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ENERGY STRUCTURE AND ECONOMIC GROWTH IN THE EU

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Abstract. This study analyses the relationship between energy structure, economic growth, and human development in the EU-27 during 2013–2023. Using panel regression models, it examines how conventional and renewable energy sources influence GDP growth, GDP per capita growth, and HDI. Results show that conventional energy continues to support economic growth, while renewable energy effects vary across technologies. Biomass and wind energy are generally linked to positive outcomes, whereas solar energy and renewable intensity display mixed effects. A higher share of renewables supports human development, while unemployment, poverty, and fossil fuel dependence negatively affect HDI, highlighting important policy implications.

1. Introduction

The energy sector is one of the most important and frequently discussed topics in economic policy, especially in Europe. The transition from fossil fuels to renewable energy is not only a long-term goal but also a current challenge for EU countries. Policies like the European Green Deal, REPowerEU, and the Net Zero by 2050 strategy show the European Union's commitment to building a sustainable economy while reducing the effects of climate change. In this context, it is important to understand how different energy sources—renewable and conventional—affect economic growth and human development.

Although many studies have analyzed the link between energy use and economic performance, some key gaps still remain. First, the results often differ depending on the type of energy and the country studied. Second, most research focuses only on economic indicators or environmental impact, without also looking at social aspects such as the Human Development Index. Third, few studies examine energy, climate, and economic factors together, especially in the context of the EU during the last decade of major policy changes and energy shocks.

This study fills those gaps by offering a complete and updated analysis of how renewable and conventional energy affect both GDP and HDI in the 27 EU countries between 2013 and 2023. It uses economic models to test several hypotheses based on existing literature and includes a wide range of variables: energy, climate, investment, education, and innovation.

The contribution of this paper is twofold. First, from a methodological point of view, it brings together many types of indicators into one model to give a more complete picture of how energy affects growth and well-being. Second, it offers one of the most recent and detailed analyses of how the energy mix is connected to development outcomes in the EU, including the effects of recent green policies and energy market changes.

Moreover, the paper looks at how the structure of energy use affects public spending, private investment, and macroeconomic performance. For example, although renewable energy often

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needs higher initial investment, it can reduce energy risks and bring long-term benefits to the economy and society. On the other hand, using fossil fuels may support short-term growth but comes with rising environmental costs and economic risks.

In conclusion, this study provides useful evidence for energy-related financial decisions and public investment strategies in the EU. The results are relevant for policymakers, especially in areas such as budget planning, sustainable infrastructure, and green investment.

2. Literature Review

In the following section, it will be presented the empirical studies that examine the relationship between renewable energy, non-renewable energy, and economic growth. The literature has paid particular attention to the link between energy consumption, both renewable and conventional, and economic performance. The findings differ considerably depending on the methodologies applied, the geographical context, and the period under analysis.

Most studies show that higher primary or total energy consumption is linked to higher economic growth. For the United States, changes in total, industrial and residential energy use have noticeable effects on GDP (Salari, Kelly, Doytch, & Javid, 2021). In Greece, economic growth is closely connected to rising energy demand (Huseynli, 2024). A similar relationship appears in MENA countries, where overall energy consumption supports long-term growth, even if short-term effects are limited (Belloumi & Aljazea, 2024). At a global level, total energy use remains an important driver of output in both developed and developing economies. Evidence from Mediterranean countries also shows that electricity consumption, often used as a measure of primary energy, moves together with GDP and even influences it in both directions (Zrelli, 2017).

Taken together, these studies suggest that primary energy consumption generally supports economic activity, which is consistent with the hypothesis.

According to the literature, renewable energy generally supports economic growth, although the magnitude of this effect varies across countries and technologies. In the EU, higher renewable energy production is associated with increased GDP per capita, while evidence from Bulgaria shows positive effects from both renewable energy consumption and renewable electricity generation activity (Armeanu, Vintila, & Gherghina, 2017), (Can & Korkmaz, 2019).

Studies from Indonesia and Malaysia also report positive impacts of renewable electricity and hydropower, though these effects tend to be weaker or more context-specific and depend on the pace of adjustment to changes in the energy mix (Heru, Ukhti, Arivina, & Ahmad, 2023), (Seriram, V. Zainuddin, Ahmad Hamidi, & Abdullah, 2024). Broader panel analyses confirm that renewable energy contributes to economic growth while strengthening energy security and complementing innovation and foreign investment (Hoa, Xuan, Thu, & Huong, 2024), (Yang, Namahoro, Wu, & Su, 2022), (Xie, Zhu, Hu, & Huang, 2023).

However, the growth-enhancing role of renewable energy is conditional. In OECD countries, positive effects are more likely under moderate political and financial risk, while in emerging economies outcomes depend strongly on policy support and technological development (Wang, Ali, Chen, & Xu, 2023). Evidence from the EU-25 further suggests that renewables not only foster economic growth but also improve overall well-being, with solar and wind energy showing particularly strong effects (Ostrowska, Kotlinski, & Markowski, 2024).

Across the literature, non-renewable energy remains a major driver of economic growth, particularly in countries where fossil fuels dominate the energy mix. Empirical evidence from the United States, Indonesia, Iran and other fossil-fuel-dependent economies shows that conventional energy use is closely linked to GDP growth, often with stronger and more stable effects than those observed for renewable sources (Salari, Kelly, Doytch, & Javid, 2021), (Aswadi, Jamal, Syahnur, & Nasir, 2023), (Mansouri, 2015).

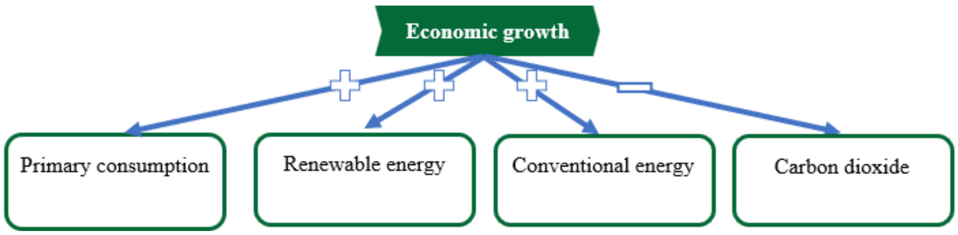

FIGURE 1. The Relationship Between Economic Growth, Energy Consumption and Carbon Emissions

Large cross-country studies further confirm that non-renewable energy contributes more strongly to economic growth in both developed and developing economies. In advanced countries, growth tends to drive fossil fuel consumption, while in developing economies the relationship is often bidirectional (Mohammadi, Saghaian, & Gharibi, 2023), (Ivanovski, Hailemariam, & Smyth, 2021). Similar conclusions are reported for the Visegrád countries, BRICS and South Africa, where fossil fuels continue to support output expansion, even as CO_2 emissions rise alongside economic activity (Supron & Myszczyszyn, 2023); (Banday & Aneja, 2019).

Overall, the literature consistently indicates that conventional energy remains an important pillar of economic growth, although its environmental costs and long-term sustainability pose increasing policy challenges. Across the studies reviewed, CO_2 emissions show a mixed but generally important relationship with economic growth. In many developing countries, higher emissions tend to accompany economic expansion, reflecting the strong reliance on non-renewable energy sources in the early stages of development (Turedi & Turedi, 2021). For several European countries, evidence suggests that CO_2 emissions and economic activity influence each other, particularly in economies where fossil fuels still play a major role (Asiedu, Hassan, & Bein, 2021). Research from the Visegrád group also indicates that CO_2 emissions can negatively affect growth, especially as countries begin shifting toward cleaner technologies, although in some cases emissions still appear to move in line with economic output (Supron & Myszczyszyn, 2023). Larger regional studies show similar patterns: in Northeast Asia, for example, non-renewable energy raises emissions while supporting growth, creating a trade-off between economic performance and environmental quality (Wang, Ali, Chen, & Xu, 2023). Overall, the literature suggests that CO_2 emissions often rise as economies grow, but their impact becomes more negative once countries reach higher levels of development, where environmental constraints and sustainability goals become more central to economic decisions.

The empirical evidence reviewed aligns with most of the hypotheses formulated in this study, although the strength and direction of the relationships vary across countries, time periods and types of energy sources.

3. METHODOLOGY

The methodology of this study is designed to empirically assess the multidimensional relationship between energy use, economic performance, and human development across EU-27 countries. Given the complex and interdependent nature of energy systems, socio-economic structures and environmental pressures, the methodological approach integrates a broad set of variables to capture these dynamics as accurately as possible. This chapter first formulates the research hypotheses grounded in the existing empirical literature, then describes the database and the construction of variables, and finally presents the econometric modelling strategy. By combining panel-data techniques with an extensive set of energy, climate, economic, social, and

TABLE 1. Summary of hypotheses and evidence from the literature

Hyp.	Statement	Support in Literature	Main Conclusion
H1	Primary energy consumption positively affects economic growth	Strongly supported	Higher total/primary energy use is consistently associated with higher GDP across regions and methodologies.
H2	Wind energy negatively affects economic growth	Partially supported	Renewable energy generally supports growth, but wind energy shows mixed or weaker effects in some EU contexts.
H3	Renewable energy (especially biomass) positively affects economic growth	Broadly supported	Biomass and renewables are generally linked to higher GDP, especially in emerging economies, though effects vary by technology.
H4	Conventional energy positively affects economic growth	Strongly supported	Fossil fuels remain key drivers of production and output, particularly in fossil-dependent economies.
H5	CO_2 emissions affect economic growth	Supported	Emissions often rise with growth in early stages but may constrain growth in advanced economies.
H6	Renewable energy positively affects HDI	Supported	Higher renewable shares are associated with improved well-being, environmental quality, and human development outcomes.

Source: Own analysis.

environmental indicators, the study aims to isolate the specific channels through which renewable and conventional energy sources influence both economic growth and human development. The methodological framework thus ensures coherence between the theoretical foundations established in the literature review and the empirical investigation that follows.

3.1. **Research Hypotheses.** To establish a coherent analytical framework, the study begins by examining how energy consumption shapes economic performance. Since energy remains a fundamental input for production and overall economic activity, the first hypothesis is defined as follows:

Hypothesis 1: Primary energy consumption has a positive effect on economic growth.

The role of renewable energy has gained increasing attention in recent years, not only for its environmental benefits but also for its potential contribution to long-term development. Considering the structural differences across renewable energy sources, the study proposes the following hypotheses:

Hypothesis 2: Wind energy exerts a negative influence on economic growth.

Hypothesis 3: Renewable energy, particularly biomass-based sources, supports economic growth per capita.

Conventional energy continues to play a central part in the energy systems of many economies, which motivates the formulation of the next hypothesis:

Hypothesis 4: Conventional energy contributes positively to economic growth.

Given the environmental implications of energy use, it is also important to explore how emissions affect economic outcomes. Therefore, the study tests the following hypothesis:

Hypothesis 5: Carbon dioxide emissions negatively affect economic growth.

Finally, to capture the broader socio-economic dimension of the energy transition, the study investigates whether renewable energy can foster improvements in human well-being:

Hypothesis 6: Renewable energy has a positive impact on the Human Development Index (HDI).

3.2. **Database and Variables.** The study was conducted for the EU-27 countries (Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, and Sweden). Data were collected from Eurostat, the Climate Policy Database, and the World Bank, covering the maximum available period 2013–2023. This period was selected because it represents the longest continuous interval for which harmonized, comparable, and complete data are available across all member states. Although certain indicators exist prior to 2013, many of the variables used in this study—particularly those related to renewable energy subcomponents, sector-specific energy consumption, environmental indicators and social or innovation measures—are systematically reported only from 2013 onward. Earlier years display methodological breaks or substantial missing observations that would undermine the reliability of panel estimations. Therefore, restricting the analysis to 2013–2023 ensures data consistency and robustness, while aligning with the period in which EU energy and climate policies became more extensively monitored and standardized.

Three dependent variables were selected: the growth rate of real GDP, the growth rate of GDP per capita, and the Human Development Index (HDI).

Renewable energy variables: share of renewable energy in total gross final consumption, share of renewable energy in transport, share of renewable energy in the energy industry, share of renewable energy in heating and cooling, solar energy production, wind energy production, hydropower generation, solid biomass energy, biogas energy, geothermal energy, renewable energy consumption, and biofuels in industry.

Non-renewable energy variables: total primary energy consumption, natural gas production, lignite production, diesel oil production, fuel oil production, bituminous coal production, nuclear energy production, natural gas consumption in industry, oil products consumption in industry, non-renewable waste consumption in industry, total energy consumption in industry, residential energy consumption, economy's dependence on energy imports.

Climate variables: annual average temperature, total annual precipitation.

Economic variables: general government expenditure by function, government expenditure on environmental protection, trade openness, foreign direct investment (net inflows and outflows), gross fixed capital formation.

Education variables: population by educational attainment, sex, and age.

Labor force variables: unemployment rate, GINI coefficient, employment rate, labor activity by sex and age group.

Innovation variables: research and development expenditure.

Environmental variables: resource productivity, greenhouse gas emissions from the energy sector, total greenhouse gas emissions (index relative to 1990), CO_2 emissions.

Social variables: risk-of-poverty rate before social transfers, population.

These variables were selected in order to capture as accurately as possible the multiple and interdependent influences of energy, economic, social, and environmental factors on economic development, in line with those used in the studies reviewed in the literature section. It should also be noted that, due to the lack of available data for several countries on geothermal, nuclear, lignite, and bituminous coal production, these variables were not included in the regression equations.

Table 2 below provides a list of the variables, their abbreviations used in the study, their description, the time period for which data were available, and the source.

Table 2. Description of variables

Name	Abbreviations	Description	Period	Source
		Dependent variables		
Human Development Index	HDI	Measures overall human development through life expectancy, education, and standard of living. Higher scores indicate better development.	2013-2023	Eurostat
Real GDP growth rate	GDP_GR	The calculation of the annual GDP growth rate is intended to enable comparisons of economic development dynamics both over time and between economies of varied sizes.	2013-2023	Eurostat
GDP per capita growth rate	GDP_GV	The GDP per capita growth rate reflects the evolution over time of economic output relative to population, providing a picture of individual economic progress.	2013-2023	Eurostat
		Energy		
Primary energy consumption	PRIM_CON	Natural logarithm of the total amount of energy required in an economy, including end-user consumption and losses in energy production, transformation, and distribution.	2013-2023	Eurostat
Residential energy consumption	CON_REZI	The natural logarithm of final energy consumption in households refers to all energy used in homes for domestic activities, including energy produced at home.	2013-2023	Eurostat
Dependence on energy imports	DEP_IMP	The percentage of an economy's total energy needs that is covered by net energy imports	2013-2023	Eurostat
Total industrial energy consumption	CON_INDT	Natural logarithm of energy used directly by industrial sectors (according to NACE classification), excluding energy transformed into other forms of energy, which is reported separately in the energy transformation sector.	2013-2023	Eurostat
Natural gas energy production GWh	PRD_NAGAZ	Natural logarithm of the amount of electrical and/or thermal energy obtained by burning natural gas, expressed in gigawatt-hours.	2013-2023	Eurostat
Production of lignite energy GWh	PRD_LIGN	Brown coal with low carbon content and lower calorific value than bituminous coal, used mainly for electricity generation in thermal power plants; due to lack of data, used only for graphs.	2013-2023	Eurostat
Diesel energy production GWh	PRD_DISEL	The natural logarithm of the amount of electricity produced by burning diesel fuel, expressed in gigawatt-hours (GWh)	2013-2023	Eurostat
Fuel oil energy production in GWh	PRD_PACU	The natural logarithm of the amount of electricity produced from fuel oil, expressed in gigawatt-hours (GWh)	2013-2023	Eurostat
Energy production from other bituminous coal GWh	PROD_BIT	Natural logarithm of energy generated from burning other types of bituminous coal (such as hard coal) with high calorific characteristics, expressed in gigawatt-hours, due to lack of data, used only for graphs.	2013-2023	Eurostat
Nuclear energy production GWh	PRD_NCL	Natural logarithm of the amount of electricity produced in nuclear power plants through nuclear fission, expressed in gigawatt-hours, due to lack of data, used only for graphs.	2013-2023	Eurostat

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Name	**Abbreviations**	**Description**	**Period**	**Source**
Industrial gas energy consumption	CON_INGA	Natural logarithm of energy used directly by industrial sectors (according to NACE classification), excluding energy transformed into other forms of energy, which is reported separately in the energy transformation sector.	2013-2023	Eurostat
Industrial energy consumption of oil and petroleum products	CON_INDP	Natural logarithm of energy used directly by industrial sectors (according to NACE classification), excluding energy transformed into other forms of energy, which is reported separately in the energy transformation sector.	2013-2023	Eurostat
Industrial energy consumption from non-renewable waste	CON_INDNR	Natural logarithm of energy used directly by industrial sectors (according to NACE classification), excluding energy transformed into other forms of energy, which is reported separately in the energy transformation sector.	2013-2023	Eurostat
Biogas energy production GWh	PROD_BIOGAS	The natural logarithm of the amount of electricity produced from biogas, expressed in gigawatt-hours (GWh)	2013-2023	Eurostat
Solid biofuel energy production GWh	PROD_BIO	Natural logarithm of the amount of energy produced from solid biomass (wood, pellets, plant residues, etc.)	2013-2023	Eurostat
Solar energy production GWh	PRD_PHV	Natural logarithm of the energy generated from solar sources, either through photovoltaic panels or solar thermal systems, expressed in gigawatt-hours.	2013-2023	Eurostat
Wind energy production GWh	PRD_WIN	Natural logarithm of the electrical energy produced by wind turbines using wind power, expressed in gigawatt-hours.	2013-2023	Eurostat
Geothermal energy production GWh/ (total energy production)	PRD_GEO	Natural logarithm of the energy obtained from the Earth's internal heat, used for heating or electricity production, expressed in gigawatt-hours, due to lack of data, used only for graphs	2013-2023	Eurostat
Hydropower production GWh	PRD_HYD	The natural logarithm of the amount of electricity produced from hydropower sources (rivers, dams, etc.), expressed in gigawatt-hours.	2013-2023	Eurostat
Renewable energy (% of total energy)	REN_ENTO	The percentage of energy from renewable sources used in total gross final consumption, which includes final energy consumption, network losses, and self-consumption by power plants.	2013-2023	Eurostat
Renewable energy (% of total energy) in transport	REN_ENTR	Percentage of energy from renewable sources used in gross final consumption of the transport industry.	2013-2023	Eurostat
Renewable energy (% of total energy) in energy	REN_ENER	Percentage of energy from renewable sources used in gross final consumption of the energy industry.	2013-2023	Eurostat
Renewable energy (% of total energy) in heating and cooling	REN_ENRI	Percentage of energy from renewable sources used in gross final consumption for heating and cooling.	2013-2023	Eurostat

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Name	**Abbreviations**	**Description**	**Period**	**Source**
Industrial energy consumption from renewable sources and biofuels	CON_INDR	Natural logarithm of energy used directly by industrial sectors (according to NACE classification), excluding energy transformed into other forms of energy, which is reported separately in the energy transformation sector.	2013-2023	Eurostat
		Climate		
Average annual temperature	TEMP	Natural logarithm of the average temperature calculated over one year.	2013-2023	Global data lab
Total annual precipitation	PREC	Natural logarithm of annual precipitation	2013-2023	Global data lab
		Economic		
General public expenditure by function (% of GDP)	GGE	Expressed as a percentage of GDP, "general government expenditure by function (COFOG)" refers to a method of categorizing and reporting government expenditure according to the purposes for which it is intended.	2013-2023	Eurostat
Public expenditure on environmental protection (% of GDP)	EPE	It is expressed as a percentage of GDP and represents public expenditure on environmental protection.	2013-2023	Eurostat
Trade openness (%GDP)	TO	It is expressed as a percentage of GDP and measures the degree of integration of an economy into international trade, expressed as the share of exports and imports in GDP.	2013-2023	World Bank
Foreign direct investment, net inflows (% of GDP)	FDINI	Expressed as a percentage of GDP, foreign direct investment represents the net flow of investment into a foreign economy.	2013-2023	World Bank
Foreign direct investment, net outflows (% of GDP)	FDINO	Foreign direct investment refers to the flow of equity capital invested in an economy. This includes the sum of equity capital, reinvested earnings, and other forms of long-term capital.	2013-2023	World Bank
Gross fixed capital formation (% of GDP)	CAPEX	Reflects investments made by resident producers in fixed assets (buildings, dwellings, equipment, vehicles), less their sales.	2013-2023	Eurostat
		Education		
Education - Population by level of education, sex, and age (%)	PBE	Education - Population by level of education, sex, and age (%) is an indicator that reflects the dynamics or characteristics associated with education in the economic or social context.	2004-2023	Eurostat
		Labor force		
Unemployment, total (% of total labor force)	UNEM	Represents the percentage of unemployed people compared to the total labor force.	2013-2023	World Bank
Employment and activity by sex and age - annual data	EM	Percentage of total population. These data provide insight into the structure of employment and economic activity within different demographic categories.	2013-2023	Eurostat
GINI coefficient – EU-SILC survey	GINI	The Gini coefficient is an indicator that shows how unequally income is distributed within a population, the higher the value, the greater the inequality.	2013-2023	Eurostat
		Innovation		

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Name	Abbreviations	Description	Period	Source
Research and development expenditure (% of GDP)	RD	Percentage of GDP is allocated to research and development activities in the economy, including in the public and private sectors.	2013-2023	Eurostat
		Environment		
Resource productivity (PPS/kg)	RP	Being the natural logarithm and representing the efficiency with which an economy generates GDP using material resources, expressed in PPS/kg.	2013-2023	Eurostat
Greenhouse gas emissions from the energy sector	GGE_ENR	Natural logarithm of greenhouse gas emissions from energy sector activities	2013-2023	Eurostat
Greenhouse gas emissions (logarithmic, 1990 index)	GGE_LOG	Change in total GHG emissions relative to 1990 levels, expressed as a logarithmic index.	2013-2023	Eurostat
CO_2 emissions	CO2	Natural logarithm of the amount of carbon dioxide emitted into the atmosphere from the burning of fossil fuels.	2013-2023	Eurostat
		Social		
At-risk-of-poverty rate before social transfers (by gender) – EU-SILC survey	POV	Percentage of people with disposable income (equivalent) below 60% of the national median, before social transfers. Old-age and survivors' pensions are included in income, not as transfers.	2013-2023	Eurostat
Population	PPL	The natural logarithm of population is an indicator that reflects the dynamics or characteristics associated with society in an economic or social context.	2013-2023	Eurostat

Source: Own analysis

3.3. **Econometric Models.** In line with the econometric approaches presented in the studies by Huseynli (2024), Wang, Ali, Chen, & Xu (2023), Armeanu, Vintila, & Gherghina (2017) and Heru, Ukhti, Arivina, & Ahmad (2023), the econometric models formulated in this research aim to analyze the influence of several structural dimensions on economic and human development.

$$Y_{it} = \beta_0 + \beta_1 E_{it} + \beta_2 C_{it} + \beta_3 Ec_{it} + \beta_4 Ed_{it} + \beta_5 M_{it} + \beta_6 In_{it} + \beta_7 Env_{it} + \beta_8 S_{it} + \varepsilon_{it} \quad (1)$$

where:

- Y_{it} = dependent variables: (GDP_GR, GDP_GV, HDI)
- E_{it} = energy-related variables
- C_{it} = climate-related variables
- Ec_{it} = economic variables
- Ed_{it} = education variables
- M_{it} = labor market variables
- In_{it} = innovation variables (R&D)
- Env_{it} = environmental variables
- S_{it} = social variables
- ε_{it} = error term specific to each unit and period

The specific regression models are as follows:

$$\text{GDP\_GR}_{it} = \beta_0 + \sum \beta_j X_{jit} + \varepsilon_{it} \quad (2)$$

$$\text{GDP\_GV}_{it} = \beta_0 + \sum \beta_j X_{jit} + \varepsilon_{it} \quad (3)$$

$$\mathrm{HDI}_{it} = \beta_0 + \sum \beta_j X_{jit} + \varepsilon_{it} \tag{4}$$

where X_{jit} corresponds to the variables related to energy, climate, economy, education, labour force, innovation, environment, and social factors.

The models were estimated using panel data for a sample of EU countries over the period 2013–2023. Initially, approximately three hundred regression equations were estimated for all dependent variables. From this initial set, models were screened based on a Durbin–Watson statistic between 1.5 and 2.5 and an R-squared value above the mean R-squared across all estimated regressions. Following this procedure, forty-five model specifications were retained.

Based on the variance inflation factor criterion (VIF < 5), 32 of the 45 retained model specifications were selected for further analysis. Heteroskedasticity was examined using the Breusch–Pagan–Godfrey test, with detailed results reported in Appendix A.

Subsequently, the Hausman test was applied to determine the appropriate specification between fixed-effects and random-effects models. Following Brooks (2008) when the Hausman test indicated correlation between individual effects and the explanatory variables, the fixed-effects estimator was preferred. When the null hypothesis was not rejected, the random-effects model was selected. This latter case applies to regression equations 24, 28, 29, and 31.

Finally, all selected models were re-estimated using heteroskedasticity-robust standard errors of the White cross-section type to ensure consistent and reliable statistical inference.

4. Results of the Empirical Study

4.1. **Descriptive Statistics and Correlation Analysis.** The descriptive statistics analysis for the variables included in the dataset, taking into account the mean, extreme values (maximum and minimum), and the standard deviation. The variables were grouped into thematic blocks relevant to the objectives of the study.

Conventional energy. This category includes variables related to the production and consumption of non-renewable energy sources, such as natural gas, diesel oil, fuel oil, bituminous coal, and industrial consumption of gas, oil, and non-renewable waste. The mean values of these variables range between 4.08 and 9.16 (natural logarithm), with standard deviations between 0.96 and 2.65, reflecting high consumption levels and significant variability across countries and periods. These sources are theoretically expected to have a short-term positive impact on GDP growth due to their intensive use in industry and infrastructure, but a negative or neutral effect on HDI in the long run, due to environmental degradation and associated health costs.

Renewable energy. This category refers to the production and use of renewable energy sources, including biomass, biogas, solar, wind, geothermal, and hydropower. It also includes the shares of these sources in total consumption. The variables are: PROD_BIO, PROD_BIOGAS, PRD_PHV, PRD_WIN, PRD_HYD, REN_ENTO, REN_ENTR, REN_ENER, REN_ENRI and CON_INDR. The mean values range between 6.36 and 38.49, while the standard deviations vary between 1.31 and 19.03, indicating a very uneven adoption of renewables across economies. Theoretically, these variables are expected to positively influence both GDP growth and HDI, especially in the long run, as they reduce emissions, increase energy security, and encourage sustainable development.

General energy. This sub-group reflects aggregate indicators of energy consumption at the macro level. The variables analyzed are: PRIM_CON, CON_REZI, CON_INDT, and DEP_IMP. The mean values range between 3.72 and 53.48, while the standard deviations vary between 0.92 and 19.48, highlighting substantial dispersion in countries' energy behavior. A higher level of energy consumption is associated with stronger economic activity (positive effect on GDP), but its effect on HDI depends on efficiency and accessibility with excessive dependency on imports potentially lowering development outcomes.

Climate. Average annual temperature (TEMP) and total precipitation (PREC) exhibit stable logarithmic mean values with small standard deviations (below 0.5). Mean values range between –3.58 and 2.36, and standard deviations are low, between 0.21 and 0.29, making them reliable control variables in econometric models. Increased temperature may have a non-linear effect: moderate warmth could boost agriculture and GDP in colder climates, but extremes harm both GDP and HDI, especially via food insecurity or health risks.

Economy. Economic variables capture macroeconomic activity, investments, and external trade relations. This category includes: GGE, EPE, TO, FDINI, FDINO, and CAPEX. Mean values vary between 0.75 and 106.46, while standard deviations range between 0.33 and 42.60, reflecting pronounced dynamics across economies. Most of these indicators are expected to positively influence GDP growth, while their impact on HDI depends on allocation efficiency for example, productive foreign investment (FDI) can improve living standards if it creates jobs and boosts public revenue.

Education. PBE (population by educational attainment) has a mean of 26.23% and a standard deviation of 10.64, showing significant cross-country differences in educational structure. Higher educational attainment is expected to have a strong positive effect on both GDP and HDI, by enhancing productivity, innovation capacity, and social inclusion.

Labor force. This category includes the unemployment rate, employment rate, and participation by age group and gender. Mean values range between 8.11% and 71.47%, with standard deviations between 4.54 and 6.78, indicating moderate differences in labor market structure. High employment and labor force participation contribute positively to GDP growth and HDI, while high unemployment has a negative expected effect on both dimensions.

Inequality and poverty. This category covers indicators such as the Gini coefficient and the at-risk-of-poverty rate before social transfers. Mean values range between 25.79% and 29.92%, with standard deviations close together, between 3.68 and 3.71, suggesting low but important variation across states. Higher inequality and poverty rates are associated with lower HDI and in the long term, may constrain inclusive economic growth, despite potential neutral short-run effects on aggregate GDP.

Demographic indicators. This category is represented by the total population expressed in natural logarithms. The mean value is 16.47 with a standard deviation of 0.97, reflecting predictable variation in population size across economies. Population growth may have a mixed effect: while a larger population can support market expansion (GDP), its effect on HDI depends on infrastructure, education, and healthcare access.

Environment and emissions. The variables on emissions are: GGE_LOG, GGE_ENR, and CO_2. Mean values range between 0.59 and 18.16, while standard deviations range between 0.49 and 1.05, pointing to a homogeneous level of ecological pressure across countries. Higher emissions are typically associated with short-term industrial GDP gains but have a negative impact on HDI due to health costs, environmental damage, and reduced quality of life.

Innovation and productivity. Expenditure on research and development reflects economies' involvement in innovation. The mean is 1.91%, with a standard deviation of 0.93, indicating a moderate but uneven effort towards technological progress. Innovation spending is expected to positively impact both GDP and HDI, by driving technological advancement, job creation, and better access to knowledge and healthcare.

The correlation matrix is presented in the Appendix C and is used as a first step in building regression models. A threshold of $|\rho| \geq 0.5$ is used to identify relatively strong correlations between variables. Based on this criterion, variables that show high correlations with each other are not included together in the regression models, in order to reduce multicollinearity and obtain more reliable results.

4.2. **Multicollinearity Assessment Using Variance Inflation Factors (VIF).** In the following section, the variance inflation factors (VIF) are reported for the models that exhibit VIF values below the threshold of five. As a result, out of the initial forty-five model specifications, thirty-two models were retained for further analysis.

Table presented in the Appendix D presents the variance inflation factors for the models estimated with annual changes in real GDP as the dependent variable. Overall, the reported VIF values indicate a low to moderate degree of multicollinearity across the retained specifications. For many explanatory variables, VIF values remain well below conventional critical levels, suggesting that collinearity is unlikely to distort the estimated coefficients or their statistical significance.

Energy-related variables, including renewable energy production and consumption indicators, display VIF values ranging between approximately 1.5 and 3.0, which consistent with an acceptable level of correlation in panel data settings. Similarly, control variables such as capital expenditure, unemployment, and financial development indicators exhibit moderate VIF values, indicating that they contribute additional explanatory power without introducing severe multicollinearity.

Although slightly higher VIF values are observed for a limited number of variables in specific model specifications, these remain below the adopted threshold and therefore do not raise concerns regarding multicollinearity. Consequently, the retained models can be considered econometrically well specified from the perspective of collinearity, allowing for reliable inference in the subsequent regression analysis.

The table presented in the Appendix E reports the variance inflation factors for the model specifications estimated with annual real GDP per capita growth as the dependent variable. Consistent with the selection criterion adopted in this study, all reported VIF values presented remain below the threshold of five, indicating the absence of severe multicollinearity across the retained models.

Energy-related variables, including both renewable and non-renewable energy production and consumption indicators, display VIF values ranging between approximately 1.3 and 3.8. These values are well within the accepted threshold and reflect moderate correlation patterns that are common in macroeconomic panel data analyses. Importantly, renewable energy variables maintain stable VIF levels across specifications, suggesting that they capture distinct explanatory effects rather than overlapping information.

Control variables such as capital expenditure, unemployment, financial development indicators, and inequality measures also exhibit VIF values below the adopted cutoff. While some specifications display higher VIF values compared to others, none exceed the threshold of five, and therefore multicollinearity is not considered to pose a concern for coefficient estimation or statistical inference.

Overall, the VIF results confirm that the selected models explaining real GDP per capita growth are appropriately specified from a multicollinearity perspective, supporting the reliability of the subsequent regression results.

Table presented in the Appendix F presents the variance inflation factors for the model specifications estimated with annual HDI growth as the dependent variable. Consistent with the selection criterion applied throughout the analysis, all reported VIF values remain below the threshold of five, indicating that multicollinearity does not represent a significant concern for the retained models.

Energy-related variables, including both renewable and non-renewable energy production indicators, generally exhibit VIF values between approximately 1.5 and 3.5. These values suggest moderate correlations that are typical in panel data analyses involving closely related macroeconomic indicators. Importantly, renewable energy variables display stable and relatively low VIF values across specifications, indicating that they provide distinct explanatory information for human development dynamics.

Socio-economic control variables, such as income inequality, public expenditure, capital investment, unemployment, and institutional quality indicators, also present VIF values well below the adopted cutoff. While isolated specifications show comparatively higher VIF values—particularly for certain consumption-related variables—these remain within acceptable limits and do not compromise the reliability of coefficient estimates.

Overall, the VIF analysis confirms that the models explaining annual HDI growth are well specified from a multicollinearity perspective, supporting the robustness and interpretability of the subsequent regression results.

4.3. **Empirical Results from Panel Data Models.** This subsection presents the regression results for the models that use GDP growth, GDP per capita growth, and HDI growth as dependent variables. The discussion focuses exclusively on statistically significant coefficients.

Results for Real GDP Growth. Primary energy consumption (PRIM_CON) shows a consistently positive association with GDP growth across specifications. This pattern suggests that higher energy availability supports production, industrial activity, and overall economic output. Even in models where the coefficient is not statistically strong, its stable positive sign highlights the role of energy as a fundamental input in the growth process, especially in energy-intensive sectors.

By contrast, disaggregated renewable energy variables display more heterogeneous effects, indicating that the impact of renewable energy on growth depends on the specific technology and the stage of energy transition. Some renewable sources tend to be positively associated with growth, reflecting their contribution to energy diversification, investment, and technological upgrading. Other renewable indicators show weaker or mixed effects, which may be explained by adjustment costs, infrastructure constraints, or the still limited scale of certain renewable technologies in the short run. These results suggest that renewable energy does not affect growth uniformly, but rather through conditional and source-specific channels.

Conventional energy-related variables generally preserve a positive link with GDP growth, underlining the continued importance of fossil fuels in supporting economic activity during the transition period. This finding reflects the current structure of EU economies, where conventional energy sources still provide reliability and scale, particularly for industry and transport. However, the lack of strong statistical significance in some specifications may indicate diminishing marginal returns or increasing efficiency improvements that reduce the growth dependence on fossil fuels.

Beyond energy variables, social and labor market factors also influence growth dynamics. Poverty-related variables (POV) tend to be positively associated with GDP growth, suggesting that redistribution mechanisms may support short-term demand through higher household consumption. Income inequality (GINI) and unemployment (UNEM) are linked to lower growth, reflecting constraints on inclusive economic expansion and productive capacity. Government expenditure (GGE) shows mixed effects, often leaning negative, which may point to inefficiencies in public spending rather than a direct crowding-in effect on growth.

Results for Real GDP Per Capita Growth. Across the estimated models, GDP per capita growth appears to be closely linked to both energy-related variables and key socioeconomic factors. Primary energy consumption (PRIM_CON) shows a consistently positive association with income per capita growth whenever included, suggesting that higher energy availability supports productivity, capital accumulation, and living standards. This result highlights the continued importance of energy as an input for economic activity at the individual level, not only for aggregate output.

Renewable energy variables display more heterogeneous effects. Bioenergy-related indicators (PROD_BIO and PROD_BIOGAS) are generally associated with higher GDP per capita growth, indicating that biomass-based energy production may contribute to income growth

Table 3. Regression results on the determinants of annual changes in real GDP

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
PRIM_CON								14.62***
PRD_DISEL				0.37*				
PRD_PACU	0.09	0.06	0.07		0.00	0.00		0.08
PROD_BIO	0.51							
PROD_BIOGAS				0.71				
PRD_WIN							-0.21	
PRD_HYD	-0.17	-0.36	-0.39					-0.33
REN_ENTO							-0.36	
REN_ENTR								0.03
REN_ENER	-0.02	0.03	0.02	0.04	0.00	0.00		
CON_REZI	10.20							
DEP_IMP	0.03	-0.01	0.00					0.04
CON_INDT		10.72	10.39					
CON_INGA					4.59	4.56		
CON_INDR				-1.79	-0.21	-0.22		
TEMP				-14.17				
PREC	0.18	-0.25	0.05	-0.34	-0.48	-0.29	0.74	1.13
GGE	-0.56	-0.50	-0.49	-0.51*	-0.55*	-0.54*		-0.44*
EPE	-0.93	-1.22	-1.25		-0.72	-0.80		-0.61
TO							0.15*	
FDINI		0.05			0.01**		0.01***	
FDINO	0.04		0.04	0.00***		0.01***		0.14***
CAPEX	-0.03	-0.07	-0.03	0.01	-0.06	-0.05	-0.11	0.09
PBE					-0.10	-0.10	-0.08	
UNEM	-0.23	-0.21	-0.22	-0.33	-0.17	-0.18	-0.29***	-0.28
GINI	-0.17	-0.40**	-0.39**		-0.35***	-0.34***	-0.15	-0.21**
RP							0.24	
POV	0.80**	0.93**	0.94**	0.85***	0.89***	0.89***	0.70***	0.78**
R-squared	0.40	0.41	0.40	0.41	0.40	0.40	0.35	0.47
Adjusted R-squared	0.29	0.31	0.30	0.32	0.30	0.30	0.25	0.38
F-statistic	3.57	3.90	3.79	4.38	3.87	3.84	3.62	4.94
Durbin-Watson stat	2.22	2.24	2.25	2.24	2.15	2.15	2.47	2.30
Total panel	224	226	226	251	237	237	273	215

Source: Author's calculations. Variable descriptions are provided in Table 2.
*** indicates statistical significance at the 1% level. ** indicates statistical significance at the 5% level. * indicates statistical significance at the 10% level.

through value added, investment, and employment effects. These findings suggest that certain renewable technologies can support economic performance when they are sufficiently integrated into the productive structure. By contrast, the share of renewable energy in heating and cooling (REN_ENRI) shows a negative association with GDP per capita growth in several specifications, possibly reflecting short-term adjustment costs and efficiency constraints in this segment of the energy transition. This may reflect short-term adjustment costs, high initial investment requirements, or transitional inefficiencies during the shift toward cleaner energy sources, rather than a negative long-term effect of renewables.

Foreign direct investment outflows (FDINO) are positively associated with GDP per capita growth in several specifications, suggesting that outward investment may reflect stronger domestic firms, international expansion, and feedback effects on income through profits, productivity, or reinvestment at home. In contrast, government expenditure (GGE) tends to be negatively related to income growth per capita in multiple specifications. This pattern may point to inefficiencies in public spending or to a limited capacity of government outlays to stimulate productive investment in the analysis context.

Labor market and social variables also play an important role. Unemployment (UNEM) is consistently linked to lower GDP per capita growth, reflecting reduced labor utilization and weaker household income. At the same time, poverty-related indicators (POV) show a positive association with income growth in several models. This result may capture short-term demand effects generated by redistribution or social support mechanisms, which can temporarily stimulate consumption and income per capita, even if they do not necessarily ensure long-term growth.

Finally, climate variables such as temperature (TEMP) are negatively associated with GDP per capita growth in some specifications, suggesting that higher temperatures may reduce productivity or increase economic vulnerability. Overall, the results indicate that GDP per capita growth in the EU is shaped by a combination of energy availability, the structure of the energy mix, investment dynamics, and social conditions, with energy variables playing a central but differentiated role depending on the source and stage of transition.

In continuation of the analysis, the focus shifts to the set of models where the Human Development Index (HDI) serves as the dependent variable. These regressions aim to explore how various energy sources and socioeconomic variables affect human development outcomes across EU countries during the 2013–2023 period.

Results for Human Development Index. From an energy perspective, conventional energy sources—proxied by petroleum and coal production (PRD_PACU)—tend to be negatively associated with HDI across most specifications. This suggests that a higher reliance on fossil fuels is linked to weaker human development performance, likely due to environmental degradation, health costs, and lower sustainability of growth. Similar negative effects are observed for gasoline consumption (GGE) and, in some cases, industrial energy consumption, pointing to the social and environmental limits of conventional energy-intensive activities.

In contrast, several renewable energy indicators show a positive relationship with HDI, although the effects differ by technology and sector. Renewable energy use in transport (REN_ENTR) consistently exhibits a positive association with human development, indicating that cleaner mobility solutions contribute to improved quality of life. Wind energy production (PROD_WIN) also displays a positive effect in multiple models, supporting the idea that scalable and low-emission technologies can enhance development through job creation, regional investment, and better environmental conditions. Moreover, higher shares of renewables in total final energy consumption (REN_ENTO) are associated with improved HDI, reflecting the broader benefits of energy transition beyond purely economic outcomes.

At the same time, not all renewable sources generate uniformly positive effects. Bioenergy production (PROD_BIO) is frequently linked to a negative association with HDI, suggesting that certain renewable technologies may involve trade-offs related to land use, energy efficiency, or social costs. Hydropower also shows mixed or negative effects in some models, possibly reflecting environmental pressures or location-specific constraints. These findings underline that the developmental impact of renewable energy depends on technological maturity, policy design, and integration within the energy mix.

Among control variables, unemployment and poverty consistently exert a negative influence on HDI, confirming that labor market exclusion and income deprivation remain major barriers to human development. Primary energy consumption per capita (PRIM_CON), when significant, tends to have a positive effect, indicating that access to energy remains essential for basic living standards. Climate variables such as precipitation occasionally display positive associations, potentially capturing indirect effects through agriculture or environmental conditions.

TABLE 4. Regression models on the determinants of annual real GDP per capita growth

	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)
PRIM_CON	15.59***					17.29**	17.76***				19.31**	
PRD_DISEL			0.26									
PRD_PACU	0.00	0.03				0.07	0.08				0.09	
PROD_BIO				1.02*	0.89*			0.93*	0.83*	0.97*		
PROD_BIOGAS			1.46**									
PRD_NCL												
PRD_PHV				-0.33	-0.21			-0.34	-0.21	-0.03		-0.14
PRD_HYD	-0.46	-0.68		-0.11	-0.51	-0.85	-0.87	-0.13	-0.51	-0.46	-0.95	-0.06
REN_ENTO		-0.08				-0.02						
REN_ENTR	-0.07			-0.13			0.00	-0.14				
REN_ENER			0.03		-0.04				-0.04		0.03	
REN_ENRI										-0.14***		-0.18***
DEP_IMP	0.01	-0.01				0.03	0.03				0.03	
CON_INDT		9.95										
CON_INDR			-1.80									
TEMP			-14.02		-15.22*				-15.42*	-14.45		
PREC	-0.00	-0.21	-1.06	0.24	-0.59	0.88	0.86	0.35	-0.55	-0.44	0.88	0.45
GGE	-0.44*	-0.48	-0.49*	-0.51*	-0.49*	-0.41*	-0.41*	-0.51*	-0.49*	-0.50*	-0.40*	-0.47
EPE	-0.21			-0.56		-0.44	-0.48	-0.68			-0.62	
FDINI	0.17***		0.01***	0.01**	0.01***							
FDINO		0.06				0.18***	0.18***	0.01**	0.01**	0.01*	0.18***	0.01*
CAPEX	0.07	0.09	0.12	0.09	0.10	0.23	0.22	0.10	0.11	0.11	0.22	0.08
PBE				-0.09				-0.08				-0.13
UNEM	-0.28	-0.25	-0.24	-0.11	-0.18	-0.25	-0.25	-0.13	-0.19	-0.23	-0.22	-0.28*
GINI	-0.13	-0.28		-0.37**		-0.08	-0.08	-0.38***			-0.08	
RD												-0.36
RP				0.00	2.07			0.05	2.09			
POV	0.80**	1.01***	0.95***	0.93***	0.82***	0.82**	0.82**	0.92***	0.82***	0.89***	0.83**	0.98***
R-squared	0.53	0.45	0.44	0.41	0.43	0.55	0.54	0.41	0.43	0.44	0.55	0.40
Adjusted R-squared	0.44	0.35	0.36	0.31	0.35	0.46	0.46	0.31	0.35	0.35	0.46	0.31
F-statistic	6.17	4.70	5.06	4.15	4.88	6.57	6.57	4.13	4.87	5.14	6.59	4.47
Durbin-Watson stat	2.05	1.94	1.99	1.98	1.90	2.01	2.01	1.98	1.90	1.91	2.00	1.98
Total panel	215	226	251	258	258	215	215	258	258	258	215	260

Source: Author's calculations. Variable descriptions are provided in Table 2.
*** indicates statistical significance at the 1% level. ** indicates statistical significance at the 5% level. * indicates statistical significance at the 10% level.

Table 5. Regression models on the determinants of annual HDI growth

	(22)	(21)	(23)	(24)	(25)	(26)	(27)	(28)	(29)	(30)	(31)	(32)
PRIM_CON		0.02**		0.02**								
PRD_PACU	-0.002**	-0.003***	-0.002**	-0.002**	-0.002**	-0.002**						
PROD_BIO	-0.001		-0.001					-0.001***	-0.001**	-0.001**		-0.002***
PROD_BIOGAS								0.0003				-0.001
PRD_PHV									0.001***	0.001***		
PRD_WIN								0.005***			0.004***	0.01***
PRD_HYD	0.003	0.002	0.003	-0.004**	0.003	0.002	0.002	-0.001	-0.001	-0.0001	0.0002	0.002
REN_ENTO		0.001***					0.001***				0.0005***	
REN_ENTR	0.001***		0.001***	0.001***	0.0005***			0.0004*				0.0003
REN_ENER								0.00003	0.0002***			0.0001
REN_ENRI						0.001***				0.0005***		
CON_REZI	-0.005		-0.005									
DEP_IMP	0.00004	0.00004	0.00004	0.0001	0.0001	-0.00002						
CON_INDT					-0.01**	-0.002	0.004					
TEMP									0.01**	0.01		
PREC	0.004*	0.002	0.004*	0.01*	0.004*	0.004*	0.003	0.01**	0.01	0.01**	0.004	0.003
GGE	-0.0004*	-0.0002	-0.0004*	-0.0001	-0.0005*	-0.0003		-0.0003	-0.0002	-0.0002	-0.0002	-0.0002
EPE	0.004		0.004	0.001	0.01	0.004		0.01				0.001
TO							0.0001*					
FDINI	-0.00001	0.00002		-0.000001			0.000008	-0.000002	0.000001	0.000003	0.000006	
FDINO			-0.00002		0.000	0.000						0.000
CAPEX	0.001	0.001	0.001	0.001	0.001	0.0005	0.0005	0.001	0.001	0.001	0.001	0.0005
PBE							-0.0001	0.0002			0.00002	-0.0001
UNEM	-0.002***	-0.001***	-0.002***	-0.001***	-0.001***	-0.001***	-0.001***		-0.001***	-0.001***	-0.001***	-0.002***
EM								0.001***				
POV	-0.001*	-0.001***	-0.001*	-0.001***	-0.001*	-0.001**	-0.001	-0.0004**	-0.0004**	-0.001***	-0.001*	-0.0003
R-squared	0.98	0.98	0.98	0.45	0.98	0.98	0.98	0.51	0.48	0.98	0.48	0.98
Adjusted R-squared	0.97	0.97	0.97	0.41	0.97	0.97	0.97	0.48	0.46	0.97	0.46	0.97
F-statistic	246.44	253.17	246.73	13.60	258.38	266.89	284.46	19.00	20.82	291.17	23.09	261.90
Durbin-Watson stat	1.81	1.93	1.81	1.31	1.82	1.93	1.63	1.56	1.53	1.77	1.50	1.74
Total panel	225	216	225	216	227	227	264	273	259	259	264	262

Source: Author's calculations. Variable descriptions are provided in Table 2.
*** indicates statistical significance at the 1% level. ** indicates statistical significance at the 5% level. * indicates statistical significance at the 10% level.

Overall, the results suggest that human development in the EU benefits from a cleaner and more diversified energy structure, particularly through renewables used in transport and electricity generation, while continued dependence on fossil fuels is associated with weaker social outcomes. However, the heterogeneous effects across renewable technologies indicate that the energy transition must be carefully managed to maximize social benefits and avoid unintended consequences.

Based on this analysis, the research hypothesis introduced in Section 3.1 can now be confirmed or rejected:

- **Hypothesis 1 is confirmed:** Primary energy consumption contributes positively to economic growth.
- **Hypothesis 2 is rejected,** as wind energy was not found to be significant in relation to GDP or GDP per capita growth.
- **Hypothesis 3 is supported:** Renewable energy, particularly biomass, positively influences economic growth, consistent with the findings of Armeanu, Vintila, & Gherghina (2017), Wang, Dong, Li, & Wang (2022), Wang, Ali, Chen, & Xu (2023), Salari, Kelly, Doytch, & Javid (2021) and Can & Korkmaz (2019).
- **Hypothesis 4 is confirmed:** Conventional energy positively affects economic growth, consistent with Supron & Myszczyszyn (2023), Banday & Aneja (2019).
- **Hypothesis 5 cannot be confirmed,** since CO_2 emissions were not significant in the presented equations, contrary to the results of Heru, Ukhti, Arivina, & Ahmad (2023), who found a negative relationship.
- **Hypothesis 6 is confirmed in several cases:** Renewable energy positively affects the HDI. Some forms of renewable energy (e.g., solar, wind, transport-related renewables) positively impact HDI, while others (e.g., biomass, hydropower) may have negative effects due to structural or environmental inefficiencies.

5. Conclusions and Recommendations

This study investigated the complex relationship between energy structures, comprising both conventional and renewable sources, and economic growth within the European Union, focusing on the twenty-seven member states. The empirical analysis demonstrates that there is no single, linear relationship between energy sources and economic development, but rather an interdependence shaped by factors such as the stage of economic development, public policies, energy infrastructure, innovation capacity, and social or climate-related risks.

The main contribution of this research lies in the construction of an extensive set of econometric models that simultaneously integrate energy variables (disaggregated into renewable and conventional), as well as climate, economic, educational, social, and environmental indicators. Unlike many existing studies, this work captures the interdependencies among these factors and evaluates their differentiated influence on key economic and human development indicators, focusing not only on correlations but also on statistical and economic significance.

The findings confirm that conventional energy (especially primary energy consumption) continues to play a key role in supporting short and medium-term economic growth. However, the associated environmental costs, particularly CO_2 emissions and pollution-related externalities, limit the sustainability of this growth trajectory and are incompatible with the EU's long-term decarbonization goals.

Renewable energy, on the other hand, is emerging as a viable long-term alternative, not only in terms of sustainability but also as a driver of innovation, reduced energy vulnerability, and improved quality of life. Still, the findings show that its positive impact on economic growth is often conditional on the type of renewable source and the level of investment in research, technology, and human capital. For instance, solar energy has been found to exert a negative effect on economic growth, possibly due to high costs or integration inefficiencies in some regions, while wind energy is not statistically significant for GDP but demonstrates a positive impact on HDI. This may be explained by the development of wind infrastructure, which creates jobs, attracts investment in less developed areas, and improves living conditions—factors reflected in HDI components such as education, income and health.

The analysis also reveals important differences within the category of bioenergy. Biomass (typically used in direct combustion systems) shows a negative and statistically significant impact on HDI, potentially due to its lower energy efficiency, pollution concerns, or competition for land with agriculture. In contrast, biogas shows a positive and significant effect on GDP per capita, highlighting the role of technological maturity and integration in maximizing the developmental impact of renewables.

Another key result of the research highlights the role of renewable energy in shaping broader socio-economic indicators such as the Human Development Index (HDI), unemployment rate, and poverty risk. A positive link emerges between the energy transition and human development, suggesting that the benefits of renewable energy extend beyond the economic sphere and encompass social dimensions as well. These findings reinforce the importance of tailoring public policies not only by type of renewable energy but also by national context, ensuring that energy transitions promote both economic performance and inclusive development.

In conclusion, this research confirms that the energy transition is not only an environmental challenge but also an economic and social opportunity. Renewable energy is not yet a perfect substitute for conventional sources, but it is increasingly becoming a strategic pathway toward sustainable economic growth and the achievement of long-term development goals.

Policy Implications. Based on the empirical findings, several recommendations can be formulated to guide future energy and development strategies in the EU:

(1) *Diversify the energy mix:* National and EU energy policies should ensure a balance between conventional and renewable sources, with a gradual reduction of fossil fuel dependency and stronger support for clean technologies.
(2) *Support research, innovation, and investment:* Particularly in areas such as energy storage, grid digitalization, and energy efficiency technologies.
(3) *Integrate social and environmental criteria into economic policies:* Indicators such as HDI, income inequality, and poverty rates should be considered in assessing the impact of energy policies, ensuring a just and inclusive transition.
(4) *Adapt policies to the specific context of each economy:* EU member states differ significantly in terms of resource availability, economic development, and energy consumption structures. Policies should therefore be flexible and differentiated, avoiding a "one-size-fits-all" approach.

Study Limitations. Despite its strengths, the study presents several limitations.

First, data availability and consistency across EU countries for the 2013–2023 period limited the inclusion of some relevant variables (e.g., recent green investment or real-time energy prices).

Second, while the panel data structure enables a robust estimation of general trends, country-specific effects or non-linear dynamics (e.g., threshold effects of renewables) are not fully captured.

Finally, institutional factors (e.g., governance quality, regulatory stability) were not explicitly included, although they likely influence the effectiveness of energy and development policies.

Directions for Future Research. Building on these findings, future research could explore:

- Dynamic panel models or structural equation models (SEMs) to capture complex, time-lagged effects between energy variables and development indicators.
- Country-specific case studies or regional clusters (e.g., Southern vs. Nordic EU countries) to analyse differentiated transition pathways and bottlenecks.
- Inclusion of institutional quality, fiscal policy variables, and green finance indicators to better assess enabling conditions for effective energy transition.

- Assessment of synergies between digitalization, smart grids, and renewable deployment, particularly in accelerating decarbonization without sacrificing economic growth.

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APPENDIX

APPENDIX A: Breusch–Pagan–Godfrey Test Results.

Equation	p-value	Conclusion
1	0.03	Heteroskedasticity
2	0.01	Heteroskedasticity
3	0.01	Heteroskedasticity
4	0.09	Homoskedasticity
5	0.11	Homoskedasticity
6	0.10	Homoskedasticity
7	0.38	Homoskedasticity
8	0.10	Homoskedasticity
9	0.21	Homoskedasticity
10	0.00	Heteroskedasticity
11	0.00	Heteroskedasticity
12	0.07	Homoskedasticity
13	0.00	Heteroskedasticity
14	0.23	Homoskedasticity
15	0.23	Homoskedasticity
16	0.08	Homoskedasticity
17	0.00	Heteroskedasticity
18	0.00	Heteroskedasticity
19	0.18	Homoskedasticity
20	0.03	Heteroskedasticity
21	0.00	Heteroskedasticity
22	0.00	Heteroskedasticity
23	0.00	Heteroskedasticity
24	0.00	Heteroskedasticity
25	0.00	Heteroskedasticity
26	0.00	Heteroskedasticity
27	0.00	Heteroskedasticity
28	0.00	Heteroskedasticity
29	0.00	Heteroskedasticity
30	0.00	Heteroskedasticity
31	0.00	Heteroskedasticity
32	0.00	Heteroskedasticity

Source: Author's calculations.

APPENDIX B: Descriptive statistics.

	Mean	**Maximum**	**Minimum**	**Std. dev.**	**Obs.**
HDI	0.9	1.0	0.8	0.0	193
GDP_GR	2,202,073	24.6	(10.9)	3,908,417	193
GDP_GV	2,101,036	23.5	(11.4)	4,206,295	193
PRIM_CON	3,722,795	5,731,073	1,481,605	1,002,573	193
CON_REZI	9,032,328	110,432	7,144,598	0.9	193
DEP_IMP	534,782	91,506	11,344	1,947,776	193
CON_INDT	8,909,541	1,095,337	6,643,325	1,049,011	193
PRD_NAGAZ	9,156,966	1,187,755	4,574,711	158,376	193
PRD_DISEL	4,084,605	8,524,268	(1,877,317)	2,298,454	193
PRD_PACU	5,324,168	9,153,558	(5,809,143)	2,649,685	193
CON_INGA	7,538,106	9,946,722	4,960,681	1,261,745	193
CON_INDP	6,701,355	8,238,057	380,495	1.0	193
CON_INDR	6,380,642	8,549,786	2,969,902	1,309,825	193
CON_INDNR	4,668,809	7,167,297	0.9	1,235,909	193
PROD_BIOGAS	6,357,211	1,043,055	2,302,585	1,766,534	193
PROD_BIO	7,563,712	9,446,755	–	1,661,444	193
PRD_PHV	7,188,547	1,105,999	(2,703,063)	241,891	193
PRD_WIN	9,045,381	1,185,323.0	478,795	1,345,068	193
PRD_HYD	875,521	1,125,248	2,596,672	2,126,163	193
REN_ENTO	2,415,325	66,393	5,415	1,249,918	193
REN_ENTR	8,773,637	33,645	0.9	581,432	193
REN_ENER	3,849,248	87,764	9,924	1,902,658	193
REN_ENRI	2,874,597	70	4,925	1,628,672	193
TEMP	2,360,492	2,831,447	1,593,512	0.3	193
PREC	(3,583,744)	(3,057,608)	(4,074,542)	0.2	193
GGE	4,663,368	61.7	20.6	7,882,454	193
EPE	0.7	1.6	0.2	0.3	193
TO	1,064,598	2,501,085	5,393,948	4,259,851	193
FDINI	3,597,591	7,474,517	(3,077,753)	9,237,154	193
FDINO	286,421	5,974,981	(2,884,996)	9,318,004	193
CAPEX	2,149,793	53	11	4,440,415	193
PBE	2,623,109	59	11	1,064,061	193
UNEM	8,114,984	26,094	2,015	4,539,602	193
EM	7,147,202	83	55	6,784,698	193
GINI	2,991,969	41	24	3,714,194	193
RD	1,913,472	4	0	1	193
RP	1	1,466,329	(0.5)	0	193
GGE_ENR	113,191	1,359,495	8,890,989	1,049,592	193
GGE_LOG	1,167,811	1,377,179	932,337	1.0	193
CO2	1,815,968	2,037,006	1,578,136	1.0	193
POV	2,578,912.0	38.3	15.6	3,679,566.0	193
PPL	164,677.0	182,372.0	145,205.0	1.0	193

Source: Author's own calculations. The description of the variables is provided in Table 2.

APPENDIX C: Correlation matrix.

	HDI	GDP_GR	GDP_GV	PRIM_CON	CON_REZI	DEP_IMP	CON_INDT	PRD_NAGAZ	PRD_DISEL	PRD_PACU
HDI	1									
GDP_GR	-0.06	1								
GDP_GV	-0.15	0.91	1							
PRIM_CON	0.32	-0.15	-0.19	1						
CON_REZI	0.21	-0.14	-0.17	0.96	1					
DEP_IMP	0.21	0.01	0.00	0.12	0.02	1				
CON_INDT	0.39	-0.18	-0.23	0.97	0.90	0.11	1			
PRD_NAGAZ	0.14	-0.04	-0.03	0.62	0.57	0.62	0.57	1		
PRD_DISEL	0.35	-0.06	-0.09	0.68	0.56	0.35	0.61	0.58	1	
PRD_PACU	0.02	-0.01	-0.02	0.37	0.33	0.26	0.29	0.25	0.60	1

	CON_INGA	CON_INDP	CON_INDR	CON_INDNR	PROD_BIOGAS	PROD_BIO	PRD_PHV	PRD_WIN	PRD_HYD	REN_ENTO
CON_INGA	1									
CON_INDP	0.68	1								
CON_INDR	0.36	0.45	1							
CON_INDNR	0.75	0.46	0.60	1						
PROD_BIOGAS	0.77	0.41	0.15	0.59	1					
PROD_BIO	0.41	0.38	0.73	0.52	0.32	1				
PRD_PHV	0.66	0.54	0.23	0.48	0.55	0.20	1			
PRD_WIN	0.55	0.74	0.51	0.48	0.32	0.43	0.53	1		
PRD_HYD	0.28	0.30	0.50	0.51	0.04	0.16	0.25	0.22	1	
REN_ENTO	-0.57	-0.21	0.31	-0.23	-0.54	0.27	-0.21	0.01	0.22	1

	REN_ENTR	REN_ENER	REN_ENRI	TEMP	PREC	GGE	EPE	TO	FDINI	FDINO
REN_ENTR	1									
REN_ENER	0.46	1								
REN_ENRI	0.61	0.64	1							
TEMP	-0.62	-0.22	-0.45	1						
PREC	-0.18	0.09	-0.27	0.04	1					
GGE	0.27	0.19	0.31	-0.08	0.06	1				
EPE	-0.36	-0.46	-0.46	0.59	0.04	0.21	1			
TO	-0.12	-0.22	-0.35	-0.16	0.17	-0.56	-0.00	1		
FDINI	-0.07	-0.13	-0.13	-0.03	0.10	-0.27	-0.09	0.27	1	
FDINO	-0.03	-0.09	-0.10	-0.08	0.06	-0.09	-0.02	0.15	0.88	1

	CAPEX	PBE	UNEM	EM	GINI	RD	RP	GGE_ENR	GGE_LOG	CO2
CAPEX	1									
PBE	-0.16	1								
UNEM	-0.47	0.47	1							
EM	0.40	-0.38	-0.71	1						
GINI	-0.40	0.37	0.37	-0.50	1					
RD	0.22	-0.27	-0.32	0.65	-0.68	1				
RP	0.02	0.29	0.10	0.06	-0.26	0.22	1			
GGE_ENR	-0.21	0.06	-0.00	-0.08	0.03	0.04	0.42	1		
GGE_LOG	-0.19	0.09	0.00	-0.09	0.03	0.04	0.45	1.00	1	
CO2	-0.22	0.07	-0.03	-0.01	0.00	0.11	0.40	0.98	0.97	1

	POV	PPL
POV	1	
PPL	-0.16	1

Source: Author's own calculations. The description of the variables is provided in Table 2.

APPENDIX D: Variance Inflation Factor of annual changes in real GDP.

	1	2	3	4	5	6	7	8
PRIM_CON								2.36
PRD_DISEL				2.76				
PRD_PACU	2.26	2.12	2.14		2.03	2.03		2.48
PROD_BIO	3.01							
PROD_BIOGAS				1.91				
PRD_NCL								
PRD_PHV								
PRD_WIN							2.60	
PRD_HYD	2.36	2.78	2.79					2.80
REN_ENTO							1.61	
REN_ENTR								2.43
REN_ENER	1.79	1.68	1.66	1.42	1.93	1.92		
CON_REZI	3.22							
DEP_IMP	1.37	1.37	1.37					1.54
CON_INDT		2.71	2.73					
CON_INGA					3.02	3.03		
CON_INDR				3.11	2.52	2.51		
TEMP				2.78				
PREC	1.48	1.32	1.32	1.44	1.62	1.63	1.50	1.50
GGE	2.25	2.04	2.03	1.48	2.10	2.10		2.20
EPE	2.75	2.54	2.54		2.83	2.83		2.60
TO							4.64	
FDINI		1.09			1.15		1.09	
FDINO	1.07		1.07	1.11		1.13		1.19
CAPEX	1.95	1.99	2.00	1.65	1.98	1.99	1.69	2.22
PBE					1.88	1.87	2.58	
UNEM	2.83	2.75	2.74	2.22	3.22	3.22	2.17	2.85
GINI	2.44	2.54	2.55		2.22	2.23	2.00	2.93
RP							2.13	
POV	1.95	1.92	1.93	1.57	2.04	2.04	2.19	2.35

Source: Author's calculations. Variable descriptions are provided in Table 2.

APPENDIX E: Variance Inflation Factors of annual real GDP per capita growth.

	9	10	11	12	13	14	15	16	17	18	19	20
PRIM_CON	2.31					3.79	2.37				2.60	
PRD_DISEL			2.82									
PRD_PACU	2.44	1.66				2.41	2.49				2.42	
PROD_BIO				2.30	2.02			2.30	2.03	1.96		
PROD_BIOGAS			1.91									
PRD_NCL												
PRD_PHV				1.99	2.28			1.99	2.29	2.24		1.77
PRD_HYD	2.80	3.53		1.78	1.46	2.92	2.80	1.78	1.46	1.36	2.30	1.28
REN_ENTO		2.44				3.79						
REN_ENTR	2.44			1.98			2.43	1.98				
REN_ENER			1.43		1.27				1.28		1.69	
REN_ENRI										1.79		1.86
DEP_IMP	1.52	1.57				1.73	1.52				1.48	
CON_INDT		3.64										
CON_INDR			3.08									
TEMP			2.73		2.26				2.26	2.54		
PREC	1.50	1.46	1.44	1.94	1.54	1.44	1.50	1.94	1.54	1.38	1.28	1.22
GGE	2.24	2.18	1.48	2.13	1.70	2.90	2.19	2.13	1.70	1.84	2.21	2.42
EPE	2.59			2.24		3.14	2.59	2.23			2.77	
FDINI	1.20		1.13	1.03	1.03							
FDINO		1.06				1.19	1.19	1.05	1.03	1.04	1.19	1.05
CAPEX	2.12	2.01	1.66	1.74	1.52	2.21	2.23	1.73	1.51	1.50	2.21	1.58
PBE				1.64				1.68				1.49
UNEM	2.88	2.18	2.22	2.09	2.05	2.82	2.87	2.08	2.04	2.03	2.82	1.89
GINI	2.87	2.57		2.97		2.68	2.95	2.97			2.66	
RD												2.22
RP				2.58	1.62			2.57	1.61			
POV	2.31	1.81	1.57	2.42	1.54	2.14	2.36	2.42	1.55	1.53	2.12	1.62

Source: Author's calculations. Variable descriptions are provided in Table 2.

APPENDIX F: Variance Inflation Factors of annual HDI growth.

PRIM_CON	21	22	23	24	25	26	27	28	29	30	31	32
PRD_NAGAZ	3.45			2.18								
PROD_BIO	1.77	2.30	2.32	2.40	2.21	2.09						
PROD_BIT		2.97	2.96					3.32	1.97	1.95		3.50
PRD_NCL								3.14				3.30
PRD_WIN									2.17	2.24		
PRD_GEO								2.55			1.27	2.87
REN_ENTO	2.59	2.57	2.57	2.36	2.64	3.15	2.07	2.08	1.41	1.36	1.37	1.73
REN_ENTR	2.85						2.06				1.57	
REN_ENER		2.26	2.26	2.19	2.18			3.10				2.85
REN_ENRI								1.76	1.26			1.76
CON_REZI						4.39				1.75		
DEP_IMP		2.87	2.87									
CON_INDT	1.64	1.36	1.35	1.43	1.37	1.66						
CON_INGA					2.37	4.95	3.22					
PREC									2.17	2.52		
GGE	1.35	1.39	1.39	1.35	1.33	1.54	1.20	1.38	1.23	1.38	1.30	1.45
EPE	2.27	2.13	2.11	1.97	1.88	2.61		1.85	1.70	1.83	1.55	2.07
TO		2.61	2.61	2.48	2.25	2.87		1.90				1.94
FDINI							4.83					
FDINO	1.17	1.08		1.18			1.05	1.03	1.02	1.02	1.02	
CAPEX			1.06		1.06	1.06						1.06
PBE	1.68	1.71	1.72	1.78	1.74	1.64	1.56	1.52	1.52	1.50	1.53	1.57
UNEM							2.36	1.34			1.35	1.33
GINI	2.15	2.84	2.84	2.84	2.75	2.73	2.23		2.04	2.04	1.64	2.21
RD								2.54				
PPL	1.52	1.64	1.64	1.68	1.66	1.59	1.39	2.03	1.54	1.53	1.60	1.97

Source: Author's calculations. Variable descriptions are provided in Table 2.