652	0.0002	227699.1180	CZ	0.7154	<0.0001	1.1473
DE	−0.1542	0.3156	−31424.2600	DE	0.4387	0.0037	0.3723
GE	−0.4071	0.0071	−1889994.7890	GE	0.6759	<0.0001	0.3854
ES	0.6838	<0.0001	86415.5520	ES	0.8498	<0.0001	0.9146
IR	0.5336	0.0004	271854.1575	IR	0.8317	<0.0001	1.9539
GR	0.2964	0.0507	348947.8491	GR	0.8656	<0.0001	1.1668
SP	0.6206	<0.0001	3439939.2923	SP	0.6653	<0.0001	1.7224
FR	0.6443	<0.0001	5590801.5120	FR	0.7793	<0.0001	0.5584
CR	0.1937	0.2049	58814.0730	CR	0.8024	<0.0001	0.6068
IT	0.1225	0.4282	346370.9734	IT	0.0198	0.9159	0.0357
LA	0.2569	0.0910	45118.2789	LA	0.7787	<0.0001	1.0418
LI	0.8577	<0.0001	229679.4744	LI	0.6891	<0.0001	0.7931
LU	0.5731	0.0001	28348.8228	LU	0.3676	0.0151	0.3712
HU	0.4704	0.0018	251775.8348	HU	0.0356	0.8327	0.0695
NE	0.3123	0.0394	258969.8620	NE	0.5465	0.0003	0.5851
AT	0.7391	<0.0001	513580.8000	AT	0.4625	0.0022	0.6771
PL	0.8972	<0.0001	1110604.5240	PL	0.3123	0.0394	0.3102
PO	0.3834	0.0112	385621.5198	PO	−0.1225	0.4282	−0.0899
RO	0.9526	<0.0001	1052589.4320	RO	0.8158	<0.0001	0.5438
SL	0.8577	<0.0001	147595.1670	SL	0.7312	<0.0001	0.5039
SK	0.2332	0.1256	120240.7092	SK	0.1779	0.2452	0.2622
SW	0.2806	0.0645	532473.4178	SW	0.7233	<0.0001	1.0539
Total	0.6443	<0.0001	13566515.1311				

Appendix C. Mann-Kendall's test for Renewables GJ (Left) and for GDP million Euro (Right)

Series\Test	Kendall's tau	p-value	Sen's slope	Series\Test	Kendall's tau	p-value	Sen's slope
BG	0.8182	<0.0001	1352788.5744	BG	0.9842	<0.0001	11452.7000
BU	0.6759	<0.0001	537698.1636	BU	0.9921	<0.0001	2477.7000
CZ	0.9921	<0.0001	2692840.9032	CZ	0.9051	<0.0001	7771.7154
DE	0.6126	<0.0001	1078535.9620	DE	0.9842	<0.0001	6962.8600
GE	0.7787	<0.0001	9495892.6740	GE	0.9763	<0.0001	74361.3333
ES	0.4704	0.0018	146847.1791	ES	0.9605	<0.0001	1114.4176
IR	0.9526	<0.0001	158979.7740	IR	0.8419	<0.0001	12496.7000
GR	0.5731	0.0001	462643.4934	GR	0.0119	0.9579	86.3833
SP	0.6047	<0.0001	659393.0880	SP	0.7708	<0.0001	24647.7273
FR	0.6759	<0.0001	6374792.8958	FR	0.9684	<0.0001	47408.2500
CR	−0.0277	0.8741	−8363.9382	CR	0.7787	<0.0001	1434.4800
IT	0.4466	0.0031	9509271.8260	IT	0.8735	<0.0001	24505.4167
LA	−0.6443	<0.0001	−687212.3803	LA	0.8972	<0.0001	1154.7684
LI	−0.2964	0.0507	−99750.5100	LI	0.9605	<0.0001	1873.5647
LU	0.6917	<0.0001	26270.5597	LU	0.9921	<0.0001	2252.7647
HU	0.4071	0.0071	1902944.7940	HU	0.8972	<0.0001	4103.5000
NE	0.9526	<0.0001	418489.6909	NE	0.9763	<0.0001	17226.1500
AT	0.6917	<0.0001	1430403.4728	AT	0.9763	<0.0001	9370.8667
PL	0.6838	<0.0001	2135630.8560	PL	0.9289	<0.0001	18554.5095
PO	−0.0435	0.7917	−54488.8760	PO	0.8340	<0.0001	3805.8667
RO	0.3755	0.0130	1350777.9800	RO	0.9447	<0.0001	9417.5133
SL	−0.0988	0.5262	−30580.3872	SL	0.9130	<0.0001	1338.0857
SK	0.5731	0.0001	1473136.0470	SK	0.9842	<0.0001	3803.2688
SW	0.4941	0.0011	701327.3790	SW	0.9209	<0.0001	12933.9000
Total	0.6957	<0.0001	44923654.4332				

Appendix D. Cross-sectional dependence results

Variable	CD-test	P-Value	Correlation
Ln gas	15.85***	0.00	0.19
Ln elec	30.65***	0.00	0.38
Ln t1	50.30***	0.00	0.63
Ln t2	28.61***	0.00	0.35
Ln ren	30.23***	0.00	0.37
Ln gp	62.68***	0.00	0.78
Ln ep	52.91***	0.00	0.66
Ln GDP	60.33***	0.00	0.75
Ln Pop	24.33***	0.00	0.44
d	79.67***	0.00	1

Note: * refers to 10 %, ** is 5 %, and *** is 1 % significance level.

Appendix E. VIF values of the Gas Consumption variables

Variables	VIF	1/VIF	Mean VIF
Ln t1	2.46	0.40	2.23
Ln t2	2.33	0.42	
Ln ren	2	0.49	
Ln gp	2.48	0.40	
Ln ep	2.80	0.35	
Ln GDP	2.48	0.40	
d	1.03	0.96	

Appendix F. VIF values of the Electricity consumption variables

Variables	VIF	1/VIF	Mean VIF
Ln t1	2.49	0.40	3.29
Ln t2	2.55	0.39	
Ln gas	4.70	0.21	
Ln ren	2.06	0.48	
Ln gp	4.35	0.22	
Ln ep	4.19	0.23	
Ln GDP	4.91	0.20	
d	1.04	0.96	

Appendix G. Results from unit root test

Variable	CIPS	Stationary Level
Ln gas	−2.33	I(1)
Ln elec	−1.99	I(0)
Ln t1	−4.07	I(1)
Ln t2	−4.57	I(1)
Ln ren	−2.22	I(0)
Ln gp	−2.31	I(1)
Ln ep	−2.23	I(0)
Ln GDP	−1.55	I(0)
Ln Pop	−0.69	I(0)
d	2.61	I(0)

Appendix H. Kao co-integration test results

Model	Modified Dickey-Fuller t		Dickey-Fuller t		Augmented Dickey-Fuller t		Unadjusted Modified Dickey-Fuller t		Unadjusted Dickey-Fuller t	
variables	Statistic	P-Value	Statistic	P-Value	Statistic	P-Value	Statistic	P-Value	Statistic	P-Value
Ln gas	−1.45	0.07	−7.89***	0.00	−5.44***	0.00	−2.62***	0.00	−8.44***	0.00
Ln elec	0.49	0.30	−0.81	0.20	−1.36	0.08	−3.62***	0.00	−3.56***	0.00

Note: * refers to 10 %, ** is 5 %, and *** is 1 % significance level.

Appendix I. Model selection tests for gas

Tests	Statistics	P-Value
Hausman (Between FE and RE)	116.91***	0.00
F-Limer (Between FE and PLS)	18.17***	0.00
Autocorrelation (Wooldridge)	45.36***	0.00
Heteroscedasticity (Wald)	24793.48*	0.00
Weak Cross-Sectional dependence (Pesaran)	6.72***	0.00
Final Model	FGLS	

Note: * refers to 10 %, ** is 5 %, and *** is 1 % significance level.

Appendix J. Model selection tests for electricity

Tests	Statistics	P-Value
Hausman (Between FE and RE)	85.11***	0.00
F-Limer (Between FE and PLS)	59.38***	0.00
Autocorrelation (Wooldridge)	35.33***	0.00
Heteroscedasticity (Wald)	2675.48*	0.00
Weak Cross-Sectional dependence (Pesaran)	6***	0.00
Final Model	FGLS	

Data availability

Data will be made available on request.

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