ADVANCING SUSTAINABLE DEVELOPMENT THROUGH GREEN ENERGY: TRIPLE BOTTOM LINE ANALYSIS OF 24 EUROPEAN COUNTRIES

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Abstract. This study examines the influence of renewable energy sources (RES) and energy-efficient consumption on sustainable development through the Triple Bottom Line (TBL) framework. Using data from 24 European countries over 12 years (2010–2021), correlation analyses and the Generalized Method of Moments (GMM) were used to assess final household energy consumption, RES investments, and the impact of RES consumption on indicators including gross domestic product (GDP), employment rates, energy efficiency and CO_2 emissions. The results reveal that RES investments have a positive impact on energy efficiency and GDP growth. However, while RES consumption is positively associated with economic growth, it negatively affects employment rates in medium term, underscoring the challenges of transitioning labour forces from non-renewable to renewable energy sectors. Additionally, final household energy consumption, combined with RES investments and consumption, enhances GDP and energy efficiency but also increases CO_2 emissions, emphasizing the need for improved household level energy efficiency measures. Accordingly, the study highlights the critical role of RES and rational energy practices in achieving sustainable development goals. It provides actionable recommendations for policymakers, such as promoting RES adoption, developing workforce retraining programs, implementing targeted household energy initiatives, and reinforcing regulatory frameworks to facilitate cleaner and more efficient energy transitions.
Keywords: *renewable energy sources, rational energy consumption, economic growth, social development, sustainability assessment*

Introduction

The rapid growth of the global economy and population has placed unprecedented pressure on the planet's resources and sustainability. Consequently, modern society faces a multitude of challenges, including poverty, hunger, environmental degradation, climate change, and global warming (United Nations, 2022). To address these pressing issues, international organizations such as the European Union (EU) and the United Nations (UN) have taken active roles in promoting sustainable development, focusing on the economic, social, and environmental dimensions.

The energy sector plays a pivotal role in this context due to its fundamental contribution to powering other sectors of the economy. As highlighted by Fetting (2020), the energy sector is critical for economic growth and development but is simultaneously the largest contributor to environmental pollution. According to the EU Green Deal report, the energy sector accounts for 78% of global greenhouse gas emissions, largely due to the continued reliance on non-renewable energy sources (Fetting, 2020).

Transitioning to renewable energy sources (RES) is widely regarded as a key strategy for accelerating sustainable development (Kaygusuz, 2012). Following the fact presented

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in EU Green Deal report, investments in renewable energy sources can significantly reduce greenhouse gas emissions by as much as 1,8 gigatons, and also it can significantly affect job growth, which leads to an increase in employment rates. Accordingly, renewable energy sector employed about 11,5 million people in 2019 worldwide, and projections are showing that this number could exceed 40 million by 2050 (Fetting, 2020).

In addition, renewable energy sources, which include hydropower, wind, wave, tidal, solar energy, biogas, and biomass can represent unlimited sources of domestic energy for each country (European Commission, 2022). Their use can significantly contribute to reducing the country's dependence on imported gas and other types of fuels and energy prone to frequent price changes and uncertainty in supply. However, despite the numerous benefits of investing in RES, the renewable energy transition is expected to cause a short-term decline in jobs within the non-renewable energy sector, rising legitimate socio-economic concerns (OECD, 2020).

While previous studies have extensively examined the relationship between renewable energy adoption and economic or environmental sustainability, research that simultaneously integrates economic, social, and environmental dimensions remains limited. For instance, studies by Nițescu and Murgu (2022) and Ozturk et al. (2022) have primarily focused on either the economic benefits of renewable energy or its environmental impact, often neglecting the broader implications for social well-being. Additionally, existing literature tends to emphasize individual country analyses or regional trends rather than offering a comparative cross-national assessment that captures variations in renewable energy adoption and its impact on sustainability across different economic and policy contexts.

To bridge this gap, this paper adopts a holistic approach by applying the Triple Bottom Line (TBL) framework to assess the impact of renewable energy on sustainable development across 24 European countries. The TBL framework enables a comprehensive evaluation by integrating economic, social, and environmental dimensions, thus providing a more nuanced understanding of the role of green energy in achieving sustainability. Therefore, this research seeks to address the following key questions:

- How does the adoption of renewable energy sources influence economic growth across European countries?
- What is the impact of renewable energy transition on social sustainability, particularly in terms of employment?
- To what extent does the expansion of renewable energy contribute to environmental sustainability by reducing carbon emissions and increasing energy efficiency?

The primary objective of this study is to empirically evaluate the role of renewable energy in advancing sustainable development by applying the Triple Bottom Line approach. By conducting a cross-national analysis of 24 European countries, this research aims to provide policymakers and stakeholders with valuable insights into how green energy transition can drive economic prosperity, social well-being, and environmental protection in a balanced manner. In doing so, this study contributes to the existing body of knowledge by offering a more integrative perspective on the sustainability implications of renewable energy adoption.

Review of literature

Due to the increasing importance and focus on sustainable development and green transition, a large number of studies and scientific papers have been conducted on these

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topics (Østergaard et al., 2022). While many studies have examined the economic and environmental impacts of green energy, significant gaps remain in the integration of social aspects and the use of Triple Bottom Line (TBL) framework in this context. Most existing research focuses on individual dimensions, with limited exploration of the interconnections and synergistic effects among economic, social, and environmental factors. Given the pressing challenges of climate change, the energy transition, and the need for sustainable development, a more holistic understanding of these dynamics is essential. The following sections provide a detailed explanation of TBL model, followed by a literature review on the economic, social, and environmental effects of renewable energy adoption and energy consumption practices.

Sustainability assessment trough Triple Bottom Line model

In recent years, sustainability has become an increasingly common goal for businesses, nonprofits, and governments, but measuring an entity's sustainability or sustainable growth poses significant challenges. One approach to addressing this challenge is through sustainability assessments that provide guidance for decision-making processes that strengthen the sustainability of the system (Bond et al., 2012; Ghosh et al., 2021).

Sustainability assessment is defined as a process that informs decision-making to achieve greater system sustainability (Bond et al., 2012). According to the same authors, these assessments are often equated with terms like sustainability appraisal, sustainability impact assessment, and integrated assessment. Additionally, they are sometimes referred to as the "third generation of impact analysis" due to their integration of environmental and strategic impact considerations. Among various conceptual models developed for this purpose, the Triple Bottom Line (TBL) model is the simplest and most widely used framework, making it the focus of this paper (Bond et al., 2012; Ghosh et al., 2021).

The Triple Bottom Line (TBL) model is a framework for assessing the sustainability of a particular system that could be applied at both the micro and macroeconomic levels. Therefore, this model is used to assess the sustainability of both countries and companies due to its simplicity (Ghosh et al., 2021; Topor et al., 2022). When assessing sustainability, this model recommends analysing the performance and impact of an entity according to indicators that are grouped into the three areas, which are also called dimensions or pillars in theory (Elkington, 1997). However, a definitive list of indicators for this model has not yet been established, although numerous authors, such as Slaper and Hall (2011), have been working to address this issue by proposing more complete lists.

Accordingly, TBL model consists of three pillars named economic, social and environmental pillar. Following the work of Hammer and Pivo (2017), Slaper and Hall (2011), Li et al. (2022) and Nițescu and Murgu (2022), economic pillar refers to a financial or economic performance, including indicators such as gross domestic product (GDP), trade balances, personal income and sector-specific contributions to GDP. Social pillar focuses on an entity's impact on society and general social well-being, using measures such as employment rates, relative poverty, access to education, health-adjusted life expectancy, and labour force participation rates (Norman and MacDonald, 2004; Miller et al., 2007; Slaper and Hall, 2011). Finally, environmental pillar addresses an entity’s impact on the natural environment and its ecological footprint, considering metrics like carbon emissions, energy efficiency, energy and fuel consumption, waste management practices, and land-use changes (Jamali, 2006; Slaper and Hall, 2011; Schulz and Flanigan, 2016; Zaharia et al., 2019). *Table 1* consolidates these indicators

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providing a reference. This list is created based on the presented literature review for measuring sustainable development at the national level using the TBL framework.

Table 1. *List of indicators for measuring the sustainability trough TBL framework*

Triple Bottom Line pillars	Indicators	Authors
Economic pillar	Gross Domestic Product (GDP) Personal income Median household income Trade balances Foreign investments Sectoral contribution to GDP	Hammer and Pivo (2017) Li et al. (2022) Nițescu and Murgu (2022) Slaper and Hall (2011)
Social pillar	Employment rates Relative poverty Average commute time Female labour force rate Healthy life expectancy Access to education Violent crimes per capita	Miller et al. (2007) Norman and MacDonald (2004) Slaper and Hall (2011)
Environmental pillar	Carbon footprints Energy and fuel consumption Energy efficiency Change in land use/land cover Emission of greenhouse gases Solid and hazardous waste management	Jamali (2006) Schulz and Flanigan (2016) Slaper and Hall (2011) Zaharia et al. (2019)

In summary, the Triple Bottom Line (TBL) model, originally introduced by Elkington (1997) and later refined by scholars such as Svensson et al. (2018), Agrawal et al. (2016) and Topor et al. (2022) remains a widely recognized framework for evaluating sustainability. The appeal of this model lies in its simplicity and comprehensiveness that have contribute to its growing use in both academic research and practical applications. However, as it was stated earlier, TBL model's key disadvantage is that there is no defined list of indicators that will best measure sustainability. For this research, GDP, employment rate, energy efficiency and CO_2 emissions were selected as key indicators to measure economic, social, and environmental sustainability, respectively. This approach aligns with methodologies employed in prior studies established by authors Herding et al. (2021), Li et al. (2022), Nițescu and Murgu (2022) and Bei and Wang (2023), which also have explored the relationship between renewable energy, rational energy consumption and their impact on sustainable development of a country.

Economic footprint of renewable sources and rational energy consumption

The reviewed literature underscores the substantial economic impacts associated with the adoption of renewable energy and rational energy consumption. However, these investments are inherently time sensitive, characterized by long-term outcomes and associated risks (Popa et al., 2022).

Shifting to renewable energy and optimizing energy usage hold significant potential to lower energy costs, combat climate change, and generate employment in the green economy. This, in turn, can positively influence key economic indicators such as GDP and export performance (Nițescu and Murgu, 2022). Carley et al. (2011) highlight renewable energy investments as a driver of "Energy-based economic development,"

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noting that beyond their environmental benefits, these initiatives yield economic advantages, including cost reductions and decreased reliance on external energy imports.

While there is broad scientific consensus regarding the long-term economic benefits of renewable energy investments and rational consumption, the short-term effects remain a topic of debate. For instance, Sharma et al. (2021), as well as Ozturk et al. (2022), argue that renewable energy adoption adversely impacts economic growth in the short term but yields positive effects in the long run. In contrast to these findings, Nițescu and Murgu (2022) have proven the positive impact of renewable sources use on economic development in both the short and long term. In addition, other studies like those conducted by Carley et al. (2011), Șoavă et al. (2018), Marinaș et al. (2018), and Sahlian et al. (2021) also confirm the positive link between renewable energy, efficient energy use, and economic growth without specifying its temporal context.

On the other hand, the contribution of renewable energy sources and rational energy consumption to economic and business growth has not been sufficiently researched in the microeconomic context, or in the other words, at the level of business organizations. This lack of scientific research further influences the increased caution of business organization managers who are resistant to investments in the green development of their companies due to the high costs and uncertain long-term effects of such investments (Oliveira and Moutinho, 2021). Governments, therefore, are crucial in facilitating this transition by creating regulatory frameworks and offering financial and educational incentives to promote sustainable practices in the private sector which can further accelerate the achievement of the set sustainable development goals (Popa et al., 2022).

Finally, based on presented literature review on the economic benefits of renewable energy and rational energy consumption, it can be concluded that there is scientific consensus about positive macroeconomic impact of green investments in the energy sector. To ensure such outcomes, it is necessary to involve the government, citizens, the private sector and academia in the overall process in order to ensure the necessary conditions for a successful green transition.

Social footprint of using renewable sources and rational energy consumption

Beyond their economic advantages, investment in renewable energy and rational energy use generate numerous social benefits that complement their contribution to sustainability. The social benefits arising from increased investment in renewable energy and energy rationalisation include, among others, new jobs creation, the growth of society innovation potential, the strengthening of research and development (R&D) activities, the reduction of living costs and the improvement of general public health (Kumar, 2020).

Promoting greater use of renewable energy and rational household energy consumption, as already mentioned, accelerates the creation of employment opportunities and ensures the development of emerging industries (Khribich et al., 2021). According to the same source, reducing energy costs and providing new jobs can contribute to reducing poverty and improving social well-being. Additionally, this fact is supported by the impact of using renewable energy sources on reducing pollution, which further contributes to improving public health (Khribich et al., 2021). However, although such initiatives affect the growth of new jobs in the renewable energy sector, they also cause simultaneous effect on an employment decrease in the non-renewable energy sector. To avoid challenges during the green energy transition, it is crucial to implement changes gradually and in a well-planned manner. Governments, along with academic institutions,

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can significantly contribute to this process by offering workforce retraining and support for those affected (OECD, 2020).

Another important social benefit of investing in renewable energy and promoting efficient energy use is that it fosters innovation and speeds up research and development (R&D) efforts. These initiatives focus on creating advanced techniques and products that reduce energy consumption and enhance the efficiency of renewable energy applications (Nițescu and Murgu, 2022). Thus, beyond generating new jobs and lowering living expenses, investments in green energy can also be instrumental in developing a knowledge-based society (Wong et al., 2013).

Moreover, the shift towards renewable energy and the optimization of energy use in households boosts energy independence and help mitigate the electricity risks by reducing dependence on fossil fuels and harmful energy sources, as well as on external suppliers (Chu and Majumdar, 2012). Given the significance of energy security, particularly in today's world where geopolitical issues and energy independence are crucial for national stability and social welfare, renewable energy sources and efficient energy consumption highlight their social relevance (European Commission, 2022). In addition to enhancing security and well-being, the green transition can also promote greater social inclusion, fostering strong social cohesion and a sense of collective responsibility (Kumar, 2020).

Finally, it is worth noting that empirical research, such as that conducted by Khribich et al. (2021), underscores a strong correlation between the adoption of green energy and improvements in the Social Development Index. Their research results underscore a positive correlation between increased renewable energy utilization and enhancements in social development indicators which uncompromisingly unites and confirms the fact of their importance for a society. Based on this evidence and the arguments presented, it is clear that RES initiatives and rational energy consumption significantly and positively influence social development.

Environmental footprint of renewable sources and rational energy consumption

The economic and social advancement of countries affects the rapid growth of their energy demand (Owusu and Asumadu-Sarkodie, 2016). Moreover, Ren and Guo (2022) reveled that urbanization, population size and wealth increase are positively associated with net carbon emissions. Despite the increasing insistence on sustainable development by governments, the research implemented by Marinas et al. (2018) highlights that European countries are still largely dependent on non-renewable energy sources. Out of the 29 analysed countries, 24 of them obtain over 60% of their energy from fossil fuels. It is important to note that even countries leading the way in the green transition, like Germany and the United Kingdom, still rely on non-renewable energy sources for over 80% of their energy needs (Marinas et al., 2018).

This dependence on fossil fuels significantly contributes to environmental pollution, particularly air pollution from greenhouse gas emissions, especially CO_2. According to the International Energy Agency (IEA), the energy sector produced approximately 36.3 billion tons of CO_2 emissions in 2021, which represents a 6% increase from 2020. Notably, coal-fired energy generation accounts for more than 40% of these emissions, highlighting the urgent need for change (IEA, 2022). The environmental consequences of fossil fuel consumption, such as global warming and worsening air quality, have serious implications for public health and overall well-being (Martins et al., 2019).

In contrast, embracing renewable energy and promoting efficient energy use can lead to significant environmental advantages, with the most prominent being the reduction of

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greenhouse gas emissions and climate change mitigation. Research by Biekša et al. (2021) and Wang et al. (2023) indicates that initiatives like investing in renewable energy infrastructure and upgrading old, inefficient buildings can greatly decrease these emissions. The United Nations Environment Programme (UNEP) backs these findings, estimating that such actions could cut global emissions by up to 70% by 2050 (UNEP, 2022).

However, while renewable energy sources help mitigate the negative environmental impacts of human activity, they are not without their own challenges. These challenges include the use of arable land and water resources, visual impacts on landscapes, potential risks to wildlife, and the environmental footprint linked to the construction and operation of renewable energy facilities (Azarpour et al., 2013). Additionally, the long-term sustainability of renewable energy is hindered by market failures, limited access to raw materials, lack of information, and the high carbon footprint of daily activities (Owusu and Asumadu-Sarkodie, 2016). On the other hand, rational household energy use poses minimal environmental risks but requires widespread behavioural and systemic changes to maximize its impact.

While the adoption of renewable energy sources and rational energy consumption entails certain environmental challenges, their long-term benefits far outweigh these drawbacks. Increased investments and use of renewable energy, as well as the promotion of energy efficiency, play a pivotal role in mitigating climate change, reducing greenhouse gas emissions, and enhancing ecological sustainability. Accordingly, public policies such as the European Union’s RePowerEU Plan and the Green Deal emphasize the critical role of these initiatives in shaping a sustainable energy future. Through strategic investments, technological innovation, and regulatory support, these frameworks facilitate the green transition by ensuring that environmental benefits are maximized while potential adverse effects are effectively managed.

Materials and methods

This research analysed the influence of three key exogenous variables, including Consumption from Renewable Energy Sources (RES Consumption), Final Household Energy Consumption (Final Energy Consumption), and Country Investments in Renewable Energy Sources (Investments in RES) on four sustainable development and macroeconomic indicators based on the Triple Bottom Line (TBL) model. The chosen indicators, reflecting environmental, economic, and social dimensions of sustainable development, included Energy Efficiency (EE), CO_2 Emissions (CO_2), Gross Domestic Product (GDP), Employment Rate (ER).

The first step in conducting the research data analysis was to determine the type and nature of the relationship between the variables and indicators. Correlation analysis was used for this purpose. After the dependencies between variables and indicators were determined, the findings were further refined by implementing a two-step system Generalized Method of Moments (GMM) estimator in order to develop models that more closely describe the type and nature of the relationship between variables and indicators. Instrumental variables were used to address the endogeneity problem, whose validity, including checking whether these variables are suitable and not linked to error terms, was tested using the Hansen test. Additionally, the Arellano-Bond test was checked for autocorrelation in the residuals, helping to identify any issues with the defined model’s dynamic structure. According to Wooldridge (2001) and Hall (2003), this methodological framework for data analysis provides a good basis for precise and valid analysis on the

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basis of which conclusions can be drawn. A similar approach was used by the authors Nițescu and Murgu (2022) to prove the economic impact of using energy generated from renewable sources.

In addition, in order to ensure the robustness of the results and facilitate comparison between variables and indicators that use different measurement units and scales, a transformation using natural logarithms was used. By using this approach, distributions variables and indicators were normalized, skewness was decreased, and analysis consistency was increased (Nițescu and Murgu, 2022). *Figure 1* presents the model of conducting research analysis, specifying the exogenous and endogenous variables used to obtain key research findings and conclusions.

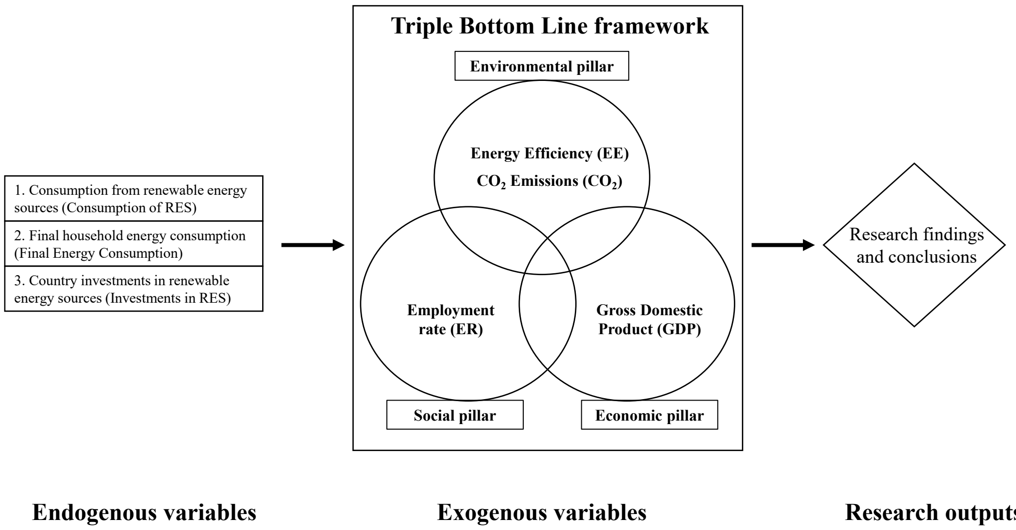

Figure 1. *List of exogenous and endogenous variables used in research*

A panel regression model was developed for each exogenous variable. The variables Consumption of RES and Investment in RES were selected to assess the impact and contribution of renewable energy sources to the sustainable development of countries. These variables were selected because they were used in previous research conducted by Bei and Wang (2023), Li et al. (2022), Nițescu and Murgu (2022), and Herding et al. (2021) who also investigated the relationship between green energy use and sustainable outcomes. Furthermore, following the work of Swan and Ugursal (2009), Zaharia et al. (2019), and Nițescu and Murgu (2022), who were engaged in proving the importance of energy consumption patterns in impacting the economic, social, and environmental elements of development, the Final Energy Consumption variable was also selected for the research with the aim to measure the impact of energy efficiency on selected indicators within the Triple Bottom Line framework.

The input data sets of the selected indicators and variables analysed through the described methodological framework were provided by trusted institutions such as The World Bank, Statista and Eurostat with the aim of ensuring their accuracy and reliability. Data sets for 24 European countries of different development levels were selected from the databases of the aforementioned institutions for a period of 12 years (2010-2021). All datasets used during the analyses are listed in *Table 2* with links and dates of their downloads.

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Table 2. *Information about datasets used in the research*

Dataset name	Source	Date of download
Share of energy from renewable sources	Eurostat (nrg_ind_ren)	May, 2024
Use of renewables for electricity - details	Eurostat (nrg_ind_ured)	
Complete energy balances	Eurostat (nrg_bal_c)	
Final energy consumption in households - quantities	Eurostat (nrg_d_hhq)	
Renewable energy investments worldwide	Statista	
GDP (current US$)	The World Bank	
Employment and activity by sex and age - annual data	Eurostat (lfsi_emp_a)	
Air emissions accounts by NACE Rev. 2 activity	Eurostat (env_ac_ainah_r2)	
Energy efficiency	Eurostat (nrg_ind_eff)	

Research sample

The research sample consisted of indicators and variables data sets for the countries Finland, Norway, Austria, Croatia, Denmark, Germany, Belgium, Netherlands, Spain, Portugal, France, Italy, Sweden, Hungary, Latvia, Poland, Estonia, Slovakia, Czechia, Greece, Romania, Bulgaria, Slovenia, and Serbia. This selection of countries represents a broad range of regions, including Western, Central, Eastern, Northern and Southern Europe reflecting the heterogeneous and highly diversified European context. *Figure 2* visually illustrates the selected countries to better understand the European coverage and regional diversity of the research sample.

Figure 2. *The countries whose data were analysed during the research*

It is important to note that the validity of the sample, in addition to its diversification due to the selection of the above-mentioned countries, is supported by the choice of a 12-year time frame (2010-2021). Authors Nițescu and Murgu (2022) state that time period

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of 12 years is long enough to be used for reliable conclusions. Additionally, period from 2010 to 2021 can be considered representative because it includes significant global and regional events such as the economic recession, the COVID-19 pandemic, and geopolitical tensions in Europe. Such a time period also ensures that the relationships between renewable energy initiatives and sustainable development indicators are analysed both in moments of stability and in moments of change, which reflects the characteristics of the modern business and social context.

Finally, based on the demonstrated representativeness of the research sample, the meticulous selection of variables confirmed by relevant scientific studies, and the use of reliable statistical models and tests, it can be concluded that the methodological framework is a strong basis for drawing valuable conclusions about how the use of renewable energy and rational energy consumption in households can affect the sustainable development of countries.

Results

Before presenting the results obtained by applying described methodological framework, it is useful to present the results of the trend analysis in renewable energy sources shares and CO_2 emissions among selected European countries. The aim of these analysis is to obtain a basic picture of the current state and the foundations of the green transition in Europe. Therefore, among European countries (*Figure 3*) it can be identified significant differences and regional disparities. For example, northern countries such as Finland, Norway and Sweden have relatively small emissions of CO_2 trough analysed period and had the highest shares of renewable energy sources in their energy mixes (*Figure 4*). The reason for this is the long-term implementation of green policies by their governments, but also the high awareness of society about the importance of sustainability and reducing the impact on the environment (CEER, 2023).

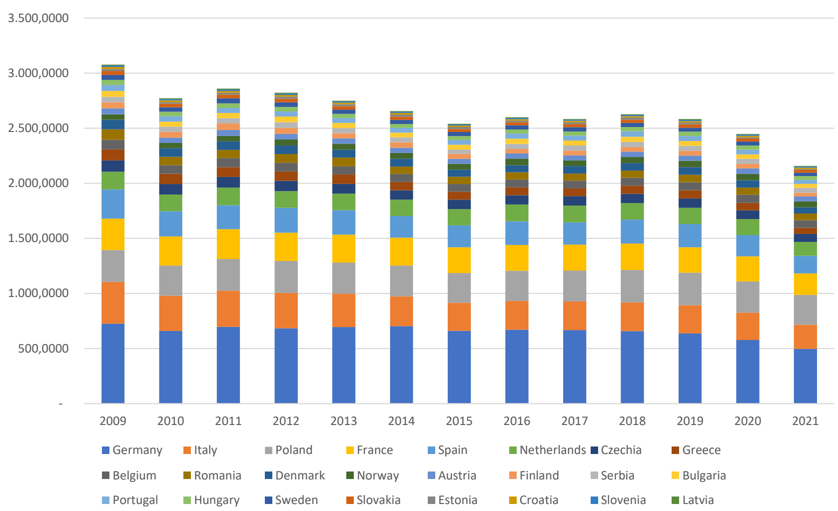

Figure 3. *CO_2 emissions of countries by year (in million tonnes)*

On the other hand, the situation in other parts of Europe is significantly different. Central and Western European countries such as Netherlands, France, Germany, Poland, Slovakia and the Czech Republic have difficulties in reducing their CO_2 emissions and

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increasing the share of renewable energy sources due to their historical dependence on fossil fuels and high level of industrialization. The situation is similar in Southern and Eastern Europe. Countries such as Italy, Estonia, Greece and Serbia have historically high CO_2 emissions per capita due to their industrial heritage and significant dependence on energy produced by coal-fired power plants (CEER, 2023).

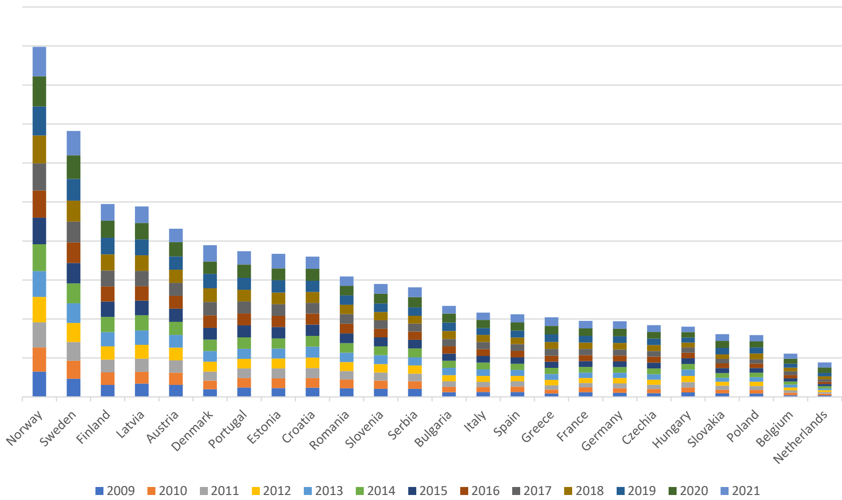

Figure 4. *Annual renewable energy sources shares by European countries (in per cents)*

Furthermore, it is important to state that wind and hydropower together account for more than two-thirds of renewable energy generation in Europe. Solar energy follows with 20.5%, while other renewable sources make up the remaining 12.8%. Hydropower dominates in most regions, except in countries with limited water resources, such as Belgium, Hungary, the Netherlands, Denmark, and Estonia. Wind energy is primarily concentrated in Western and Northern Europe, while solar energy is expanding rapidly across the continent but remains underdeveloped in the Baltic and Balkan regions. Other renewable sources play a smaller role, with Italy leading in geothermal energy and France and Spain in tidal energy.

Finally, it can be concluded that there is a strong motivation for improvement in green transition outcomes among most European countries, as evidenced by the declining trends in CO_2 emissions in recent years, but also by the rapid growth in the use of different green energy sources. These trends show that measures aimed at the energy transition are succeeding, which enhance energy security and sustainability while also assisting in the reduction of harmful emissions (CEER, 2023).

After conducting the trend analysis, the conclusions can be further deepened by applying advanced statistical methods such as panel regressions with the aim of showing the use of renewable energy and rational energy consumption in households contribution to the sustainable development of countries. The dataset for this phase of research analysis comprises 336 observations collected across 24 countries over the period from 2010 to 2021. The panel data is strongly balanced, ensuring that data is available for all 12 years for each country. This characteristic enhances the reliability of the GMM estimations by minimizing issues related to missing data. The correlation analysis (*Table 3*) identified significant relationships among most of the factors, further supporting the robustness of the analysis.

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Table 3. *Correlation analysis of variables*

	Cons. RES	FEC	Inv. RES	EE	GDP	ER	CO_2
Consumption of RES (Cons. RES)	1						
Final Energy Consumption (FEC)	0.212**	1					
Investments in RES (Inv. RES)	0.761**	0.209**	1				
Energy Efficiency (EE)	0.649**	0.257**	0.845**	1			
Gross domestic product (GDP)	0.787**	0.274**	0.918**	0.934**	1		
Employment Rate (ER)	-0.076	-0.025	0.130*	0.099	0.111*	1	
CO_2 emissions (CO_2)	0.723**	0.565**	0.815**	0.794**	0.895**	0.054	1

*significance at the level 0.05; **significance at the level 0.01

The correlation analysis revealed that factors such as Energy Efficiency (EE), Gross Domestic Product (GDP), Investments in Renewable Energy Sources (RES), and CO_2 Emissions are highly correlated. For instance, EE and GDP exhibit a strong correlation of 0,93, while Investments in RES and GDP correlate at 0.92. Similarly, CO_2 Emissions and GDP show a correlation of 0,89. Additionally, Consumption of RES demonstrates high correlations with both GDP (0,79) and CO_2 Emissions (0,72). In contrast, Employment Rate (ER) displays relatively weak correlations with economic and environmental variables like EE, GDP, and CO_2 Emissions. Finally, Final Energy Consumption shows weaker correlations with the other variables, indicating that its effects might be more isolated compared to the other exogenous variables analysed.

Consequently, following the correlation analysis, the second step in the research was applying of the Generalized Method of Moments (GMM) to examine the factors across four panel regression models. The results of this analysis are presented in *Figure 5*.

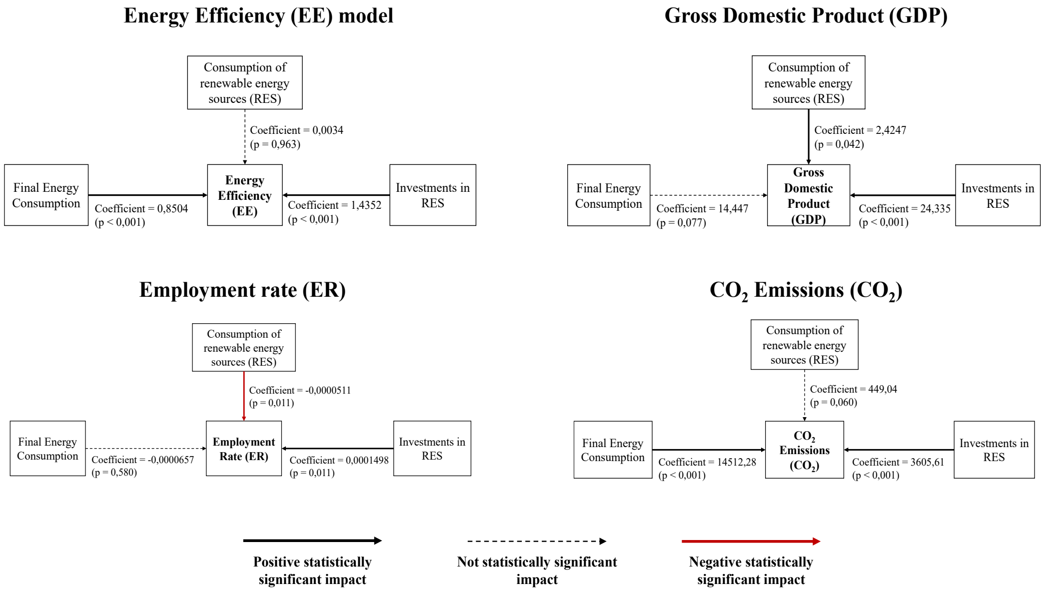

Figure 5. *GMM panel regression results*

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In the Energy Efficiency model, Consumption of RES does not exhibit a statistically significant impact on energy efficiency, as indicated by a coefficient of 0,0034 ($p = 0,963$). However, Final Energy Consumption demonstrates a robust positive effect on energy efficiency, with a coefficient of 0,8504 ($p < 0,001$). This suggests that while RES consumption may contribute to other aspects of sustainability, it does not directly enhance energy efficiency within the context of this model. In contrast, these findings also reveal the critical role of final household energy consumption optimization in driving improvements in energy efficiency which means that policy interventions focused on managing final energy consumption could be more effective in enhancing energy efficiency compared to those solely emphasizing RES consumption.

Additionally, Investments in RES show a highly significant positive effect on energy efficiency, with a coefficient of 1,4352 ($p < 0,001$), emphasizing the critical role of financial commitments toward renewable energy infrastructure in enhancing energy efficiency. This finding highlights the importance of targeted investments in renewable energy as a key driver for improving energy efficiency. While overall consumption patterns may not directly influence efficiency, a focus on renewable energy-related expenditures appears to yield measurable gains. Policymakers could use these insights to prioritize subsidies or incentives for renewable energy investments to optimize energy efficiency at a macroeconomic level.

In the GDP model, Consumption of RES has a statistically significant positive impact on GDP, with a coefficient of 2,4247 ($p = 0,042$). Final Energy Consumption also exhibits a positive effect on GDP, although only marginally significant (coef = 14,4472, $p = 0,077$). In contrast, Investments in RES demonstrate a strong and highly significant positive effect on GDP, with a coefficient of 24,3346 ($p < 0,001$). These results suggest that investments in renewable energy are impactful factor driving GDP growth. Consumption of renewable energy also plays a supportive role, indicating that integrating renewables into the economy has broader economic benefits. These findings underline the dual value of renewable energy as both an environmental solution and a driver of economic development. Encouraging greater investment in renewables could stimulate long-term economic growth while transitioning to a more sustainable energy system.

In the Employment Rate model, Consumption of RES is associated with a small but statistically significant negative effect on employment, with a coefficient of -0,0000511 ($p = 0,011$). Meanwhile, Final Energy Consumption does not significantly influence employment (coef = -0,0000657, $p = 0,580$). On the other hand, Investments in RES have a positive and significant effect on employment, with a coefficient of 0,0001498 ($p = 0,011$). This slight negative effect of renewable energy consumption on employment could reflect sectoral shifts or temporary disruptions as industries adapt to cleaner energy technologies. However, the positive influence of renewable energy investments on employment highlights job creation in construction, technology, and maintenance related to renewable energy projects. These results suggest a need for workforce reskilling programs to mitigate the short-term negative impacts of transitioning to renewable energy while capitalizing on long-term job opportunities in the sector.

In the CO_2 Emissions model, Consumption of RES has a marginally significant positive impact on CO_2 emissions (coef = 449,04, $p = 0,060$), while Final Energy Consumption has a significant positive effect, with a coefficient of 14512,28 ($p < 0,001$). Moreover, Investments in RES also significantly increase CO_2 emissions, with a coefficient of 3605,61 ($p < 0,001$). Contrary to expectations, both renewable energy consumption and investments appear to contribute to higher CO_2 emissions in the short

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term. This paradox may stem from emissions associated with the manufacturing, installation, and transportation of renewable energy technologies. These findings highlight the transitional challenges of adopting renewable energy. Policymakers should address this by encouraging cleaner production practices within renewable energy supply chains and considering lifecycle emissions in renewable energy policies.

For each of the presented models, the Hansen test of overidentifying restrictions was used to check the validity of the instruments. Across all models, the Hansen test results show that the instruments used are valid, with no evidence of instrument overfitting. The Arellano-Bond test results also confirm that there is no serial correlation in the residuals, validating the dynamic specification of the models. The results of conducted tests are shown in *Table 4*.

Table 4. *Results of Hasen and Arellano-Bond tests for each model*

Model	Hansen Test p-value	AR (1) Test p-value	AR (2) Test p-value
Energy Efficiency (EE)	0,820	0,368	0,343
Gross domestic product (GDP)	0,808	0,068	0,147
Employment Rate (ER)	0,701	0,054	0,112
CO_2 Emissions (CO_2)	0,786	0,144	0,128

Discussion

The findings of this study unequivocally highlight the substantial impact of renewable energy sources (RES) and rational energy consumption on the sustainable development of European countries, as assessed through the Triple Bottom Line (TBL) framework's economic, social, and environmental dimensions. This section synthesizes the results, contrasts them with prior literature, and discusses their implications for policymakers, industries, and society.

From an economic perspective, the results confirm that investments in RES significantly contribute to gross domestic product (GDP) growth, as demonstrated by the strong coefficient (24,33, $p < 0,001$). This aligns with Nițescu and Murgu (2022), who emphasized the economic benefits of green energy investments. The observed impact supports the positive effect of energy sector development on sustainable development, which is also proven in the work of Kaygusuz (2012), as well as the concept of "energy-based economic development" defined by Carley et al. (2011), which underscores the dual role of renewable energy in reducing costs and enhancing energy security. Additionally, as Chukwu et al. (2022) state, developing countries should focus their efforts on defining public policies in the field of renewable energy with the aim to influence their economic growth, and in case they do not have enough money to invest in RES, these countries could use this area as a important source for attracting foreign direct investment, as discussed in the work of Vukmirovic et al. (2021).

However, the marginally significant effect of RES consumption on GDP ($p = 0,042$) warrants further exploration to understand the nuanced mechanisms through which renewables influence economic performance. Unlike Sharma et al. (2021), who reported negative short-term effects of renewable energy adoption on economic growth, this study highlights long-term benefits, particularly for developed European economies.

The role of Final Energy Consumption presents a more complex narrative. While it exhibits a marginally significant positive relationship with GDP (coef. = 14,45,

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p = 0,077), its economic impact is less pronounced compared to RES investments. These results suggest that higher energy consumption by households can indirectly support economic activity, consistent with findings by Zaharia et al. (2019), which emphasize the importance of household energy use in sustaining domestic industries. However, overreliance on increased consumption, rather than efficiency improvements, risks undermining environmental goals, as will be discussed further.

In the social dimension, the results reveal a nuanced relationship between renewable energy and employment. The negative correlation between RES consumption and employment (-0,000051, p = 0.011) likely reflects sectoral shifts from fossil fuels to green energy, leading to temporary disruptions in the labour market. This finding is consistent with OECD (2020), which emphasized the importance of workforce reskilling programs to mitigate the social costs of the energy transition. Conversely, the positive and significant effect of RES investments on employment (p = 0,011) underscores the potential for job creation in technology, construction, and maintenance sectors. This corroborates Khribich et al. (2021), who highlighted the role of green energy in fostering innovation and poverty reduction. Policy interventions focused on retraining workers and promoting employment in emerging green sectors are essential for ensuring an equitable transition.

Final Energy Consumption, on the other hand, appears to have a limited direct influence on employment (coef. = -0,0000657, p = 0,580), suggesting its effects are more diffuse and harder to quantify in the short term. As Zaharia et al. (2019) emphasize, the relationship between household energy consumption and broader social outcomes is influenced by factors such as energy access, affordability, and the quality of regional infrastructure. These aspects vary significantly across European countries, highlighting the need for targeted interventions. Accordingly, policymakers should prioritize energy access for vulnerable populations to improve social equity and ensure that the benefits of energy transition are distributed fairly.

In terms of the environmental dimension, the analysis uncovers a paradoxical finding. Both Consumption of RES and Investments in RES are positively correlating with increased CO_2 emissions in the short term (p < 0,001). This unexpected outcome aligns with observations of Azarpour et al. (2013), who noted that the production, transportation, and installation of renewable energy infrastructure can generate substantial emissions initially. Furthermore, this outcome is also aligned with insights of Tang et al. (2022) who state that high energy intensity and economic growth are the main drivers of CO_2 emissions. These findings underscore the importance of adopting an investment lifecycle perspective when assessing the environmental impact of renewable energy. Nevertheless, the positive relationship between energy efficiency and RES consumption or investments reaffirms the critical role of rational energy use in mitigating emissions. This aligns with the United Nations Environment Programme (UNEP, 2022), which predicts that efficiency improvements and renewable energy investments could reduce global emissions by up to 70% by 2050.

By contrast, Final Energy Consumption shows a statistically significant and positive relationship with CO_2 emissions (coef. = 14512,28, p < 0,001) and Energy Efficiency (coef. = 0,8504, p < 0,001). This result indicates that higher household energy use, without corresponding efficiency measures, exacerbates environmental pressures. Similar conclusions were drawn by Nejat et al. (2015), who identified residential energy use as a major contributor to carbon emissions in developed countries. The findings suggest that promoting energy efficiency at the household level—through measures such as

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retrofitting, appliance upgrades, and consumer education—could significantly alleviate these pressures.

The implications of these findings are multifaceted and significantly support the goals, actions and implementation of the EU GreenDeal, as well as the RePower plan and other national and international public policies in the area of renewable energy and rational energy consumption. Therefore, policymakers should provide greater subsidies for renewable energy and rational energy consumption, paying attention to minimizing the environmental impact of RES capacity construction and energy efficiency measures. This approach ensures these initiatives fully support sustainable development and achieve their greatest impact what will further affect business organisations and other industry players to invest in research and development to enhance the efficiency and sustainability of green technologies. Additionally, governments should take into account the gradual reduction of jobs in the non-renewable energy sector during the transition process by providing and supporting education and retraining programs. Using these ideas in accordance with energy trends and risks via methods examined in research of Boltürk and Öztayşi (2018), European countries can improve their plans to make the green transition faster, more sustainable, and inclusive.

Conclusion

This study provides a comprehensive analysis of the causal relationships between renewable energy sources (RES), rational energy consumption, and sustainable development in European countries, utilizing the Triple Bottom Line (TBL) framework. The research findings show that RES and rational energy use significantly boost economic and social growth, especially by increasing GDP and creating jobs. However, the analysis also points out the short-term environmental and social impact, including a rise in CO_2 emissions and decrease in job creation linked to the consumption of RES. Obtained results align with existing literature while uncovering areas that require further examination, especially regarding the paradoxical environmental impacts of renewable energy sources.

From an economic and social perspective, investments in RES demonstrate a strong and positive influence on GDP and employment rates, confirming their pivotal role in fostering sustainable economic and social development. However, the marginal effect of RES consumption on GDP suggests the need for more integrative policies that simultaneously stimulate renewable energy adoption and economic resilience. The research also identifies employment rates correlating negatively with RES consumption as a key social challenge, emphasizing the importance of reskilling programs to mitigate temporary labour market disruptions in non-renewable sector and ensure a just transition to green energy.

The role of final household energy consumption represents another significant finding of the analysis. While the findings show a positive impact of final energy consumption on GDP and energy efficiency, the effects are less pronounced compared to RES investments. Higher household energy use supports economic activity indirectly, particularly through the stimulation of domestic industries. However, this increased final consumption also correlates with higher CO_2 emissions, emphasizing the need for measures at the household level in order to mitigate these environmentally impacts. Due to observed positive correlation with energy efficiency these measures should include interventions such as retrofitting buildings, upgrading appliances, and raising consumer

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awareness about energy conservation could balance the economic benefits of energy consumption with environmental sustainability goals.

In environmental context research findings further underscore the critical need for lifecycle assessments of renewable energy technologies to address transitional emissions effectively due to positive correlation between CO_2 and RES investments and consumptions. Policymakers must prioritize cleaner production processes and incentivize energy efficiency measures to achieve long-term environmental benefits. Additionally, targeted initiatives to optimize household energy use could alleviate pressures on both economic and environmental fronts.

Despite these research contributions, several limitations should be acknowledged. The research dataset is confined to European countries, which may limit the generalizability of the findings to other regions with differing economic, social, and environmental contexts. Furthermore, although the use of the TBL model offers a comprehensive overview of sustainable development, the small number of selected indicators in this research cannot fully reflect its complexity. Also, the focus of the analysis on macro-level trends may overlook microeconomic and regional dynamics that could influence outcomes at a more localized level, which could represent one of the directions for deepening the research. Lastly, the study also highlights the short-term transitional negative impacts of building renewable energy infrastructure, including emissions from producing and installing renewable technologies, what also requires further research to fully understand all long-term effects.

In conclusion, this research underscores the strategic importance of renewable energy and rational energy consumption in enhancing sustainable development. It offers practical guidelines for policymakers, such as encouraging investments in renewable energy, launching workforce retraining programs, creating targeted energy initiatives for households and strengthening promotional activities and other types of initiatives that will influence the faster adoption and development of renewable energy sources and connected technologies. These findings contribute to the advancement of the existing body of scientific literature, with clear implications for global energy sector, sustainable development and green transition policies.

Conflict of interest. The author has declared that there is no conflict of interests regarding the publication of this article.

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