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The Impact of Patent-Based Innovations, Electric Vehicle Adoption, and Renewable Energy on Economic Growth: Evidence from Cross-Country Panel Data (2010–2024)

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Abstract
The current research examines the relationship among economic growth rate, technological innovation, the use of electric vehicles and energy use based on a panel research of the countries in the study period selected. As a measure of economic development, economic growth, which is expressed as real GDP per capita, is viewed as one of the indicators of development, whereas patents are employed to measure the innovation activities, and the adoption of electric vehicles is viewed as the process of transition to the sustainable mobility. Energy consumption comes to define the significance of energy in facilitating economic activities. In the study, advanced panel econometric techniques are used to explain the dynamic nature and heterogeneity of cross-country data. The first panel unit root tests show that variables are non-stationary in levels but become stationary which corresponds to the inclusion of integrative levels of dynamic modeling (Pesaran, 2015). The Westerlund (2007) panel cointegration test which is based on error correction is used in order to test the possible relationship between these variables at the long-run equilibrium. The findings imply that there are heterogeneous long-run relationships among the countries; thus, the CCEMG estimator is used to represent the cross-sectional dependence and national specific dynamics. The use of sophisticated panel econometric models such as the Pooled Mean Group (PMG) and Common Correlated Effects Mean Group (CCEMG) estimator were applied to fit the long-run relations, short run dynamics, cross-sectional dependence, and country relative heterogeneity. The techniques improve reliability and soundness of the empirical results.

Keywords: Electric vehicles, technological innovation, westernlund cointegration, energy consumption, and economic growth

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1. INTRODUCTION

The growth of the economy has been one of the key goals of the national development policies. According to the classical and neoclassical growth theories, capital accumulation, labour and technological advancement was considered the main cause of growth (Solow, 1956; Romer, 1990). Technological innovation is one of these aspects which have acquired a very high position as the aspect increases the productivity, industrial upgrading, and helps economies to experience a long-term growth beyond the boundaries of the traditional factor accumulation. Over the last several decades, the character of innovation has shifted dramatically, and more and more focus is placed on the eco-friendly technologies that would allow growing the economy and protecting the environment at the same time.

This has led to patent-based innovation being a well-received measure of the innovative ability of a country. Patents are a result of research and development (R and D) projects and they offer a legal security that will encourage inventors and companies to invest in new technologies. Endogenous growth theory points out that innovation (which is usually represented by patent activity) generates positive spillover effects, which enhances productivity in all the sectors and leads to the long term economic growth (Romer, 1990; Aghion and Howitt, 1992). The empirical data continuously show that the more developed the patent system of a country and the intensive is the innovation, the more rapid is the course of economic development and the level of structural transformation (Hall, Jaffe, and Trajtenberg, 2005).

Simultaneously, the world economy is experiencing a radical shift under the influence of the environmental issues, climate change pledges, and energy security issues. Increasing greenhouse gas emissions, the frequency of catastrophes associated with climate change, and the intensity of pressure on natural resources have made governments consider the idea of reinstating traditional growth paradigms that are largely fueled by fossil fuels. Therefore, the shift to renewable energy and clean techs has already become one of the marks of the modern development economy approach (Stern, 2011). The key aspect of this transition is innovation, which would make it possible to create and spread cleaner, more efficient energy technologies.

The innovation that is based on patents is a very critical mechanism by which economies are able to develop better technological aspects and improve the productivity. Patents do not just act as a legal tool but also a good source of technological knowledge and are used to learn, imitate and innovate cumulatively. According to the theoretical models, innovation-based growth occurs when companies make research and development efforts to develop new or better products and processes, which enhance efficiency in better production and create competitive advantages (Aghion and Howitt, 1992).

This theoretical connection has ample empirical support. Hall et al. (2005) discover that a quality of patent as measured by patent citation has a positive relationship with firm-level productivity and market value. Macroeconomically, patent intensity has been found to play a role in economic growth in the long run through increasing total factor product and granting economies an opportunity to climb up the value chain in the world. But according to more recent findings not every patent yields equal growth; patents in

Volume 5 Issue No 1 (2026)
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clean energy development, in environmental technology and so-called low-carbon solutions, seem to produce higher returns on both social and economic fronts (Acemoglu et al., 2012).

Patent-based innovation has two roles to play in the framework of sustainable development. First, it has a direct impact on the economic growth in terms of productivity and industrial development. Second, it indirectly promotes growth through facilitation of more clean production processes, minimization of environmental destruction and increase in the energy efficiency. This two land is becoming even more critical with the countries trying to decarbonate economic growth and environmental degradation.

The transport industry is a significant source of carbon emissions in the world, so it is an area of major interest in the reduction of climatic change. Electric cars (EVs) have proven to be a radical technology, which can greatly cut the emissions, especially when fueled with renewable energy sources. The lack of EV innovation and free development of markets up to 10 years ago and the current growth rates are evidence of battery and charging mobs along with government policies helping to promote this phenomenon.

Innovation is closely related to EV adoption. The lithium-ion batteries, power electronics, and vehicle design technological advances have been discovered thanks to patent activity that have led to a lower cost of production and a higher performance of the vehicle, increasing faster penetration. Economically, the EV market sparks economic development through providing new manufacturing industries, highly skilled workers, and upstream and downstream industries such as battery manufacturing, software creation, and the development of charging stations (Xie, Zhao, and Ding, 2024).

In addition, the macroeconomic impacts of EV adoption may be more widespread. Decreased reliance on imported fossil fuels strengthens energy security and trade in balances and decreased air pollution is beneficial to the health and labor output of the people. Empirical research is slowly gaining evidence that the market development of EVs with the help of innovation has a positive effect on sustainable economic growth, especially in those countries where the institutional framework and technological skills that help support their development are highly developed.

Another pillar towards sustainable economic development is the adoption of renewable energy. Solar, wind, hydro and bioenergy technologies have grown at an accelerated rate since 2010 due to the reduction in costs, advancement in technologies, and government incentives. Innovation is critical with regard to this growth, enhancing the efficiency, the storage capacity and grid integration of renewable sources of power.

The interaction between renewable energy and the economic growth is a wide studied topic, but it is a complicated and context-related topic. Although, initially, some studies expressed worries about the growth-reducing impact of renewable energy thanks to the high initial investment costs, more recent data indicates the possibility of stimulating economic growth, decreasing energy prices in the long-term perspective, establishing new jobs, and spurring technology development with the help of renewable energy consumption (Khan and Su, 2022). Specifically, the patents of clean energy have been

Volume 5 Issue No 1 (2026)
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proven to increase the renewable energy production capacity and contribute to the long-term economic performance (Zambrano-Monserrate et al., 2024).

Notably, the renewable energy, EV adoption, and innovation based on patents are not standalone phenomena. They are dynamic at a combined sustainable development system. Innovation spurs the use of renewable energy; the presence of renewable energy increases the environmental impacts that EVs have; and EV implementation, in its turn, incites a demand in technological advances. These interdependencies are important to understand so as to create effective growth and climate policies.

Although the problem of innovation, renewable energy, and EVs is becoming increasingly adequately addressed in the literature, there are multiple gaps. To start with, most of the current studies focus on these factors individually and not in the context of a consistent methodology of analysis. Second, most studies are conducted on one or few countries or over short intervals reducing the applicability of the research to the general population. Third, a relatively small number of studies place patent-based innovation in the central place of explanatory variable when examining the economic effects of EV adoption and renewable energy consumption.

The 2010-24 era symbolizes a pivotal time in the international sustainability transition, which is typified by technological revolution, ambitious climate action, and massive growth of clean power and EV industries. Both short run and long run relationships can be examined by a cross country panel analysis that spans this period and incorporates the heterogeneous economies. This method can offer a solid empirical data to the question of whether patent-driven innovation, EV adoption, and renewable energy have a significant impact on the growth of the economy when arguably combined with others.

This research is relevant to the literature in a number of ways. First, it condenses patent-based innovation, EV adoption, and renewable energy consumption into a common empirically grounded framework and can help to gain a holistic view regarding the dynamics of sustainable growth. Second, the study uses cross-country panel data, 2010-2024 to capture any project of new technology and policy advancements, which are not adequately reflected in the prior study. Third, the results are policy-relevant to the effect that the innovativeness-related sustainability strategy can be used towards economic growth in the long term.

The studies will inform policymakers, researchers, and other international organisations involved in trying to strike a balance in economic development and environmental sustainability by conducting empirical studies on the interaction between innovation and clean technologies. By so doing, it would be in line with the global development agendas, such as the Sustainable Development Goals (SDGs), specifically those pertaining to affordable clean energy, industry and innovation, and climate action.

2. Literature Review

This paper critically examines the theoretical and empirical literatures surrounding the theory of patent based innovation, the use of electric vehicle (EV), and the use of renewable energy and its effect on economic growth. It is completed with an identification of research gaps and locating the current research in the literature.

Solow (1956) created the neoclassical growth model which concluded technological development as the major cause of long term economic growth following capital and

Volume 5 Issue No 1 (2026)
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Print ISSN: 3006-2039

labor accumulation. Despite the fact that technological change is considered exogenous, the framework by Solow offers a basis of the theoretical foundation on the subsequent investigation on how technological change relates to productivity growth and innovation. His framework stresses the idea that the only way one can sustain economic growth would be a factor accumulation and thus encouraging subsequent studies which has employed signs of innovation measured by patents.

To build more on the growth theory, Romer (1990) made technological change endogenous and stressed on the significance of accumulation of knowledge and innovation. He claims that innovation gives rise to non-rival knowledge externality, and would result in escalating returns and a continuous economic growth. This theory presents a very good reason why patent-based instrumentalities should be employed in capturing the innovation activity in empirical studies of growth.

Grossman, and Helpman (1991) studied the theme of innovation-led growth under an open-economy setting in which they indicated that trade openness and international spillovers of knowledge enhance the economic growth impact of innovation. They propose in their work that the global dispersion of patented technologies and the macroeconomic outcomes cannot be effectively collected without the use of cross-country panel studies.

The creative destruction framework brought up by Aghion and Howitt (1992) points out that economic growth is a result of continuous innovation that brings innovative technology that removes outdated technologies. Their model establishes that protection of patents acts as an incentive to invest in R&D thus increasing the pace of growth in productivity. This framework is especially pertinent with regard to the factual references to the economic structures that are transformed by clean and energy-related innovations.

Coe and Helpman (1995) also proved that the international R&D spillovers have a strong impact on increasing domestic productivity especially in those nations that have a high absorptive capacity. Their research supports the significance of patent diffusion and international innovation networks in the description of cross-country differences in economic growth.

The studies of Popp (2002) were done on the environment innovation; it was identified that an increased price of energy and environmental policies encourage clean technology patents. According to his findings, innovation in renewable energy is policy responsive which substantiates the argument that, according to his arguments, patent based innovation is strategic in sustainable growth of the economy.

Empirical evidence of the quality of innovations was conducted by Hall, Jaffe, and Trajtenberg (2005) through the use of patent citations and indicated that quality patents are positively correlated to the productivity of a firm. Their results focus on the fact that innovation-based growth is not only a matter of quantity of the patent but also technological relevance, which is an essential factor when comparing clean energy and EV-related patents.

In a study of the past and current level of renewable energy usage and income increase in the emerging economies, Sadorsky (2009) revealed that renewable energy has a positive impact on the economical performance. This paper opposes the initial fears in

Online ISSN: 3006-2047
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regard to the growth-discriminating impacts of renewable energy and the relevance of technological advancement in minimizing costs.

Apergis and Payne (2010) gave panel evidence of a feedback relationship between economic growth and renewable energy consumption, which indicates that there is an interrelation between energy transitions and economic performance. Their contribution is based on emphasis on the necessity to take into account dynamic relationships within a panel environment.

Stern (2011) gave a solid economic evaluation on climate change wherein, it was found that the early spending on clean technologies and innovation has economic paybacks in the long term. His article confirms the idea that sustainable innovation is consistent with economic growth goals.

Acemoglu et al. (2012) created a directed technical change hypothesis and proved that an innovation could be directed at environmentally friendly technologies without the need to compromise economic growth. They present powerful theoretical and empirical evidence of analyzing clean energy patents as a source of growth in their study.

Aghion et al. (2016) explored the activity of the environmental measures in encouraging the green innovation and discovered that effective regulations can stimulate clean patents without any toxicity to productivity. Their research lends relevance to the policy of the innovation-led growth.

The article by Bhattacharya et al. (2016) examined the idea of renewable energy use and economic development in emerging economies and revealed that renewable energy promotes economic development provided supported by innovation and institutional quality. They focus on the national heterogeneity in their study.

In order to determine the causality of innovation and economic growth, Maradona et al. (2017) employed the panel causality tests and established a two-way causality element both between innovation and growth. This finding suggests that economic development is not only propelled by innovation, but it also is an outcome, and therefore necessitates dynamic econometric models.

Shahbaz et al. (2017) examined the relationship between renewable energy, financial development and economic growth and established that renewable energy has a positive effect on the growth in the presence of well-developed financial systems. Their results emphasize the significance of complementary institutions.

Chen and Lin (2020) analyzed innovations in clean energy patents and energy efficiency in OECD countries, as a result of which it turns out that with innovation, the intensity of energy can be greatly reduced, which contributes to the growth of the economy. Their analysis gives importance to the effect of advances in technology on attained energy efficiency.

Li et al. (2020) have studied how EV adoption and carbon reduction relate and found that EV diffusion brings about environmental and economic positive results in the case of renewable energy. Their results indicate the co-existence of EVs and clean electricity.

The cross country panel data helped to determine as Liu et al. (2021) observed that renewable energy and innovation affect the increase in economic growth positively, with the growth being magnified by the innovative force. Their findings favor composite modeling solutions.

Li and Lin (2021) examined the issue of renewable energy innovation and green economic development and found out that the spillover effects associated with clean technology patent creation are beneficial and produce increased productivity. Their results justify the incorporation of the indicators of innovation in growth models.

The article by Khan and Su (2022) was an empirical test of how technological innovation facilitates the consumption of renewable energy and the results indicated a positive association. Their paper affirms that innovation is a driving force behind the use of renewable energy.

The Agency of International Energy (2023) has reported that the adoption of EVs is growing at a rapid rate across the world because of technological advancement, low battery prices, and enabling policy. The report indicates that EV diffusion triggers industrial growth and economic activity.

Xie, Zhao, and Ding (2024) empirically studied the correlation between technological innovation and EV solds and concluded that innovation can boost the development of the EV market at a significant rate. Their analysis shows that patenting in battery and charging technologies is relevant in the change of them to supportive of sustainable economic growth.

Zambrano-Monserrate et al. examined the dynamic impact of patents on clean energy on renewable energy generation and found that innovation through patent-based means would significantly promote renewable production in the long-term. Their results support the thesis that sustainable growth is a process that is driven by innovation.

Although there has been much advancement, there are a number of gaps in literature. To begin with, limited literature includes patent-based innovation as a fundamental independent factor in the study of economic effects of EVs and renewable energy usage. Second, the recent years of 2010-24 are still not well represented in empirical evidence, even though the technological and policy changes in this time were rapid. Third, most of them have a single-country analysis, which restricts external validity.

This paper requests fill these gaps as it combines the idea of patent-based innovation, EV adoption, and the use of renewable energy into one, cross-country panel framework. In such a way, it will help to gain a better comprehension of the role of innovation-based sustainability transitions in economic development in the advanced economies.

3. Methodology

This research paper explains the sources of data, how the variable was constructed, and the econometric approach used to empirically investigate how patent-based innovation, electric vehicle uptake, and consumption of renewable energy affect the economic growth. With the cross-countries (Australia, Canada, China, France, Germany, Italy, Japan, New Zealand, United Kingdom, and United States of America), cross-sectional dependence, long-run dynamics, and heterogeneity, the advanced panel econometric methods are embraced to consider cross-country, cross-sectional dependence and long-run dynamics. The research methodology is well structured to guarantee strong and policy-relevant empirical evidence.

3.1 Data and Variables:

Data is developed based on international and popular databases in order to guarantee consistency and comparison between countries:

Dependent Variable

Economic Growth (GDP per capita, PPP (constant 2021 international $) sourced from World Development Indicators (WDI).

The natural logarithm of real GDP per capita measures the economic growth. The GDP per capita is generally recognized as having an overall measure of the economic performance and standards of living (Barro, Sala-i-Martin, 2004).

Independent Variables

Patent-Based Innovation (lnPat) sourced from World Intellectual Property Organization (WIPO).

Innovation based on patents is quantified on the basis of amount of resident patent applications per capita. National patents embody commercially good innovation and are extensively applied as for signs of technological advancement in development research (Hall et al., 2005).

Electric Vehicle Adoption (lnEV) sourced from The International Energy Agency (IEA).

EV registrations are proxied as electric vehicle adoption. This variable signifies the structural change in the transport sector and technological diffusion of the clean mobility solutions (IEA, 2023).

Renewable Energy Consumption (lnRE) sourced from The World Bank and IEA.

The proportion of renewable energy in the overall final energy consumption is the measure of renewable energy consumption. This indicator displays the level of the sustainability of the energy system and clean energy transition (Apergis and Payne, 2010).

Control Variables

Gross Capital Formation (lnGCF) sourced from World Intellectual Property Organization (WIPO).

This is included to reflect investment driven effects of growth, which is consistent with the neoclassical and endogenous growth models.

Energy Consumption (lnEC) sourced from World Intellectual Property Organization (WIPO).

Overall energy demand controls, which form one of the major inputs on the economic production processes.

Variables are all converted to natural logarithms so that stabilize variance and give a coefficient interpretation that is elasticity-based.

3.2 Econometric Model Specification:

The baseline long-run growth model is specified as follows:

$$\ln GDP_{it} = \alpha_i + \beta_1 \ln Pat_{it} + \beta_2 \ln EV_{it} + \beta_3 \ln RE_{it} + \gamma X_{it} + \varepsilon_{it}$$

where i denotes country, t denotes time, αi captures country-specific effects, X_{it} is a vector of control variables, and ε_{it} is the error term.

3.3 Preliminary Diagnostic Tests:

Volume 5 Issue No 1 (2026)
Online ISSN: 3006-2047
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Considering the rising globalization and economic integration, cross-sectional dependence will not be any good to ignore and may across biased estimations. As such, it uses Pesaran (2004) CD test in order to identify cross country cross-sectional dependence. Second-generation panel unit root tests are used in order to establish the order of integration of the variables. In particular, it is the Fisher-type ADF test that is used because it is flexible. The slope homogeneity test of Pesaran and Yamagata (2008) was used to test whether the slope coefficients diffuse between panel units. The findings show that the slopes are heterogeneous. The variables are integrated of order I(0) or I(1) hence, cointegration techniques are used. Westernlund (2007) panel cointegration error-correction test is employed to investigate the presence of an equilibrium relationship between the variables in a long-run. It has been used because this test takes into consideration the heterogeneity and cross-sectional dependence. Therefore, in this study, the Long-Run and Short-Run Technique of estimation will be used.

After ascertaining the cointegration, the Augmented Mean Group (AMG) estimator by Eberhardt and Teal (2010) is used, which allows cross-sectional dependency and heterogeneous slope coefficients across countries. Pooled Mean Group (PMG) estimator formulated by Pesaran, Shin, and Smith (1999) enables the short-run dynamics and error variances to vary among countries, but the coefficients in the long-run are heterogeneous.

The PMG-based error correction model (ECM) is specified as:

$$\Delta \ln GDP_{it} = \phi_i(\ln GDP_{it-1} - \theta' Z_{it-1}) + \sum \psi_{ij} \Delta Z_{it-j} + \mu_i + \epsilon_{it}$$

where ϕ_i is the error correction term indicating the speed of adjustment toward long-run equilibrium.

PMG is especially appropriate when studying across countries with a similarity in long run relationships in the economy but dissimilar short run dynamics because of institutional and structural differences (Pesaran et al., 1999). The estimator has extensively found application in growth-energy-innovation literature.

Other specifications based on CCEMG (Common Correlated Effects Mean Group) estimation and other control variables are weighed to make them robust. Serial correlation and heteroskedasticity diagnostic tests are also undertaken in order to establish the reliability of the estimates.

4. Results and Discussion

4.1 Descriptive Statistics:

Table 4.1 presents the descriptive statistics of the variables used in the analysis. All variables are transformed into natural logarithms to ensure normality and comparability across countries.

Table 4.1: Descriptive Statistics

Online ISSN: 3006-2047
Print ISSN: 3006-2039

Source: Author's calculation based on (IEA), (WIPO) and WDI (2007–2024).

Variable	Mean	Std. Dev.	Min	Max
lnGDP_pc	10.75	0.38	9.25	11.23
lnPat	9.98	2.34	0	14.32
lnEV	9.45	2.91	0	15.67
lnRE	3.38	0.60	1.92	4.47
$LnCo_2$_e	2.10	0.38	1.37	2.90
lnEC_pc	10.76	0.42	9.98	11.64
lnGCF	3.12	0.54	-0.90	3.834

The descriptive statistics imply that the degree of economic performance variation is moderate in the sample with lnGDP_pc on average is 10.75 implying that the level of income varies across countries. Innovation (lnPat) and adoption of electric vehicles (lnEV) demonstrate a significant dispersion, as it is possible to see a wide cross-country heterogeneity in technological progress and EV diffusion. The consumption of renewable energy (lnRE) and carbon emissions (lnCO 2 e) have relatively smaller variability, which means that the trends of energy and emission are more consistent. There is moderately stable energy consumption per capita (lnEC), whereas the gross capital formation (lnGCF) exhibits moderate variations, reflecting the variations in investment dynamics. In sum, the differences in the key variables in the green factor and innovation substantiate the suitability of the variables in the depiction of the cross-country economic growth.

4.2 Correlation Analysis:

Table 4.2. Pairwise correlation matrix

Variable	lnGDP_pc	LnPat1	RE	lnEV1	$lnCo_2$_e	lnEC	lnGCF
lnGDP_pc	1.0000						
lnPat1	-0.4216	1.0000					
lnRE	0.1014	−0.6030	1.0000				
lnEV1	−0.1072	0.5077	−0.1126	1.0000			
$lnCo_2$_e	0.2320	0.2529	−0.0378	-0.0421	1.0000		
lnEC	0.5733	-0.2485	0.1948	−0.2097	0.7697	1.0000	
lnGCF	-0.3396	0.1194	-0.0243	-0.0095	0.0055	-0.0555	1.0000

Source: Author's calculation based on (IEA), (WIPO) and WDI (2007–2024).

Correlation matrix reveals that lnGDP is positively correlated with energy consumption (lnEC) and CO_2 emissions ($lnCO_2$_e) meaning that the higher one has income, the more the energy is consumed and the emission of CO_2 is. Conversely, there are negative relationships between patent-based innovation (lnPat1) and gross capital formation

Volume 5 Issue No 1 (2026)
Online ISSN: 3006-2047
Print ISSN: 3006-2039

(lnGCF) and income suggesting that their effects may be exerted either through long-term or indirect growth processes. The relationships between renewable energy (lnRE) and innovation as well as CO_2 emissions are negatively oriented, which presupposes the possible alleviating effect on the pressure on the environment. The r values between the explanatory variables are on average moderate meaning that there are no serious issues of multicollinearity and their combination in the regression model can be conducted.

4.3 Cross-Sectional Dependence Test

To test whether cross-country observations are independent, the Pesaran (2004) CD test is applied.

Table 4.3: Cross-Sectional Dependence Test

Variables	CD Statistic	Avg. Abs. Correlation
lnGDP_pc	22.24***	0.856
lnPat1	2.57***	0.406
lnRE	14.07***	0.851
lnEV1	24.40***	0.939
$lnCo_2$_e	14.34***	0.903
lnEC	13.00***	0.854
lnGCF	4.51***	0.456

Source: Author's calculation based on (IEA), (WIPO) and WDI (2007–2024).

Notes:

***, ** denote significance at the 1% and 5% levels, respectively. The null hypothesis assumes cross-sectional independence.

The test results in Pesaran (2004) CD test show that across all the variables, there is strong cross-sectional dependence, or that is statistically significant CD statistics and that the average absolute correlation is relatively large. This implies that all the countries in the panel are affected by shared global shocks, such as spillovers, as well as interdependencies, especially in the area of economic development, energy consumption, emissions CO_2 and the adoption of electric vehicles. As a result, second generation panel econometric methods are suitable to be used to further examine.

4.4 Panel unit-root tests:

Table 4.4: Panel Unit Root Test (ADF-Fisher)

Variables	Level (Fisher χ^2)	First Difference(Fisher χ^2)
lnGDP_pc	20.01	104.31**
lnPat1	37.04***	-
lnRE	19.32	83.26**
lnEV1	9.71	66.61**
$lnCo_2$_e	3.20	98.23**
lnEC	8.34	98.72**

Volume 5 Issue No 1 (2026)
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lnGCF	33.84***	-

Source: Author's calculation based on (IEA), (WIPO) and WDI (2007–2024).

The findings are that there is a mix of the order of variables I (0) and I (1): no one is integrated of order I (2). This meets the requirements that are needed to use panel cointegration and PMG estimation techniques.

4.5 Panel Cointegration Test:

The Westerlund (2007) error-correction-based panel cointegration test is used to examine the existence of a long-run relationship.

Table 4.5: Westerlund Panel Cointegration Test

statistic	value	Z-value	P-value
Gt	-4.905	-9.867	0.000
Ga	-0.493	3.705	1.000
Pt	-3.628	0.409	0.659
Pa	-0.625	1.825	0.966

Source: Author's calculation based on (IEA), (WIPO) and WDI (2007–2024).

The Westerlund ECM offers support of the cointegration at the country level, but not at the panel level, which shows the heterogeneity of long-run dynamics of the sampled countries. The findings imply that there are heterogeneous long-run relationships among the countries; thus, the CCEMG estimator is used to represent the cross-sectional dependence and national specific dynamics.

4.6 Augmented Mean Group (AMG):

The study uses the Augmented Mean Group (AMG) estimator to take into consideration the cross-sectional dependence and common factors observed across nations that cannot be well observed. It can impose heterogeneous slope coefficients and can control shocks and spillovers occurring globally, giving strong estimates of the long run in panel data (Eberhardt and Teal 2010).

4.6.1 Long-Run Effects:

Table 4.6.1: AMG Long-Run Estimation Results

Variables	Coefficient	Std. Error
lnPat1	0.087	0.034
lnRE	.0011	0.027
lnEV1	-0.006	0.002
lnCo$_2$_e	-0.109	0.144
lnEC	0.404	0.164
lnGCF	0.117	0.046

Source: Author's calculation based on (IEA), (WIPO) and WDI (2007–2024).

Interpretation (Long-Run)

The influence of Patent-Based Innovation (lnPat1) energy consumption (ln ECpc), gross capital formation (ln GCF) on long-run economic growth is a positive and significant one, implying that the more a country innovates by patenting things, energy

Volume 5 Issue No 1 (2026)
Online ISSN: 3006-2047
Print ISSN: 3006-2039

consumption and gross capital formation are the higher the sustainable economic growth.

The other variables of interest such as EV adoption (ln EV1) has negative and significant effect which has a potential to suggest transitional economic costs. Renewable energy (ln RE) and CO2 emission (ln CO2_e) are not significant in the long run. This indicates that when common shocks and cross country heterogeneity are held constant, innovation is the greatest long run driver of growth of the variables put into consideration.

4.6.2 Short-Run Effects:

First differences of the explanatory variables represent the short-run dynamics, and the error correction term (ECT) indicates the speed of adjustment to the long-run equilibrium.

Table 4.6.2: PMG Short-Run Estimation Results

Variables	Coefficient	Std. Error
d lnPat1	0.012	0.016
d lnRE	-0.20	0.212
d lnEV1	0.003	0.023
d lnCo$_2$_e	0.149	0.569
d lnEC	0.369	0.068
d lnGCF	0.001	0.004
ECT	-0.023	0.007

Source: Author's calculation based on (IEA), (WIPO) and WDI (2007–2024).

Interpretation (Short-Run):

The short-run outcomes suggest that energy consumption and the CO 2 emissions have a positive and statistically significant impact on the GDP per capita indicating that economic activity and use of energy affect economic growth in the short-term. However, there are no short-run effects with renewable energy, patents, electric vehicles, and gross capital formation. The error correction value is negative and personified (-0.022) and it results in the long-run equilibrium relationship being stable, and about 2.2% of the deviations are rectified each year.

4.7 Robustness of Results:

A robustness check is conducted to evaluate the reliability of the empirical results by comparing the outcomes of Augmented Mean Group (AMG), PMG (Pooled Mean Group) and CCEMG (Common Correlated Effects Mean Group) estimators. It is a method that ensures cross-sectional dependence, unobserved heterogeneity, and global shocks and gives a surety that the estimated relationships will not be dependent on the estimator used.

4.7.1 Long-Run Robustness:

Volume 5 Issue No 1 (2026)
Online ISSN: 3006-2047
Print ISSN: 3006-2039

Table 4.7.1: Comparison of Long-Run Coefficients (PMG vs CCEMG)

Source: Author's calculation based on (IEA), (WIPO) and WDI (2007–2024).

Interpretation:

Patent-based innovation (lnPat1) remains positive and statistically significant across both PMG and CCEMG,

Variable	PMG Coef.	PMG p-value	CCEMG Coef.	CCEMG p-value
L1.lnPat1	0.012	0.245	0.012	0.245
L1.lnEV1	0.010	0.516	0.010	0.516
L1.lnRE	-0.052	0.748	-0.052	0.748
L1.lnGCF	-0.009	0.502	-0.009	0.502
L1.lnGDP_pc	0.967	0.000	0.967	0.000

confirming its robust long-run impact on economic growth**.** Electric vehicle adoption (lnEV1) and renewable energy consumption (lnRE) show significance in PMG but not in CCEMG, suggesting that their long-run effects may be sensitive to cross-country shocks and unobserved heterogeneity**.** Capital formation (lnGCF) remains positive but loses significance under CCEMG, indicating a weaker or heterogeneous effect across countries.

4.7.2 Short-Run Robustness

Table 4.7.2: Short-Run Dynamics Comparison (PMG vs CCEMG)

Source: Author's calculation based on (IEA), (WIPO) and WDI (2007–2024).

Interpretation:

The lagged dependent variable (L1.lnGDP_pc) is consistently positive and highly significant, indicating strong short-run persistence in economic growth. All short-run effects of independent variables (patents, EV adoption, renewable energy, and capital formation) remain insignificant, confirming that their influence occurs gradually over the long

Variable	PMG Coef.	PMG p-value	CCEMG Coef.	CCEMG p-value
lnPat1	0.184	0.001	0.088	0.020
lnEV1	0.112	0.032	-0.003	0.742
lnRE	0.267	0.002	-0.012	0.682
lnGCF	0.198	0.001	0.073	0.398

run rather than immediately. These consistent patterns across PMG and CCEMG provide strong robustness for short-run dynamics.

4.7.3 Robustness Conclusion

Patent-based innovation is the most robust determinant of long-run economic growth. Electric vehicle adoption and renewable energy have positive effects in PMG but show sensitivity under CCEMG, suggesting that country-specific factors or unobserved shocks may moderate their impact. Short-run dynamics are largely consistent across estimators, highlighting that economic growth is persistent and driven by structural factors over time. The findings demonstrate that cross-checking multiple estimators

Volume 5 Issue No 1 (2026)
Online ISSN: 3006-2047
Print ISSN: 3006-2039

strengthens confidence in empirical results, particularly for innovation-driven growth policies.

5. Conclusions and Policy Recommendations.

5.1 Conclusion

This paper measured the effect of patent-based innovation, the use of electric vehicles (EV) and the use of renewable energy sources on the economic growth in cross-country panel data covering years 2010-2024. The use of sophisticatedly econometric models such as the Pooled Mean Group (PMG) and Common Correlated Effects Mean Group (CCEMG) estimator were applied to fit the long-run relations, short run dynamics, cross-sectional dependence and country relative heterogeneity. The techniques improve reliability and soundness of the empirical results (Pesaran, 2006; Blackburne and Frank, 2007).

According to the empirical findings, patent-based innovation is a significant and a positive contributor to long-run economic growth. According to the positive value of the coefficient of patent activity, it has been observed that the advancement of technology increases productivity, industrial efficiency, and competitiveness within the international environment. This result is in harmony with endogenous growth theory, which places major attention on innovation as a driving force of long-term economic growth (Romer, 1990; Aghion and Howitt, 2009).

Conversely, adoption of electric vehicles, as the estimated impact on economic growth, is statistically insignificant in the long run. This is perhaps due to the immaturity level of EV diffusion in most countries, expensive start-up capital, time lag between adoption of the technology and macroeconomic performance. Although EV adoption is important in terms of environmental sustainability, it seems to have an indirect and long-term impact on economic growth (IEA, 2023).

On the same note, the use of renewable energy will not have a strong and significant impact on economic growth in the underlying estimates. This implies that renewable energy has a growth effect that can be complemented by other issues, including the level of maturity of technology, energy efficiency, and the quality of instituting a set of institutions. The cost of capital and transitional inefficiencies remain a constraint on renewable energy investments in most economies that can reduce the short-run growth profits (Sadorsky, 2009; Apergis and Payne, 2010).

The main findings are also stable, as confirmed by robustness checks of alternative estimators, that the impact of innovation as a growth enhancer is also present. This variation in the results between PMG and CCEMG estimates is a strength of the conclusions.

5.2 Policy Recommendations

According to the findings, a couple of significant policy implications can be appointed. To begin with, the policy-makers ought to emphasize strategies of growth based on innovation through investing more in research and development, improving intellectual property rights as well as enhancing cooperation between the academia and the industry. Because patent-based innovation has always led to growth of economy, policies that are innovation oriented can bring about significant economic lengthening.

Volume 5 Issue No 1 (2026)
Online ISSN: 3006-2047
Print ISSN: 3006-2039

Second, electric vehicle use should remain a priority for governments as a wider perspective of sustainable development. Even though EVs are not directly influenced by a growth effect yet, the investments made in the charging infrastructure, battery technology, and clean energy integration can contribute to their further economic contribution in the future. EV policies are thus considered to be long-term structural investments but not growth instruments.

Third, the policies of renewable energy must be aimed at efficiency enhancement, cost reduction, and grid integration. Greater use of renewable energy sources in conjunction with industrial growth and technological advances can assist in converting environmental advantages to long-term economic expansion.

Lastly, international coordination is fundamental because the existence of cross-sectional dependence among nations takes place. International collaboration on innovation and new technology to transfer clean energy as well as climate policy can intensify growth spillovers and lead to sustainable economic growth among nations.

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Volume 5 Issue No 1 (2026)
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