ENABLERS OF GREEN GROWTH IN EUROPEAN UNION: THE ROLE OF GREEN TECHNOLOGY AND GREEN ENERGY

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Abstract

This study examines the combined impact of green innovation and green energy on green growth in the European Union from 2005-2024. The study employs an econometric approach to analyze both short-run and long-run impacts using the PMG-ARDL model and strengthens the results by applying robustness tests, as well as two different green growth *proxies*, to ensure the validity of the findings. The study's findings show that green innovation and green energy have a significant and positive impact on green growth in both the short-run and the long run. Similarly, the study's control variables, such as investment, show a positive relationship with green growth in both the short run and the long run. Furthermore, military expenditure and trade openness have a mixed impact on green growth: in the long run, they have a positive impact, while in the short run both variables have a negative impact. These findings are consistent with the robustness tests, as well as with the alternative green growth *proxy*. This study contributes empirically to the green growth literature and based on its findings, recommends policies to help promote green growth in the EU.

Key Words: Green innovation, green energy, green growth, investment, military expenditure

JEL: O31, O13, F64, F21, P18

1. Introduction

The global ecosystem is under multiple challenges, as climate change and geopolitical conflicts have together become serious threats to achieving the 2030 United Nations Sustainable Development Goals (Böcskei et al., 2025). According to National Centers for Environmental Information, 2024 was the warmest year on record, with global temperatures about 1.46°C above pre-industrial levels. This rapid warming is mainly caused by human activities, especially greenhouse gas emissions. If emissions continue, global temperatures are expected to rise significantly in the future (Lindsey et al., 2025), which will affect the global economy, and in particularly the European Union. The European Environment Agency anticipates that, by the end of this century, climate change is expected to reduce the GDP of the European region by 7% (European Environment Agency, 2025). In this context, balancing economic growth and environmental sustainability remains a serious challenge for academic scholars (Saleem et al., 2022).

To overcome this challenge, academic scholars and policymakers have proposed several solutions. One of the most suitable is the green growth (Abro et al., 2023; Hussain et al., 2022; Wang et al., 2023). In previous studies, many authors have conducted research on the impact of green growth and its enablers (Chen et al., 2023; Javed et al., 2024; Teklie et al., 2024; Wei et al., 2023). However, the literature highlights two types of studies on green growth: on the one hand, those in which green growth is the main dependent variable (Chen et al., 2023; Teklie et al., 2024); and on the other hand, those in which green growth and its enablers are examined alongside with other dependent variables, such as environmental quality, carbon emissions, and load capacity factors (Javed et al., 2024; Murtaza et al., 2024; Wei et al., 2023). Green innovation is an environmentally friendly factor and can be used as an effective tool for emission reductions (Caglar et al., 2024). It helps reducing production process costs, fuel waste, and equipment damage, and allows enhancing the efficiency of production and increasing green growth (Bouattour et al., 2025). Green innovation, as an enabler, helps to promote green growth. Nonetheless, most countries, including the European region, are struggling to fight climate change, and the zero-carbon era is still not in sight (Ahmad et al., 2022). Likewise, previous literature recognizes the significance of green innovation for environmental safety. However, the concept of green innovation is still unclear (Bouattour et al., 2025) and different authors use multiple terminology, such as green technological innovation (Li et al., 2022), cleaner innovation (Deng et al., 2024), sustainable innovation (Fernandes et al., 2021), and environmental innovation (Luan et al., 2024). To achieve the green growth goal, the significant contribution of technological change and green energy to economic activities cannot be denied (Wei et al., 2023; Wiebe et al., 2016). While there is a general consensus that green energy is helpful, it is still unclear which energy sources or green growth strategies are most effective (Gorji et al., 2023).

Based on the previous green growth literature review analysis, the present study fills the existing gaps in the green growth literature in different ways. In previous literature, the impacts of green innovation and green energy on green growth are measured individually or alongside other dependent variables. Based on the authors' knowledge, no previous study has examined the combined impacts of green innovation and green energy on green growth. Hence, this study fills this gap by examining the combined impact of green innovation and green energy on green growth, contributing to the empirical evidence in the green growth literature. This study includes additional control variables that may help promote green growth, such as investment, military expenditure, and trade. There is also a population gap in the literature that is overcome by this study. While this paper focuses on the European Union, previous research has focused on other regions (BRICS, 10 manufacturing countries, OECD, African countries, 10 green future economies, and ASEAN) (Chang et al., 2024; Chen et al., 2023; Javed et al., 2024; Mohd Suki et al., 2022; Teklie et al., 2024; Wei et al., 2023). The European Union region has an important global role, it significantly contributes to global GDP and is actively working toward environmental sustainability, with the Green Deal serving as a key example.

The aim of this study is to examine the combined impact of green innovation and green energy on green growth, providing three new contributions to the literature. The first contribution is the analysis of the combined impact of green innovation and green energy on green growth. The second contribution is the use of the PMG-ARDL model to provide empirical evidence for both short-run and long-run results. The third contribution is the employment of two different *proxies* for green growth, robustness tests, and diagnostic tests to ensure the validity of the outcomes, whose results are valuable for stakeholders.

2. Literature review on green growth and its enablers' impact

2.1 Green Growth

The concept of green growth has been accepted by global institutions, such as the World Development Indicators (WDI), the Asian Development Bank (ADB), and the Organisation for Economic Co-operation and Development (OECD), and the experts from these institutions have contributing to promote green growth frameworks (Citil, 2024). The American marine biologist, Rachel Carson, in 1962, had already published a book titled Silent Spring, which explains how human activities contribute to pollution and negatively impact both ecosystems and human well-being (Hussain et al., 2022). Similarly, the British economic scholar Pearce developed the concept of green growth and the green economy in 1989 in his book Green Economy - Blue Book (Wang et al., 2021). In this book, Pearce argued that excessive use of natural resources has a negative impact on economic growth (Wang et al., 2021). Furthermore, academic scholars unanimously agree that green growth not only protects the environment but also helps promote economic growth (Adamowicz, 2022; Bouattour et al., 2025). In previous studies, scholars have examined the green growth relationship independently and used different *proxies*, including production-based CO_2 (Wei et al., 2023), GDP per capita divided by CO_2 (Lu et al., 2025), environmentally adjusted multifactor productivity (Chang et al., 2024), the Green Growth Index (Qian et al., 2025), environmental resource productivity (Saqib et al., 2024), GDP per capita at constant 2015 US dollars (Naimoğlu et al., 2025), and adjusted net savings (both including and excluding emissions) (Eltayeb, 2025; Wani et al., 2024). Moreover, many authors have used green growth as a dependent variable and measured it with other independent variables such as carbon emissions, carbon neutrality, environmental quality, and load capacity factor (Behera et al., 2025; Chang et al., 2024, 2024; Javed et al., 2024).

2.2 Green innovation and its impact on green growth

Prior research shows there is no full consensus among scholars about the relationship between green growth and green innovation (Chen et al., 2023). Still, much of the debate assumes that green innovation supports economic development, even though its overall impact depends on the type of innovation and the specific features of each economy (Teklie et al., 2024).

One line of research argues for a positive relationship between green growth and green innovation, suggesting that advances in green technologies improves efficiency (Ahmed et al., 2022; Fernandes et al., 2021). The adoption of these innovations encourages the use of green energy and technologies, reduces emission levels, and ultimately supports green growth (Ahmed et al., 2022; Fernandes et al., 2021). Likewise, in the BRICS region, the nexus between green growth and green innovation, along with the role of financial globalization, shows that in the long run, green innovation acts as an enabler of green growth (Chen et al., 2023). Similarly, for the OECD countries, green innovation has a significant but mixed impact on green growth, and consequently the level of green technology should be enhanced to foster economic growth and improve environmental quality (Qamruzzaman et al., 2024).

Another line of research suggests a negative relationship between green growth and green innovation. It argues that firms often pursue innovation mainly to maximize profits, while neglecting environmental consequences. As a result, such practices may increase pollution, waste resources, and weaken the foundations of green growth (Zhang et al., 2021). Empirical evidence also points in this direction: a 1% increase in economic growth has been associated

with a 3.2% decline in green innovation, which in turn can hinder green growth (Yu et al., 2023). In addition, the impact of green innovation on green growth appear to differ across the European countries depending on income levels (high, middle, and low) (Lu et al., 2025).
Although extensively studied, the relationship between green innovation and green growth remains inconclusive. Overall, the literature points to mixed findings, shaped by differences in economic structures, regional contexts, and how innovation is applied. These unclear results provide a basis for form formulating new hypothesis and further investigation.
H1: There is a positive and statistically significant relationship between green innovation and green growth in the European regions.

2.3 Green energy and its impact on green growth

Energy is a key indicator of human economic activities and plays a significant role in modern society, supporting heating systems, lighting, transportation, and industrial activities (Nur et al., 2025). Nevertheless, the overuse of energy consumption damages environmental quality (Nur et al., 2025). In this context, recent statistics show that between 2020 and 2024, energy use per person increased both globally and in the European region, rising from 20,032 kWh to 21,654 kWh and from 38,125 kWh to 39,225 kWh (Our World in Data, 2024). An extensive literature review on green growth and green energy shows that the results are inconsistent due to differences in methodologies, data periods, and data types (Wang et al., 2023). One strand of the literature emphasizes a positive relationship between green energy and green growth, arguing that the transition from non-renewable to renewable energy improves environmental quality while supporting economic production (Sohag et al., 2021). This effect trends to be stronger when combined with trade openness and technological progress (Danish et al., 2020; Wang et al., 2023). Similarly, incorporating green energy into economic policy frameworks can further promote green growth (Danish et., 2020; Teske et al., 2018). Empirical evidence from the European Union suggests that green energy is more effective when supported by factors, such as technological innovation and investment, reinforcing its positive link with green growth (Bouattour et al., 2025). Furthermore, in N-11 countries, green governance plays a mediating role in the relationship between green energy and green growth (Murshed, 2024). However, other scholars raise doubts about this relationship. They argue that the transition to renewable energy does not always significantly reduce dependence on fossil fuels (Holechek et al., 2022). In such cases, the shift may be insufficient to rapidly lower emissions, limiting its contribution to green growth (Hickel et al., 2020). Moreover, the effectiveness of green energy can be constrained by high costs, structural challenges in countries dependent on energy imports, and difficulties in policy implementation (Maji Et Al., 2019; Naimoğlu, 2022).
Overall, while green energy is increasingly recognized as important for both environmental quality and green growth, the evidence remains mixed due to factors, such as costs, availability, and varying economic conditions. Based on this evidence, these findings help formulate a hypothesis to examine the relationship.
H2: There is a positive and statistically significant relationship between green energy and green growth in the European regions.

3. Study Data and Methodology

3.1 Data and samples

This study examines the short-run and long-run impacts of green innovation and green energy on green growth. It focuses on 27 European countries, excluding Malta due to unavailable data, and covers the period from 2005 to 2024. The data are drawn from the World Development Indicators (WDI) and Our World in Data (OWDI).

Green growth is the dependent variable and is measured using two *proxies* to ensure robustness: (1) GDP per capita (US$) divided by CO_2 emissions per capita, and (2) GDP per capita (constant 2015 US$). These measures have been widely used in previous studies, including research on European economies and Turkey (Lu et al., 2025; Naimoğlu et al., 2025).

The main independent variables are green innovation and green energy, while investment, military expenses, and trade openness are included as control variables. Table 1 presents the detailed information regarding variables and data sources and figure 1 depicts the chosen study variables. Equation 1 expresses the variables relationship.

Table 1 Details of the variables, symbols, measurements, and data sources

Variables	Symbol	Measurements	Source
Green Growth	GG_1	Green growth = GDP per capita (US $) / CO_2 emissions per capita	WDI
Green Growth	GG_2	GDP per capita (constant 2015 US$)	WDI
Green Energy	GE	Share of primary energy consumption from renewable sources (%)	OWDI
Green Innovation	GII	Research and development expenditure (% of GDP)	WDI
Investment	IVE	Gross capital formation (% of GDP	WDI
Military Expenditure	ME	Military expenditure (% of GDP)	WDI
Trade Openness	TO	Sum of Import and Exports (goods and services (% of GDP))	WDI

Source: Authors' work

$$GG_{1,2} = f\,(GI, GE, CV) \qquad \textbf{(1)}$$

Where;

$GG_{1,2}$ = Green Growth

GI = Green Innovation

CV = Control Variables (Investment, Military Expenditure and Trade openness)

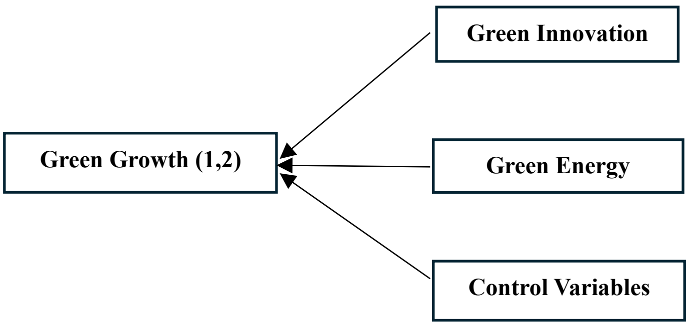

Fig. 1. Selected variables of the study. **Source:** Authors' work

3.2 Empirical Model

This study investigates the joint effects of green innovation (GI), green energy (GE), and green growth (GG) in European countries. To analyze the data, it applies a panel econometric approach. Among the available methods, the Panel Autoregressive Distributed Lag (ARDL) model is particularly suitable for capturing short-run dynamics, while also identifying long-run relationships. This approach has been widely used in previous research, including studies on green growth in G-7 countries (Qian et al., 2025), and on green financial development in Asian NDC countries (Ashraf et al., 2025).

The panel ARDL model, introduced by Pesaran et al., (1999) has the advantage that variables do not need to share the same order of integration, which makes it flexible for empirical analysis (Huang et al., 2015). This study employs the Pooled Mean Group (PMG) estimator, which allows short-run effects to differ across countries while assuming a common long-run relationship among them (Ashraf et al., 2025).

Before employing the Panel ARDL model, several conditions must be satisfied. First, all variables must be stationarity at level I(0) or at first difference I(1), with none integrated at I(2). To verify this and ensure the validity of the variables, this study employs three panel unit root tests: LLC (Levin-Lin-Chu), IPS (Im-Pesaran-Shin), and the Augmented Dickey-Fuller (ADF) test. Second, cross-sectional dependence must be tested, as strong correlations across countries can bias the results, turning it to be invalid. Third, co-integration tests, specifically Pedroni and Kao tests, are conducted to confirm the existence of a long-run relationship between variables. Finally, the error correction term (ECT) must be negative and statistically significant, indicating that the model is stable and correctly specified. The general econometric equation of the panel ARDL model is shown as follows:

$$\Delta\, GG_{1t} = \alpha_0 + \sum_{\vartheta=1}^{n} \alpha_1\, \Delta\, GG_{it-\vartheta} + \sum_{i=0}^{n} \alpha_2\, \Delta\, GI_{it-\vartheta} + \sum_{i=0}^{n} \alpha_3\, \Delta\, GE_{it-\vartheta} + \sum_{k=1}^{n} \alpha_4\, \Delta\, CV_{it-\vartheta} + \beta_0\, GG_{it-1}\ \beta_1\, GI_{it-1} + \beta_2\, GE_{it-1} + \beta_3\, CV_{it-1} + \varepsilon_t \qquad \textbf{(2)}$$

In Equation 2, the indices (t) and (i) denote time periods and cross-sectional units, respectively. Variables expressed in first differences (Δ) represent short-term effects, whereas the remaining variables reflect long-term relationships. The term (ε_{it}) denotes the error term of the model.

To examine the impact of green innovation and green energy on green growth, the study applies the ARDL framework. It also uses an alternative *proxy* for green growth to strengthen the validity of the findings. Moreover, FMOLS (Fully Modified Ordinary Least Squares) and DOLS (Dynamic Ordinary Least Squares) are employed as robustness checks to ensure the validity of the Panel ARDL results.

4. Results and Discussion (Green Innovation, Green Energy and Control Variable Impact on Green Growth)

4.1 Study Results

4.1.1 Summary of the Variables

Table 2 shows the descriptive statistics of the dataset from 2005 to 2024. Military expenditure has the lowest mean value, while green growth has the highest. Green growth also presents the highest minimum, maximum, variability, and median values, whereas green energy shows the least variation.

Table 2 Descriptive Statistics

Variables/Details	GG	GI	GE	ME	TO	IVE
Mean	8.33	0.31	2.32	0.28	4.71	3.11
Median	8.40	0.33	2.45	0.32	4.70	3.11
Maximum	9.78	1.31	3.96	1.42	6.02	3.98
Minimum	6.39	-1.00	-4.95	-1.55	3.81	2.48
Std. Dev.	0.61	0.59	-1.01	0.45	0.43	0.20
Observations	520	520	520	520	520	520

Source: Authors' work

Military expenditure has the lowest median value, while green innovation records the lowest maximum value and green energy the lowest minimum value.

Figures 2, 3, and 4 illustrate, respectively, the trends in green growth, green innovation, and green energy across European countries from 2005 to 2024. Overall, GG shows a steady upward trend over time. In contrast, green innovation displays mixed patterns, increasing in some countries while declining in others. Green energy, on the other hand, generally follows a consistent upward trend throughout the period.

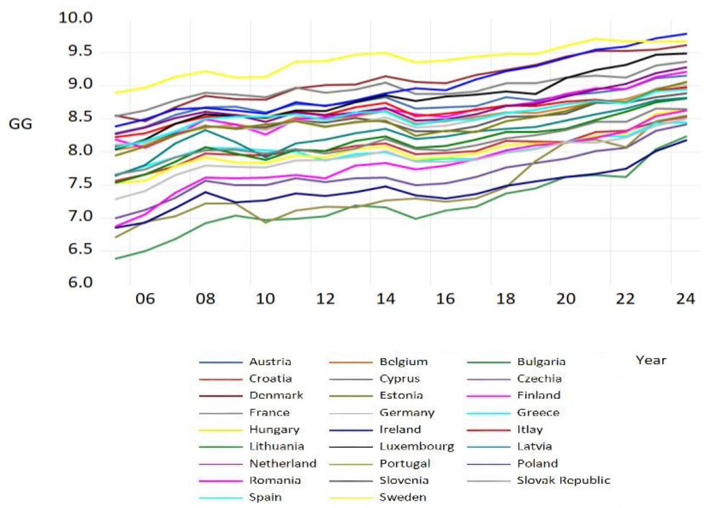

Fig. 2. Green Growth (2005-2024 European Union) - Source: Authors' work

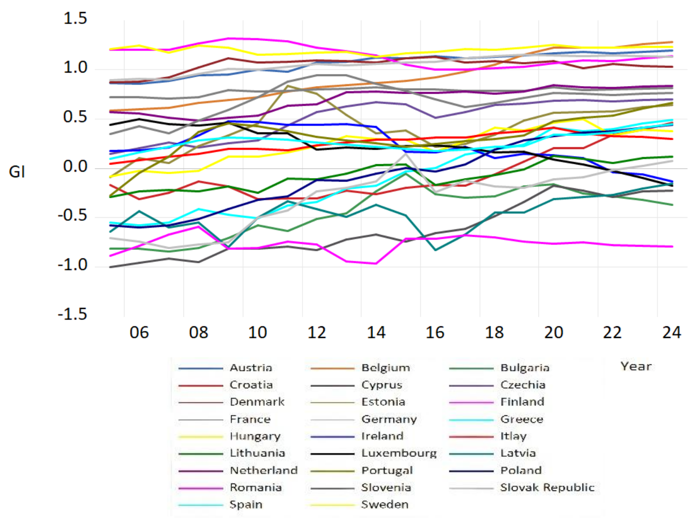

Fig. 3. Green Innovation (2005-2024 European Union) - Source: Authors' work

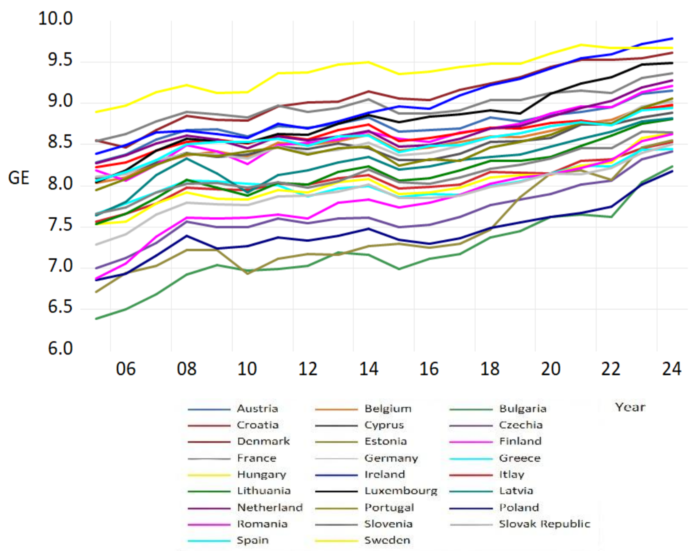

Fig. 4. Green Energy (2005-2024 European Union) - Source: Authors' work

4.1.2 Cross Section Dependence Test

Cross-sectional dependence arises in panel data when unobserved common factors affect all cross-sectional units, and if these factors are ignored, the resulting estimates may be biased (Shahbaz et al., 2018). Many countries share similar characteristics and experience common shocks, which creates the possibility of interdependence among them.

Table 3 Cross section dependence Test

Details	Stat	Prob
Breusch-Pagan LM	3662.075	0.00
Pesaran Scaled LM	130.8908	0.00
Pesaran CD	55.18212	0.00

Source: Authors' work

Table 3 presents the results of the cross-sectional dependence (CSD) tests for the study dataset covering the period 2005–2024. The Breusch–Pagan LM test yields a value 3666.075 ($p = 0.00$), while the Pesaran Scaled LM test records 130.891 ($p = 0.00$). Similarly, the Bias-Corrected Scaled LM test reports a statistic of 55.182 ($p = 0.00$). Taken together, these results reject the null hypothesis of no CSD. This evidence is consistent with previous panel studies conducted on Asian NDCs and South Asian Countries (Ahmad et al., 2024; Ashraf et al., 2025). Furthermore, the presence of CSD justifies the use of appropriate panel estimation techniques and unit root tests to ensure more reliable and accurate findings.

4.1.3 Panel Unit Root Test (LLC - Levin-Lin-Chu , IPS - Im-Pesaran-Shin, and ADF - Augmented Dickey-Fuller)

Table 4 provides the results of the panel unit root tests (LLC, IPS, and ADF) used to determine the stationarity of the study variables. Table 4(a) shows the LLC unit root test results, which indicate that all variables (GI, GE, IVE, ME, and TO) are stationary at both level and first differences. The only exception is GG, which is non-stationary at the level but becomes stationary after taking the first difference.

Table 4 Panel Unit Root Test (LLC, IPS, ADF)

Test	Variables	Level	First Difference
Levin, Lin, and Chu – LLC	GG	-1.56 (0.94)	-13.67 (0.00)
	GI	-2.26 (0.01)	-7.46 (0.00)
	GE	-6.32 (0.00)	-13.10 (0.00)
	IVE	-5.79 (0.00)	-14.74 (0.00)
	ME	4.25 (0.00)	-4.33 (0.00)
	TO	-3.99 (0.00)	-17.89 (0.00)
Im, Pesaran and Shin – IPS	GG	-5.02 (1.00)	-10.47 (0.00)
	GI	0.56 (0.71)	-7.03 (0.00)
	GE	-0.45 (0.33)	-12.62 (0.00)
	IVE	-4.58 (0.00)4	-14.08 (0.00)
	ME	3.73 (0.00)	-5.40 (0.00)
	TO	-1.16 (0.12)	-15.31 (0.00)
Augmented Dickey-Fuller – ADF	GG	12.20 (1.00)	204.88 (0.00)
	GI	50.39 (0.53)	142.92 (0.00)
	GE	59.10 (0.23)	249.48 (0.00)
	IVE	101.17 (0.00)	280.57 (0.00)
	ME	32.77 (0.01)	133.92 (0.00)
	TO	59.06 (0.23)	299.19 (0.00)

Source: Authors' work

Table 4 also presents the IPS unit root test results. The IPS outcomes show that the variables (GG, GI, GE, and TO) are stationary at the first difference, while IVE and ME are stationary at both the level and the first difference.

In addition, Table 4 reports the ADF unit root test findings. The ADF test confirms that variables IVE and ME are stationary at both level I(0) and first difference I(1). In contrast, the variables GG, GI, GE, and TO are non-stationary at level, but become stationary after taking the first difference.

4.1.4 Panel Cointegration Test

Following the panel unit root tests, the next step is to examine the long-run equilibrium relationship among the study variables (GG, GI, GE, IVE, ME, and TO). To this end, the study employs two widely used panel cointegration techniques: the Pedroni (1999, 2004) test and the Kao (1999) test. These panel cointegration methods have been extensively applied in prior empirical studies to analyze long-run relationships among variables in a panel data framework (Ashraf et al., 2025).

Table 5 (a) Kao Cointegration Test

t-statistics	Prob.
-3.806838	0.0001

Source: Authors' work

Table 5 (a) and Table 5 (b) present the panel cointegration results. Specifically, the Kao cointegration findings, presented in Table 5(a), indicate the presence of a long-run cointegrating relationship among the variables GG, GI,GE, IVE, ME, and TO.

Table 5 (b) Pedroni Cointegration Test

With Dimension

Details	Stat	Prob.	Stat	Prob
Panel v-statistic	-2.49	0.99	-3.79	0.10
Panel rho-statistic	2.66	0.97	2.30	0.99
Panel PP-statistic	-1.43	0.08	-2.23	0.01
Panel ADF-statistic	-1.99	0.02	-1.28	0.09

Between Dimensions

Details	Stat	Prob
Group rho-statistic	4.41	1.00
Group PP-statistic	-5.18	0.00
Group ADF-statistic	-2.92	0.00

Source: Authors' work

Table 5(b) reports the results of the Pedroni panel cointegration tests. These findings indicate that the variables are cointegrated, as the majority of the test statistics support the existence of cointegration among them. Overall, the panel cointegration tests confirm the presence of a long-run equilibrium relationship among the study variables (GG, GI, GE, IVE, ME, and TO). In addition, the panel unit root tests and cointegration tests collectively provide evidence that all variables are stationary and exhibit a stable long-run equilibrium. Based on these findings, the application of the PMG-ARDL model is appropriate, along with robustness checks using FMOLS and DOLS estimators, which effectively address issues of non-stationarity and endogeneity (Ashraf et al., 2025).

4.1.5 PMG-ARDL Model Outcomes

Table 6 presents the PMG-ARDL estimation results assessing the effects of GI), green energy (GE), investment (IVE), military expenditure (ME), and trade openness (TO) on green growth (GG) in the European Union in both the short-run and the long-run. The short-run results indicate that green innovation, green energy, and investment have positive and statistically significant effects on green growth, whereas military expenditure and trade openness exert negative and significant impacts. Moreover, the error correction term (ECT = −0.12, $p < 0.00$) is negative and statistically significant, confirming a stable adjustment towards long-run equilibrium. As a rule of thumb, a negative and significant ECT value validates the existence of long-run convergence. The long-run results reported in Table 6 further reveal that all explanatory variables – green innovation, green energy, investment, military expenditure, and trade openness - have a positive relationship with green growth in the European Union over the long run.

Table 6. Result of PMG-ARDL Model

Short run Results				
Details	**Stat**	**Stand Error**	**T-stat**	**Prob**
GI	0.25	0.03	1.93	0.00
GE	0.14	0.13	2.80	0.00
ME	-0.12	0.06	-1.80	0.07
TO	-0.33	0.08	-3.96	0.00
IVE	0.22	0.09	2.48	0.01
ECT_{-1}	-0.12	0.03	-3.44	0.00
Long run Results				
Details	**Stat**	**Stand Error**	**T-stat**	**Prob**
GI	0.39	0.08	5.12	0.00
GE	0.11	0.03	4.12	0.00
ME	0.89	0.07	12.41	0.00
TO	0.64	0.08	8.02	0.00
IVE	1.61	0.13	12.47	0.00

Source: Authors' work

4.1.6 Diagnostic Test

Table 7 presents the diagnostic test results for the empirical model. The findings indicate the absence of heteroskedasticity and confirm that the residuals are normally distributed. These outcomes suggest that the model is well specified and therefore, the estimated results are reliable and suitable for interpretation.

Table 7. Post Estimation Diagnostics Tests

Test	Stat	Prob.	Conclusion
Heteroskedasticity Test	-18.600	0.8529	No Heteroskedasticity
Normality (Jarque Bera)	0.0108	0.9946	Residuals are normally distributed

Source: Authors' work

4.1.7 Robustness Test (Fully Modified OLS (FMOLS) and Dynamic OLS (DOLS))

Table 8 (a) and Table 8 (b) show the robustness test results using the FMOLS and DOLS estimators. These findings are consistent with those obtained from the PMG-ARDL model, thereby reinforcing the validity and reliability of the PMG-ARDL results. In both the FMOLS and DOLS estimations, the explanatory variables (GI, GE, INE, ME, and TO) exhibit a positive relationship with green growth in the European Union.

Table 8 (a) Robustness test

FMOLS Test

Details	Coeff.	Stand Error	T-stat	Prob
GI	0.50	0.004	130.44	0.00
GE	0.19	0.004	46.04	0.00
ME	0.18	0.004	40.60	0.00
IVE	1.28	0.001	793.89	0.00
TO	0.76	0.001	705.61	0.00

DOLS Test

Details	Coeff.	Stand Error	T-stat	Prob
GI	0.51	0.045	11.44	0.00
GE	0.29	0.033	8.58	0.00
ME	0.20	0.071	2.83	0.00
IVE	0.87	0.103	8.47	0.00
TO	0.99	0.062	16.01	0.00

Source: Authors' work

4.1.8 Robustness Test (With Another Green Growth Proxy) Green Growth

This study employs two alternative *proxies* for green growth to investigate the combined effects of green innovation and green energy on green growth in the European Union, thereby ensuring the validity and accuracy of the results. Table 9 (a) and Table 9 (b) present the robustness test outcomes based on the FMOLS and DOLS estimators. The results show that the explanatory variables (GI, GE, INE, ME, and TO) are positively associated with green growth. These robustness findings are consistent with those obtained using the first *proxy* of green growth and align with the PMG-ARDL model results.

Table 9 (a) Robustness test

FMOLS Test

Details	Coeff.	Stand Error	T-stat	Prob
GI	0.77	0.003	202.14	0.00
GE	0.06	0.004	16.49	0.00
ME	0.05	0.004	11.42	0.00
IVE	1.54	0.001	959.57	0.00
TO	1.02	0.001	947.15	0.00

DOLS Test

Details	Coeff.	Stand Error	T-stat	Prob
GI	0.08	0.044	1.79	0.07
GE	0.03	0.014	2.30	0.02

ME	0.10	0.035	2.88	0.00
IVE	0.16	0.050	3.23	0.00
TO	0.39	0.076	5.15	0.00

Source: Authors' work

4.2 Discussion on the Short-run and Long-Run Results between Green Innovation, Green Energy, Control Variables, and Green Growth

This study investigates the short-run and long-run effects of green innovation and green energy on green growth. The empirical results indicate that green innovation exerts a positive and statistically significant impact on green growth in both the short and long run, with a stronger effect observed over the long run. These findings are supported by robustness estimation techniques, including FMOLS and DOLS, as well as by the application of an alternative *proxy* for green growth, thereby confirming the PMG-ARDL results. Overall, the empirical evidence supports the study's hypothesis. These results are aligned with previous studies conducted in BRIC countries (Chen et al., 2023), African countries (Teklie et al., 2024), the European Union (Abbas et al., 2024), and 12 developing countries (Abbas et al., 2024). Within the European Union, green innovation plays a critical role in enhancing environmental quality and promoting green growth. Innovation contributes by reducing costs, introducing new production methods, increasing energy efficiency, and improving green energy storage capacity. Consequently, innovation exerts a positive influence on green growth within the EU. Furthermore, the Eco-Innovation Index of EU Member States (2014–2024) supports these findings, showing substantial progress in innovation in countries such as Finland, Denmark, Austria, and Luxembourg since 2014. This progress has contributed to reduce environmental damage, strengthen resilience, and foster green growth. Similar conclusions have been drawn for the BRICS countries, where innovation promotes technological advancement, reduces energy consumption, encourages energy efficiency, and ultimately supports green growth (Chen et al., 2023).

The study also shows that green energy has a positive and statistically significant influence on green growth in both the short-run and long-run within the European Union. Robustness checks and alternative measures of green growth confirm these results, supporting the second hypothesis of the study. These outcomes are aligned with previous studies conducted in E-7 countries (Jiang et al., 2023), across 27 European Union (EU) countries (Bouattour et al., 2025), and in 10 EU countries (Aydin et al., 2024). The positive relationship between green growth and green energy can be largely explained by the European Green Deal, which promotes the transition toward environmentally friendly energy sources while simultaneously supporting economic growth. The Green Deal is based on three key pillars: ensuring affordable energy, developing an integrated energy market supported by digitally connectivity, and enhancing energy efficiency through improvements in buildings structures and energy systems. In this framework, innovation plays a central role by fostering new technologies and modern infrastructure. Innovation enhances the performance of green energy systems, thereby reinforcing green growth. Similar evidence from 12 developing countries highlights how green innovation, technological advancement, renewable energy use, and energy-efficient building materials and production processes contribute to green growth (Abbas et al., 2024).

In addition to green innovation and green energy, the control variables also play a significant role in promoting green growth and are closely interconnected. In the long run, military expenditure, trade openness, and investment a positive relationship with green growth in the European Union. These findings are consistent with prior studies conducted in the world's top 20 military-spending countries (Das et al., 2023), across 30 provinces and cities in China (Xiao et al., 2023), and BRICS countries (Feng et al., 2024). Military expenditure and trade openness are linked to investment, as trade openness facilitates investment flows that are associated with imports and exports. Military expenditure often includes investments in weapons, technology and innovation, particularly in defense systems, frequently supported by international trade. These activities can stimulate economic projects, including environmentally oriented initiatives, thereby supporting green growth (Das et al., 2023).

In the short run, however, military expenditure and trade openness have a negative impact on green growth, while investment maintains a positive effect. These results are in line with previous studies conducted in Turkey (Naimoğlu et al., 2025; Sohag et al., 2019), OECD regions (Sohag et al., 2021), and ASEAN-6 countries (Sharif et al., 2023). In the short-run, increases in expenditure and trade may divert resources away from environmental initiatives, leading to a temporary negative effect on green growth. In contrast, investment positively influences green growth in the short run for green growth, as funds are often directed toward green projects, thereby supporting sustainable economic development.

5. Conclusions, Policy Recommendations and Future Research

This study investigates the combined effects of green innovation, green energy, and key control variables on green growth in the European Union from 2005 to 2024. The analysis employs the PMG-ARDL econometric approach and ensures the validity of the results through the application of the robustness tests of FMOLS and DOLS estimators, as well as by using an alternative *proxy* for the green growth. Prior to applying the PMG-ARDL model, all necessary econometric conditions were satisfied: the variables are stationary at levels and first differences, cross-sectional dependence is properly addressed, and long-run cointegration among the variables is confirmed. The findings reveal that both green innovation and green energy have a positive and significant relationship with green growth. Moreover, these two factors reinforce each other through their joint effect, thereby promoting green growth outcomes. With respect to the control variables, military expenditure and trade openness exert a positive influence on green growth in the long run, while their effects are negative in the short run. In contrast, investment contributes positively to green growth in both the short run and the long run. Overall, the results demonstrate that green innovation and green energy have a combined impact on green growth, and that all control variables are interconnected and play a central role in promoting green growth, together with green innovation and green energy.

The robustness tests using FMOLS and DOLS yields results consistent with the baseline model, and the alternative *proxy* for green growth confirms the stability and validity of the findings. These consistent outcomes highlight a strong and reliable relationship between green innovation, green energy, control variables and green growth. Based on these findings, the study offers several policy recommendations aiming at enhancing green growth and sustainability in the European Union. First, the results indicate that green innovation is a particularly important driver of green growth. Policymakers should therefore increase investment in the innovation industry, as green innovation facilitates the energy transition process, supports the development of green energy, and ultimately promotes sustainable economic growth. Special attention should be given to European countries where innovation performance remains relatively weak, such as Poland, Bulgaria, Lithuania, Latvia, Greece, and Hungary. Policies should be designed to strengthen investment reliability and encourage innovation, as advanced technology and tools are essential for both the green energy transition and the development of modern military technologies.

In addition, policymakers should consider increasing investment in military expenditure, as a strong defense system plays a critical role in protecting energy systems and infrastructure. While this study provides evidence on the combined impact of green innovation and green energy on green growth in the European Union, it also faces some limitations. One key limitation is data availability, as the analysis relies on World Development Indicators (WDI) data. Future research could use OECD green growth indicators to compare results and enhance robustness. Moreover, future studies could further explore the combined impact of investment in green innovation and green energy in promoting green growth. Finally, the application of advanced econometric techniques, such as the Generalized Method of Moments (GMM), and the extension of the analysis to other regions, including BRICS and ASEAN countries, would provide valuable insights and strengthen the generalizability of the findings.

6. References

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