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Trade Openness and Energy Consumption: A Comparative Evidence from Developing and Developed Countries

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Abstract **Original Research Article**

There has been a rapid increase in global energy consumption, particularly given the wide acceptance of international trade as a channel for economic growth and development. Yet, energy consumption is a critical distinguishing variable between developing and developed nations. This study investigated the comparative impact of trade openness on energy consumption in developing and developed countries. Selected countries (developing and developed) for 1990 to 2023 in a panel study were estimated using the PMG, GM, and DFE models. Results from the various estimation methods showed insignificant differences. For both developed and developing countries, historical energy consumption patterns play a crucial role, indicating complementarity. For developing countries, trade openness and economic development emerged as strong key positive drivers of renewable energy use, especially in the short run, highlighting their role in facilitating technology diffusion and income-driven demand for cleaner energy sources, and environmental sustainability showed sensitivity to country-specific heterogeneity. For the developed countries, environmental sustainability and trade openness showed key positive drivers of renewable energy use, especially in the short run, and GDP per capita played a strong supportive role, reflecting income-driven demand for cleaner energy. Therefore, following Grossman's model, an increase in trade openness leads to higher energy use but lower levels of energy intensity. The study advocated, among others, for Green Trade openness. The developing countries are to concentrate on managing trade dynamics with energy policies, while developed countries are to concentrate on aligning trade policies with sustainability goals.

Keywords: Comparative study, Trade openness, Energy, Economic Development, Panel Data.

INTRODUCTION

Energy consumption has increased rapidly across the globe in recent years. However, energy consumption is a critical variable that exhibits distinct patterns between developing and developed nations (Opuala, Omoke, & Uche, 2023). The developing countries have long suffered from the challenges of poor economic development, given their energy resources and market size. This challenge has persisted for years, which is believed to have hampered the push for development among the committee of nations. Thus, given the developing countries' quest for development and the requirement for a sustained level of development by developed countries, energy consumption has been on the increase. This rise in consumption exerts pressure on the environment, creating environmental hazards such as air pollution, unclean water, land degradation, warm climate, which are exacerbated in developing countries. This is believed to be exacerbating pressure on the environment and has raised major concerns for both developing and developed countries.

Developed countries are believed to consume more energy due to higher levels of industrialization and greater technological advancements. In some cases, the energy is sourced from non-renewable energy sources, such as oil and coal, which significantly contribute to global carbon emissions and environmental degradation. In contrast, developing nations are experiencing a rapid increase in energy consumption as they drive towards modernization and enhancing their living standards, which are often carried out by relying on less clean energy sources. Although many developed and developing nations are beginning to transition towards more sustainable energy options like solar and wind power, striving to balance the trade-off between development and environmental stewardship has always been a challenge.

Trade openness has been advocated for as a vital factor in influencing economic development in both developing and developed nations. Overall, trade openness has the potential to create mutual benefits, facilitating the efficient allocation of resources and promoting sustainable economic development. An increase in trade can provide access to new markets, advanced technologies, and vital resources, which are drivers of economic growth and the alleviation of poverty in developing nations (Ghazouani & Maktouf, 2024). For developing countries, opening their markets to foreign investment can attract essential capital and expertise that stimulate innovation and increase productivity. For the developed nations, trade openness can foster competition and improve consumers' choice, contributing to economic growth and efficiency (Ahakwa, 2023). The drive to increase exports has often relied on non-renewable energy sources for their production, which exerts harm to the environment.

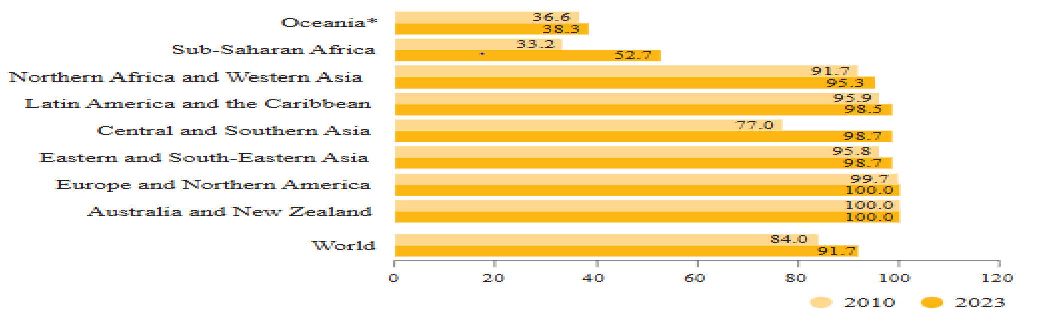
Trade openness has resulted in a global increase in trade. While developed countries have a higher share of global trade (exports and imports), developing countries have experienced slower growth rates for the past five years (UN Trade and Development, 2025b). For instance, global trade as a percentage of GDP increased from 54.39% to 58.4% between 2004 and 2014. This fell sharply to approximately 52.2% as a result of the lockdowns in 2021. It experienced a rapid recovery in 2022 with 61%, but a slight decline, standing at 56.6% in 2024. In 2010, global trade was US$ 37 trillion. This increased over the years until the sharp decline in 2021 as a result of COVID. The volume of global trade was $33 trillion in 2024 ($24 billion from exports), and it is driven mainly by growth in service sectors as well as the drive for economic development by developing economies (UN Trade and Development, 2025a).

Across the various regions, there has also been an increase in the volume of total trade, with exports growing more than imports in most regions. While the developing countries are the primary importers of manufactured goods, manufacturing exports are shared between developed and developing countries. Between 2018 and 2023, total exports in developed countries grew by 3.3% while in developing countries they grew by 5.0% (UN Trade and Development, 2025b). In 2024, developing countries outpaced developed nations, with rising imports and exports of 4% for the year (UN Trade and Development, 2025a). Specifically, in Asia, exports grew by 13% in 2006, accounting for 24.9% of global exports in 2024. In sub–Saharan African, exports are mainly driven by natural resources with high volatility in commodity prices. Total exports rose from about $402.73 billion in 2010 to about $483 billion in 2011. This dropped subsequently to about $393.1 billion in 2024 (UN Trade and Development, 2025b; UN Trade and Development, 2025c). This increase in the global volume of trade to increase economic growth and people's welfare has led to an increase in energy demand

There has been a rise in energy consumption following the rise in technology, an increase in trade openness, and an increase in population, with the developing and emerging economies accounting for about 80% of the increase in energy demand. However, the rise varies with different sources of energy. The demand for natural gas grew by 2.7% in 2024, and coal had the largest amount of consumption of about 31% of total energy consumption. Although there was a fall from energy-related carbon dioxide (CO2) emissions with about 0.8% in 2024 (IEA 2025a), according to the International Energy Agency (IEA) (2025a), global primary energy demand rose moderately to 620 exajoules in 2023 and by 2.2%, growing to 650 exajoules in 2024, with electricity demand growing from 2.6% in 2023 to 4.3% in 2024, and about 80% from renewable sources. There has also been an increase in global sales of electric cars, rising by over 25%, and accounting for one-fifth of all car sales (IEA 2025a). Furthermore, the global electricity access rate increased from 87% in 2015 to 92% in 2023, serving close to an additional 800 million people (United Nations, UNSD, 2025).

Yet, about 730 million people globally still lacked access to electricity and clean energy in 2024 (IEA 2025b). Regional disparity still exists. For instance, as reported by IEA (2025b) while number and percentage of people with electricity in Central and Southern Asia, increased from 77% in 2010 to 98% in 2024, Latin American having about 98% access, Northern African and Western Asian increased from 92% to 96%, sub-Saharan Africa where about 80% of the countries are developing countries, only had an electricity connection rose to 6.8 million in 2024, which is a 2% increase from 2023; access to electricity only increase from 32% in 2010 to 52% in 2023 (see fig 1) while more than 567 million (accounting for 85% of the global deficit) are still without access to electricity and clean energy in 2023. As of 2024, eight out of every ten people globally without electricity are from Sub-Saharan Africa (IEA, 2025b).

Figure 1.1 Proportion of Population with Access to Electricity 2010 and 2023 (Percentage)



Source: Adopted from United Nations (UNSD) (2025) Department of Economics Social Affairs, Statistic Division

The developing nations, therefore, seem to be lagging in the availability and access to good quality and quantity of energy consumption. They also seem to be lagging in their contribution to the volume of trade and getting less of the benefits of trade openness. The developing nations are faced with major challenges of a lack of access to resources and technological advancements, which may be affecting their effective competition in the global market and attraction of foreign investment. In addition to the above, developing nations often rely on agriculture and natural resource extraction as their primary sources of income, which can be unsustainable and thus hinder long-term economic development (Addai, Serener &Kirikkaleli, 2023). They are also faced with a high level of income inequality and unemployment, with a majority of the population struggling to make ends meet, holding a disproportionate amount of wealth, which can lead to social unrest and hinder overall economic development. Therefore, addressing these issues and creating more equitable economic opportunities is crucial for sustaining economic development in both developing and developed nations (Opuala, Omoke, & Uche, 2023). It is therefore paramount to ask, what is the comparative impact of trade openness on energy consumption in developing and developed countries?

Despite the evident importance of these factors, significant research gaps remain in understanding the interrelationships between trade openness and energy, particularly in a comparative context between developing and developed countries. While previous studies have explored various aspects of energy consumption and trade openness, there is therefore a need for more comprehensive analyses. For instance, the studies by Addai et al. (2023) emphasized the necessity for developing countries to adopt sustainable energy practices to drive economic growth. Similarly, research by Ghazouani & Maktouf (2024) highlights the role of trade openness in enhancing economic development outcomes. However, there remains a lack of comparative studies that systematically analyze how trade openness is related to energy consumption and its implications for policy formulation. Therefore, this study seeks to investigate the comparative impact of trade openness on energy consumption in developing and developed countries.

2. 0 LITERATURE REVIEW

2.1 Theoretical Literature

2.1.1 Theories of Trade Openness

The Comparative Advantage Theory: The theory states that countries should specialize in the production and trading of goods or services that they have a comparative advantage in. by so doing, they can produce at lower opportunity cost compared to other countries thereby producing more efficiently and gaining access to a wider variety of products through trade. The relevance of this theory to the current study is because it encourages nations to optimize the use of resource and adopting cleaner technologies in the drive for economic development and sustenance of development.

Hecksher-Ohlin Theory of International Trade: This theory was developed by Eli Hecksher and Bertil Ohlin (1977) and built on David Ricardo’s theory of comparative advantage states that countries should export the products which uses their relatively abundant and cheap factors of production. It argued that countries export what they can most efficiently produce considering their abundant resources or endowments (factors of production and Technology). The relevance of this theory to the current study is to enables both the developing and developed countries to maximize their comparative advantages in stimulating economic activities and improving the standard of living of the people.

Stolper-Samuelson Theorem: According to the theory, the returns gained by factors and their owners based on production from comparative advantage are determined by the opening of the trade by the countries that owns then to other countries. the countries gain efficiency as a result of their specialization emphasizing on high production based on the comparative advantage with in the country. This specialization can result in more gains for the owner of the abundant good increasing their income increases while there is a loss of real income for the owners of scarce goods owners (Grieco & Ikenberry, 2003). According to Grieco and Ikenberry (2003), the more a country opens its economy with trading to the world, the higher the specialization on few goods that they are endowed with the factors of production and they demand for other goods as well as state of technological advancements in the world increases.

2.1.2 Theories of Energy Consumption

The Energy Ladder Theory: Propounded by Hosier and Dowd (1987), the theory suggests that as the income of the households' increases, they tend to move from using traditional, less efficient, and often polluting fuels like firewood to a more modern, cleaner energy sources like electricity, essentially climbing up a ladder of progressively better fuel options based on factors like convenience, cleanliness and cost. It further posits that as households and economies develop; they transition from using traditional, less efficient energy sources to cleaner, more efficient ones. This transition is vital in understanding that energy consumption patterns change with economic development and the degree of trade openness, impacting environmental sustainability in both developing and developed countries.

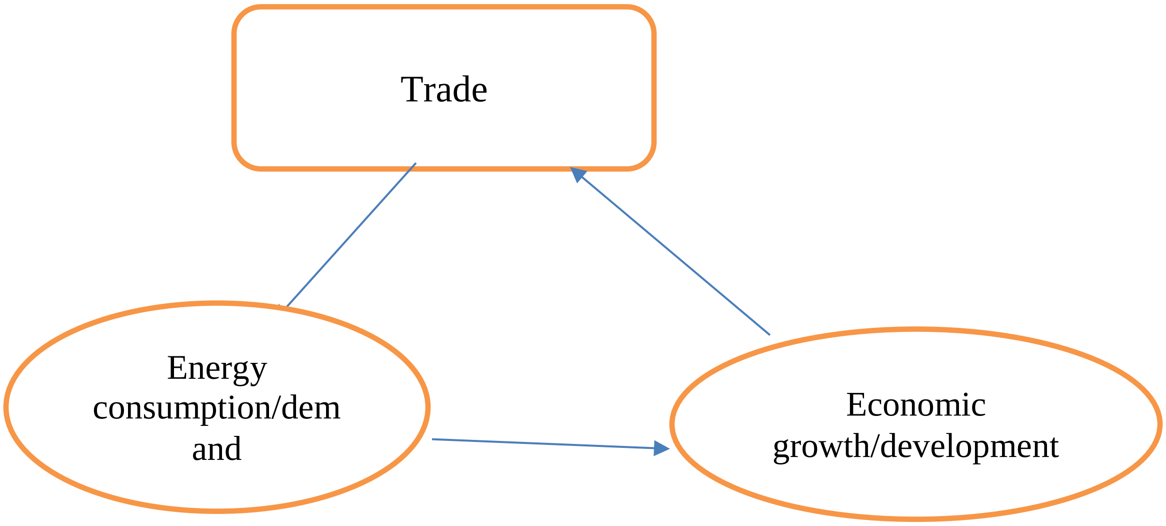
Feedback Hypothesis of Energy Consumption: This theory developed by Apergis and Payne (2010) and Yu and Hwanag (1984) postulates that there is a two-way causal relationship between the consumption of energy and economic development (trough the various drivers of economic development). This hypothesis is relevant for its highlights on how energy policies and consumption patterns in both developing and developed countries can influence economic development.

The Consumption Hypothesis: This theory was propounded by Kraft and Kraft (1987). This theory suggests that economic development drive energy consumption, meaning that as an economy grows, its energy usage increases as well, implying that policies aimed at limiting energy consumption would not necessarily winder economic progress. The relevance of this theory to the current study is the understanding that on how energy use impacts on economic development and social development.

The Energy-Led Growth Hypothesis (ELGH): this has emerged as the pivotal framework in the understanding of the dynamics of energy. The theory proposes that the consumption of energy is a major driver and necessity for economic growth in addition to factors of production such as labour and capital. Thus, more use of energy is expected to directly increase production activities, trade and economic development. This is however contrary to the theory that economic growth drives the use of energy (Behera, 2015).

The Grossman's model: this model was put forward by Grossman-Kruger. It examined the trade openness impacting on energy consumption. The model made use of scale, composition and technology effects of increase in trade on energy demand leading to higher use of energy but lower level of energy intensity as a result of technological advancement. According to the theory, increase in trade openness enhances economic growth which leads to increase in production and consumption. This expansion in production and consumption increases total energy demand. In addition, trade makes countries to specialize in particular goods with comparative advantage. When a country concentrates on energy-intensive industries for exports, the consumption of energy increases on the other hand, when a country specializes in less energy-intensive sectors (services), the use of energy falls. The theory further noted that trade increases the use of advanced, energy-efficient technologies from developed countries to developing countries reducing the intensity of energy needed for production thereby reducing the total quantity of energy demanded.

Figure 2.1 The trade and energy consumption linkage



Source: Authors' Chart.

2.2 Empirical literature

Wasti and Zaidi (2020) investigated the link among CO2 emissions, energy consumption, gross domestic product, and trade liberalization in Kuwait. The study used annual data, starting from 1971 to 2017, which was obtained from a world development indicator of the World Bank. Based on the findings, a well-defined Autoregressive Distributed Lag Model was applied to the data sets and the outcome was in support of the long and short-run relationship between variables. Carbon dioxide and energy consumption accelerate economic development; an increase in CO2 emission also plays a significant role in increasing energy consumption. Furthermore, the Granger Causality test shows evidence of bi-directional causality existing between CO2 emissions and energy consumption. A unidirectional causality is running from the gross domestic product to CO2 emissions and energy consumption to trade liberalization.

Mrshed (2020) investigated the impacts of ICT, Trade openness on renewable energy consumption and carbon emissions across selected South Asian economics using nonlinear analysis. He submitted that ICT trade directly increases renewable energy consumption, enhances renewable energy shares, reduces intensity of energy use facilitates adoption of cleaner cooking fuels and reduces carbon dioxide emission.

In the study by Zeren, and Akkuş (2020) examined the relationship between trade openness, renewable and non-renewable energy consumption for "Top Emerging Countries of Bloomberg" in 1980–2015 period is investigated. The long-run relationship between panels is examined with Dumitrescu-Hurlin (2012) panel causality test, Westerlund (2006) panel cointegration test with multiple structural breaks and Pesaran (2006) CCE-MG cointegration estimator. According to findings, it was found that the use of non-renewable energy is the one of main reason for the increase in trade openness. In addition, the increase in the use of renewable energy was founded to be an important factor in decreasing the trade openness for these Emerging Countries.

Tiago, Antonio & Jose (2021) in their evolution of the determinants of energy transition in countries of the organization for economic co-operation and development (OECD) from 1971 – 2016 employed the feasible generalized least squares (FGLS) and Panel – Corrected Standard Errors (PCSE) estimators. Their finding was that energy security and the carbon intensity of energy consumption are obstructing a low-carbon transition. Energy efficiency and trade openness are driving the energy transition while the carbon intensity of energy consumption is constraining it.

Zhang, Lee, and Zhou (2021) investigated the effects of trade openness on renewable energy consumption in 35 OECD, countries from 1999-2018. They employed smooth transition regression model. The results demonstrated the existence of a strongly non-linear relationship between trade openness and renewable energy consumption the analysis on the temporal and spatial variations of the effects shown that imports, exports, and total trade all positively impacts renewable energy consumption.

Bonus and Wang (2022) examined the triangular relationship between energy consumption, trade openness and economic development in 45 countries from 1991 to 2014 using dynamic seemingly unrelated regression (DSUR) models. They conformed a bi-directional relationship among energy consumption and income, trade openness and income and trade openness and energy consumption in the long run.

Qi, Xu, Amuji, Wang & Zhou (2022) evaluated the relationship among energy consumption and emissions trade openness and economic development in West Africa using Toda – Yamamoto model. The findings submitted that energy consumption has positive and significant impact on economic development. Trade openness and economic development are mutually reinforcing in the long run as foreign trade result to increase in economic development in West Africa Countries.

Betul, Zahoor, Mahmood &Muhlis(2022) conducted an investigation on the impact of green trade openness and renewable energy consumption on human well-being for 25 European Union (EU) member countries from 2003 to 2016. Their submission was that green trade openness increases human well-being in all quintiles (oil-o.90), while renewable energy consumption shows a significant and positive effect on human well-being across quintiles (0.1 – 0.90) in the EU Countries.

Mingming, Shichang, Chien-Chiang and Dequn (2021) explored on the trade openness' effect on the consumption of renewable energy using 35 OECD countries over the period 1999 and 2018. They employed the panel smooth transition regression model using imports, exports, and total trade were proxies for trade openness while carbon emissions was used to proxy energy consumption. A strong nonlinear relationship was found to exist between trade openness and renewable energy consumption. There were three structural breakpoints identified: 33.732, 40.945, and 76.395 for import where the effect of trade openness on energy consumption will switch from promoting to inhibiting when trade openness reaches 40.945% of the GDP. On the other hand, exports and total trade had only one structural breakpoint and were found to constantly promote renewable energy consumption. The temporal and spatial variations analysis revealed that imports, exports, and total trade positively impact on renewable energy consumption.

Elhassan (2024) investigated the impact of energy production and trade openness on Saudi Arabia economic development and environmental pollution using the fully modified ordinary least squares (FMOLS) and dynamic ordinary least squares (DOLS) method for the period of 1970 to 2020. The findings established that both expanding trade openness and increasing energy consumption result to faster economic development in Saudia Arabia.

Zhou, Guan, and He (2025) investigated if the level of CO_2 emissions is impacted by trade openness using the fully modified least squares (FMOLS), the dynamic ordinary least squares (DOLS), and the pooled mean group-autoregressive distributive lag (PMG-ARDL) estimations methods. To ensure the robustness of the result, the DCCEMG (dynamic common-correlated effect mean group) and the Driscoll–Kray were also applied while the Dumitrescu–Hurlin estimation method was used to determine the existence of Granger causality between the variables. Increase in economic growth and the openness of trade openness was found to be related with lower emissions of CO_2 while energy consumption increased the level of emissions. However, in the short term, trade openness was found not to significantly impact on energy consumption. Nevertheless, there was a two-way causality between trade openness and CO_2 emissions.

2.4 Gap in Reviewed Literature

From the foregoing, while studies have been carried out on various dimensions of energy consumption (renewable and non-renewable) and trade openness, there still exists gap in literature. Specifically, the impact of capital-labour ratio which is assumed to be higher in the developed countries and can lead to the use of less clean energy in the determination of the impact of trade openness on energy consumption has not been considered. Again, a comparative study on the level of economic development in determining the impact of trade openness have not been examined. This is particularly vital given the recent quest for development by developing countries which has resulted in increase in their level of trade participation along with the global rising levels of energy consumption as well as the effects.

3.0 METHODOLOGY

3.1 Theoretical Framework

This study rest on the Grossman's model that noted that the increase in the trade openness leads to higher use of energy but lower level of energy intensity as a result of technological advancement. This is through the impact of trade openness on economic growth/development. Increase in trade openness is expected to enhances economic growth leading to increase in production and consumption of goods and serves which increases total energy demand. However, the effect of trade on the demand of energy depends on the type of goods and services produced and the intensity of energy that is used. When a country makes use of energy-intensive industries for production of goods for exports, the consumption of energy increases but when in less energy-intensive sectors (services) is specialized on, the use of energy falls.

3.2 Model Specification

This study rest on the Pool Mean Estimations in analyzing the dynamic impact of trade openness on energy consumption. It applies the Panel PARDL specification based on Loayza and Ranciere (2006). Moreover, according to Pesaran and Smith (1995) as well as to Pesaran et al. (1999), respectively this model includes the mean group (MG), pooled mean group (PMG) estimators, as well as the dynamic fixed effect (DFE) model.:

The PARDL is given as:

$$\Delta(y_i)_t = \sum_{i=1}^{p-1} \Delta\gamma_j^i \,(y_i)_{t-j} + \sum_{i=1}^{p-1} \Delta\delta_j^i \,(X_i)_{t-j} + \varphi^i[(y_i)_{t-1} - \{\beta_0 + \beta_1(X_i)_{t-1}\}]\epsilon_{it} \quad (3.1)$$

$$\Delta(ECON)_{it} = \sum_{i=1}^{p-1} \Delta\gamma_j^i \,(ECON)_{it-j} + \sum_{i=1}^{p-1} \Delta\delta_j^i \,(X_i)_{t-j} + \varphi^i[(ECON)_{it-1} - \{\beta_0 + \beta_1(X_i)_{t-1}\}]\epsilon_{it} \ldots (3.2)$$

Where:

- ECON = Renewable Energy Consumption
- X_i = (exogenous variables; Trade Openness, Per Capita Income, Environmental Sustainability and economic development)
- Δ = Change operator
- γ_j and δ_j = Coefficients for lagged changes
- β_0 and β_1 = Intercept and coefficients for independent variables
- ϵ_t = Error term

whereby, Y represents the Renewable Energy consumption (ECON), X represents a set of independent variables which includes the Per Capital Income (PCI), Environmental sustainability (ESUS), Economic Development (EDEV), trade openness (TRDO) defined as the ratio of total trade (export plus import) to GDP and capital-labor ratio. The short-term coefficients of dependent as well as of independent variables are respectively represented by $\boldsymbol{\gamma}$ and $\boldsymbol{\delta}$, β represents the long-term coefficients,

φ represents the coefficient of speed of adjustment to the long-term status. The country and time are represented by the subscripts of i and t respectively while terms in the square brackets denote the long-term development regression.

The use of PMG and MG estimators, permits the estimation of various variables with various order of stationary, which means, it is valid for both variables of interest such as I(1) or I(0). It is also suitable for the panel data with large N and T dimensions. These estimators allow the estimation of short and long-term impacts from the PARDL model simultaneously and also overcomes the problem of endogeneity. However, the option to choose among these estimators requires a general trade-off between efficiency and consistency. Thus, the best approach is to understand the conditions and assumptions of each estimator.

The Pooled Mean Group Estimator (PMG)

$$\Delta y_{i_t} = \alpha_i + \beta_1 \Delta X_{i_t} + \beta_2 \Delta y_{i_{t-1}} + \sum_{j=1}^{p} \gamma_j \, y_{i_{t-j}} + \sum_{i=1}^{p-1} \delta_j \, X_{i_{t-j}} + \epsilon_{it} \qquad (3.3)$$

$$\Delta(ECON)_{i_t} = \alpha_i + \beta_1 \Delta(PCI)_{i_t} + \beta_2 \Delta(ESUS)_{i_t} + \beta_3 \Delta(TRDO)_{i_t} + \beta_4 \Delta(CLR)_{i_t} + \beta_5 \Delta(EDEV)_{i_t} + \beta_6 \Delta(ECON)_{i_{t-1}} + \sum_{j=1}^{p} \gamma_j \, (ECON)_{i_{t-j}} + \sum_{i=1}^{p} \delta_j \, X_{i_{t-j}} + \epsilon_{it} \qquad (3.4)$$

The key PMG permits short term coefficients, which include the intercepts, the adjustment speed to the long-term equilibrium values, and the error variances to be heterogeneous country by country, while the long-term slope coefficients are restricted to be homogeneous across the countries. it however requires the presence of a long-term relation among the variables such that the coefficient on the error-correction term to be not less than -2 and negative. The relative size of T and N is of utmost importance thus having both to be large permits the dynamic panel method that assists in preventing bias in the average estimators and overcoming the heterogeneity issue.

The Mean Group Estimator (MG) is given as:

$$\Delta y_{i_t} = \alpha_i + \beta_1 \Delta X_{i_t} + \beta_2 \Delta y_{i_{t-1}} + \sum_{j=1}^{p} \gamma_j \, y_{i_{t-j}} + \sum_{i=1}^{p-1} \delta_j \, X_{i_{t-j}} + \epsilon_{it} \qquad (3.5)$$

$$\Delta(ECON)_{i_t} = \alpha_i + \beta_1 \Delta(PCI)_{i_t} + \beta_2 \Delta(ESUS)_{i_t} + \beta_3 \Delta(TRDO)_{i_t} + \beta_4 \Delta(CLR)_{i_t} + \beta_5 \Delta(EDEV)_{i_t} + \beta_6 \Delta(ECON)_{i_{t-1}} + \sum_{j=1}^{p} \gamma_j \, (ECON)_{i_{t-j}} + \sum_{i=1}^{p} \delta_j \, X_{i_{t-j}} + \epsilon_{it} \qquad (3.6)$$

The MG estimator includes the estimation of separate regressions for each country as well as the coefficients as the un-weighted means of the estimated coefficients for the individual country. It permits all the coefficients to differ and be heterogeneous in the short and long-term and requires a large T and N (Pesaran et al. 1999).

Dynamic Fixed Effect (DFE) is given as

$$y_{i_t} = \alpha + \beta_1 X_{i_t} + \beta_2 y_{i_{t-1}} + \sum_{j=1}^{p} \gamma_j \, y_{i_{t-j}} + \sum_{i=1}^{p-1} \delta_j \, X_{i_{t-j}} + \mu_i + \epsilon_{it} \qquad (3.7)$$

$$(ECON)_{i_t} = \alpha + \beta_1 (PCI)_{i_t} + \beta_2 (ESUS)_{i_t} + \beta_3 (TRDO)_{i_t} + \beta_4 (CLR)_{i_t} + \beta_5 (EDEV)_{i_t} + \beta_6 (ECON)_{i_{t-1}} + \sum_{j=1}^{p} \gamma_j (ECON)_{i_{t-j}} + \sum_{i=1}^{p} \delta_j X_{i_{t-j}} + \mu_i + \epsilon_{it} \qquad (3.8)$$

The dynamic fixed effect (DFE) estimator limits the speed of the adjustment coefficient and the short-term coefficient to be the same or equal. Panel-specific intercepts are also allowed and allows cluster options for calculating the intragroup correlation with the standard error (Blackburne and Frank, 2007). Moreover, Baltagi, Griffin, and Xiong (2000). The DFE models are subject to a simultaneous equation bias from the endogeneity between the error term and the lagged dependent variable. Moreover, the Hausman test could be utilized to examine the significant differences among the PMG, MG, as well as the DFE with a null hypothesis of non-significance of the difference between PMG and MG estimations.

3.3 Source of Data

The study made use of secondary data sourced from the World Bank Development Indicators (WDI) (2024). The toral of 30 countries comprising of 15 developing countries, (Algeria, Ghana, Kuwait, South Africa, Egypt, Nigeria, Malaysia, Ethiopia, Morocco, Zambia, Indonesia, Vietnam, Bangladesh, Philippines and Pakistan) and 15 developed countries, (Switzerland, Iceland, Belgium, Germany, USA, Austria, New Zealand, France, Canada, Japan, Denmark, Finland, Taiwan, Sweden, Netherlands) were used. The EViews 10.0. was used for the estimation of the data.

4.0 DATA ANALYSIS, RESULT AND DISCUSSION

4.1 Descriptive Statistics

Table 4.1A: Descriptive Statistics for Developing countries

	ECON	EDEV	ESUS	PCI	TRDO	CLR
Mean	39.07719	0.062812	20.92249	2.17E+10	2.28E+14	4.543684
Median	27.78800	0.012356	3.642150	104322.5	1.89E+10	4.667893
Maximum	150.9892	0.671133	91.74071	4.18E+11	5.91E+15	50.60000
Minimum	-0.004190	-0.003910	-0.002030	0.012450	-1.40E+11	-26.00000
Std. Dev.	37.34514	0.149110	29.29937	5.90E+10	7.64E+14	4.769503
Skewness	0.748004	2.901964	1.235810	4.507303	4.653084	2.127762
Kurtosis	2.538127	9.849074	3.004840	24.95193	27.73320	31.07077
Jarque-Bera	52.09152	1712.652	129.8147	11966.94	14839.63	17129.15
Probability	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Sum	19929.36	32.03435	10670.47	1.11E+13	1.16E+17	2317.279

Sum Sq. Dev.	709881.8	11.31695	436952.7	1.77E+24	2.97E+32	11578.81
Observations	510	510	510	510	510	510

Source: Author's computation from Data (2025)

Table 4.1B: Descriptive Statistics for Developed Countries

	ECON	EDEV	ESUS	PCI	TRDO	CRL
Mean	50.93476	0.101860	20.39881	1.17E+11	5.51E+12	2.267713
Median	29.83685	0.032100	8.286929	72901.41	4.17E+10	2.274960
Maximum	263.6220	0.844000	96.93255	1.72E+12	1.03E+14	16.70000
Minimum	0.003574	-0.017780	0.003420	0.005643	-9.50E+11	-7.900000
Std. Dev.	57.05229	0.217838	26.16085	3.21E+11	2.01E+13	2.594180
Skewness	2.036059	2.702306	1.614771	3.414893	3.707783	0.114322
Kurtosis	7.388422	8.404686	4.430241	13.25789	15.32073	7.300734
Jarque-Bera	761.6082	1241.435	265.1050	3227.242	4394.310	394.1576
Probability	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Sum	25976.73	51.94868	10403.39	5.97E+13	2.81E+15	1156.534
Sum Sq. Dev.	1656776.	24.15387	348354.5	5.25E+25	2.05E+29	3425.453
Observations	510	510	510	510	510	510

Source: Author's computation from Data (2025)

The descriptive statistics for developing countries as provided in Table 4.1A reveals that Trade openness (TRDO), defined as the ratio of total trade (export plus import) to GDP, has an average of 2.28E+14, with extreme values ranging from -1.40E+11 to 5.91E+15. The standard deviation is very high (7.64E+14), indicating extreme variability across developing countries. A highly skewed distribution (4.65) and extreme kurtosis (27.73) suggesting that while most countries have lower trade openness and a few exhibiting extraordinarily high trade volumes relative to their GDP. Renewable energy consumption (ECON) has a mean value of approximately 39.08, with a wide range between -0.004 and 150.99. The standard deviation of 37.35 suggests significant variability among the countries in terms of energy consumption. Its positive skewness (0.75) and kurtosis (2.54) indicate a moderately right-skewed distribution with a few extreme values.

Economic development (EDEV), measured by the Human Development Index (HDI), has a low average value of 0.0628, indicating that on average, developing countries have relatively low human development levels. However, there is substantial variation, as shown by a standard deviation of 0.1491. The high positive skewness (2.90) and extreme kurtosis (9.85) suggest that most countries have low HDI values, with a few having significantly higher ones.

Environmental sustainability (ESUS), measured by greenhouse gas emissions, shows a mean of 20.92, with values ranging from a minimum of nearly zero to a maximum of 91.74. The standard deviation of 29.30 reveals high dispersion, and its positive skewness (1.24) indicates that most countries have relatively low emissions, but a few contribute significantly higher emissions.

Per capita income (PCI), measured by GDP per capita, has an average value of approximately 2.17E+10, though its median value is significantly lower at 104,322.5. This discrepancy, along with a very high positive skewness (4.51) and kurtosis (24.95), indicates the presence of extreme outliers, where a few developing countries have much higher per capita incomes compared to the majority. Capital-labor ratio (CLR), which measures capital abundance, has an average value of 4.54, with a wide range extending from -26 to 50.6. The standard deviation of 4.77 suggests moderate dispersion. However, the high positive skewness (2.13) and extreme kurtosis (31.07) reveal that a small number of countries have much higher capital-labor ratios, while most remain at lower levels.

The descriptive statistics for developed countries revealed significant differences in comparison to developing countries. Trade openness (TRDO) came out to be significantly larger in developed countries, with a mean of 5.51E+12, reflecting higher international trade activity. However, the extreme values, with a minimum of -9.50E+11 and a maximum of 1.03E+14, suggest strong variations across nations. The distribution is highly skewed (3.71) and exhibits extreme kurtosis (15.32), indicating the presence of major trade powerhouses among developed countries.

Renewable energy consumption (ECON) showed a higher mean value of 50.93 compared to developing countries, suggesting that developed economies consume more energy on average. However, the distribution is highly dispersed, with a standard deviation of 57.05 and a maximum value of 263.62. The strong positive skewness (2.04) and high kurtosis (7.39) indicate that while most developed countries consume moderate amounts of energy, a few have extremely high consumption levels.

Economic development (EDEV), measured by the Human Development Index (HDI), has a mean of 0.1019, which is higher than that of developing countries. However, the variation is significant, with a standard deviation of 0.2178. The high skewness (2.70) and kurtosis (8.40) suggest that while most developed nations have relatively high HDI scores, there are some outliers with extremely high values. Environmental sustainability (ESUS), measured by greenhouse gas emissions, shows a mean of 20.40, which is slightly lower than in developing countries. However, the wide range from a minimum of nearly zero to a maximum of 96.93, along with a standard deviation of 26.16, indicates large disparities among developed nations. The skewness of 1.61 and kurtosis of 4.43 suggest that while most countries maintain relatively low emissions, some exhibit significantly higher values.

Per capita income (PCI) is significantly higher in developed countries, with a mean of approximately 1.17E+11, compared to 2.17E+10 in developing nations. The extreme disparity is evident in its high standard deviation (3.21E+11), positive skewness (3.41), and extreme kurtosis (13.26), meaning that a few developed nations have exceptionally high per capita incomes, while others are relatively lower. On the other hand, CO2 emissions (CO2) have a mean value of 54,681.50, which is significantly lower than in developing nations (208,435.4). However, its extreme skewness (3.96) and high kurtosis (19.08) indicate that while most developed countries maintain relatively low emissions, a few industrialized nations contribute disproportionately to pollution levels. Capital-labor ratio (CLR), measuring capital abundance, has an average of 2.27, which is lower than in developing countries (4.54). However, the distribution is more balanced, as indicated by its lower standard deviation (2.59) and near-zero skewness (0.11). This suggests that developed countries have a more even distribution of capital relative to labor, with fewer extreme outliers.

4.2 Unit Root Test

Table 4.2A: Panel Unit Root Test for Developing Countries

Variable	Test Statistic (Level)	P-Value (Level)	Critical Value	Test Statistic (First Difference)	P-Value (First Difference)	Critical Value
EDEV	-10.4646	0.0000	1%, 5%, 10%			
ESUS	-10.9825	0.0000	1%, 5%, 10%			
ECON	-10.4744	0.0000	1%, 5%, 10%			
TRDO	-12.8092	0.0000	1%, 5%, 10%			
PCI	-5.10458	0.7183	1%, 5%, 10%	-4.8092	0.0000	1%, 5%, 10%
CLR	-3.6580	0.6103	1%, 5%, 10%	-8.84111	0.0000	1%, 5%, 10%

Source: Author's computation from Data (2025)

Table 4.2B: Panel Unit Root Test for Developed Countries

Variable	Test Statistic (Level)	P-Value (Level)	Critical Value	Test Statistic (First Difference)	P-Value (First Difference)	Critical Value
ECON	3.70052	0.9999	1%, 5%, 10%	-9.30286	0.0000	1%, 5%, 10%
EDEV	-9.58392	0	1%, 5%, 10%	0.0000	0.0000	0.0000
ESUS	6.51545	1	1%, 5%, 10%	-10.1623	0.0000	1%, 5%, 10%
PCI	7.02081	1	1%, 5%, 10%	-12.1766	0.0000	1%, 5%, 10%
TRDO	1.82473	0.966	1%, 5%, 10%	-14.017	0.0000	1%, 5%, 10%
CLR	-10.65821	0	1%, 5%, 10%	0.0000	0.0000	0.0000

Source: Author's computation from Data (2025)

Presented in Table 4.2A is the results of the Im, Pesaran and Shin (IPS) panel unit root test for the variables. The result showed that EDEV, ESUS, ECON, TRDO were stationary at levels while PCI and CLR, were stationary at order one I(1). Table 4.2B, also shows the result of unit root test for developed countries. The result revealed that all the variables were integrated of order one; I(1) with the exception of EDEV and CLR that were found to be integrated of order zero; I(0).

4.3 Cointegration Test

Table 4.3A: Summary of Pedroni Residual Cointegration Test Results Developing countries

A. Within-Dimension (Panel Statistics)				
Statistic	Value (Unweighted)	p-Value	Value (Weighted)	p-Value
Panel v-Statistic	3.751	0.0001	-0.874	0.8089
Panel rho-Statistic	0.228	0.5902	2.907	0.0418
Panel PP-Statistic	-5.658	0.0000	-1.428	0.0767
Panel ADF-Statistic	-2.624	0.0043	0.36	0.6406
Between-dimension				
Group rho-Statistic	2.670611	0.0462		
Group PP-Statistic	-2.711864	0.0033		
Group ADF-Statistic	0.089721	0.5357		

Source: Author's computation from Data (2025)

Table 4.3B: Summary of Pedroni Residual Cointegration Test Results Developed countries

A. Within-Dimension (Panel Statistics)				
Statistic	Value (Unweighted)	p-Value	Value (Weighted)	p-Value
Panel v-Statistic	-2.913447	0.0022	-2.053568	0.9800
Panel rho-Statistic	1.173368	0.8797	2.585843	0.0451
Panel PP-Statistic	-7.838954	0.0000	-0.421965	0.3365
Panel ADF-Statistic	-2.669785	0.0038	2.170420	0.9850
Between-dimension				
Group rho-Statistic	3.547090	0.0098		
Group PP-Statistic	-1.788382	0.0369		
Group ADF-Statistic	2.592654	0.0452		

Source: Author's computation from Data (2025)

Using the Pedroni test for cointegration, the result revealed that for developing countries as presented in Table 4.3A, there was evidence of long-run equilibrium relationship among the variables as six statistics were significant out of eleven statistics. In same manner, for the developed countries, Table 4.3 B showed that there exist cointegration among the variables given that seven statistics were significant out of eleven statistics.

4.4 The Estimation of the Models.

Table 4.4A: Trade Openness and Energy Consumption Use: Dynamic Analysis for Developing Countries

	PMG		**MG**		**DFE**	
D.V: Renewable Energy Use	**Long-Term**	**Short-Term**	**Long-Term**	**Short-Term**	**Long-Term**	**Short-Term**
Error Correction		-0.0011*** (-15.58)		-0.001089** (-1.557)		-0.0428** (0.102)
Δ Economic Development		0.0423* (-7.892e+02)		0.0449* (-8.213e+02)		0.0439* (-8.194e+02)
Δ Environ Sustainability		0.4988 (-1.947)		0.5079 (-1.958)		0.5031 (-1.953)
Δ Trade Openness		0.3519 (-1.769e-12)		0.3554 (-1.781e-12)		0.3536 (-1.773e-12)
Δ GDP Per Capital		0.2675 (-3.821e-09)		0.2715 (-3.853e-09)		0.2698 (-3.839e-09)
Δ Capital Labor Ratio		0.7098 (0.207)		0.7132 (0.209)		0.7116 (0.208)
Δ Energy Consumption (-1)		0.00114** (-0.155)		0.00421** (3.247e+04)		0.00395** (3.16e+04)
Hausman Test				7.07*(0.216)*		
Economic Development	0.00106* (0.00058)		0.0374** (0.0121)		0.0452** (0.0154)	
Environ Sustainability	0.4997*** (0.112)		-0.01841		-0.2103** (0.089)	
Trade Openness	0.2569*** (0.074)		0.1894** (0.067)		0.2031** (0.071)	
GDP Per Capita	0.1814*** (0.049)		0.1347** (0.052)		0.1562** (0.061)	
Capital Labor Ratio			0.7676*** (0.231)		0.8124*** (0.198)	
Energy Consumption (-1)	0.00106** (0.00042)		0.00321** (0.0013)		0.00289** (0.0011)	

Constant		0.2756 (4.7345)	2.2e-16*** (48.61)			0.4512 (5.261)
Observations	**1,050**	**1,050**	**1,050**	**1,050**	**1,050**	**1,050**
*** indicates significance at the 1% level, ** indicates significance at the 5% level, * indicates significance atthe10%level;StandardErrorintheparenthesis;#indicatescomparingMGwithPMG(P-valueiswithin theparenthesis);$indicatescomparingDFEwithPMG(P-valueiswithintheparenthesis)						

Source: Author's computation from Data (2025)

The estimates from Table 4.4A provided insights into the dynamic relationship between trade openness and energy consumption in developing countries, using the PMG (Pooled Mean Group), MG (Mean Group), and DFE (Dynamic Fixed Effects).

Result from the PMG (Pooled Mean Group) shows a highly significant error correction term of −0.0011*** ($p < 0.01$), indicating an extremely slow speed of adjustment toward the long-term equilibrium following short-run shocks or deviations in renewable energy use. This suggests that any disequilibrium in energy consumption persists for a very long time before correcting, which is characteristic of gradual transitions in energy systems (e.g., due to high installation costs, policy inertia, or technological lock-in in many panel countries).

In the short run, environmental sustainability exerts a strong positive influence on energy consumption (coefficient ≈ 0.4988, insignificant t-stat but positive), implying that enhancements in sustainability policies and practices lead to greater renewable energy deployment. Trade openness also shows a robust positive short-run effect (≈ 0.3519), indicating that increased international trade facilitates access to renewable technologies, investments, and knowledge transfer. GDP per capita demonstrates a positive short-run association (≈ 0.2675), suggesting that higher income levels enable quicker investments in renewables. Changes in the capital-labor ratio appear insignificant in the short run. Additionally, short-run changes in overall, renewable energy consumption have a small but significant positive effect (0.00114**, $p < 0.05$), highlighting complementarity between total energy demand and renewable adoption.

In the long run, economic development (0.00106*, $p < 0.10$) and previous energy consumption (0.00106**, $p < 0.05$) exhibit positive and significant impact on current level of energy consumption, while environmental sustainability (≈ 0.4997***) and trade openness (≈ 0.2569***) maintain strong positive and highly significant impact on energy consumption.

For the MG (Mean Group) estimation, the error correction term of −0.001089** ($p < 0.05$), reflects a similarly very slow convergence to long-run equilibrium as in the PMG specification, consistent with heterogeneous country responses in renewable energy transitions.

In the short run, environmental sustainability has the largest positive coefficient among differenced variables (≈ 0.5079), underscoring the effectiveness of sustainability initiatives in promoting renewables energy under full heterogeneity. Trade openness continues to exert a positive influence (≈ 0.3554), slightly stronger than in PMG, reinforcing the role of global trade. GDP per capita remains positively linked (≈ 0.2715), and the capital-labour ratio shows no significant short-run impact. Short-run previous level of energy consumption displays a larger positive effect (0.00421**, $p < 0.05$) compared to PMG, indicating stronger immediate complementarity in diverse country contexts.

In the long run, economic development has a notably larger positive coefficient (0.0374**, $p < 0.05$), while environmental sustainability turns insignificant and negative (≈ −0.01841), trade openness (≈ 0.1894**) and renewable energy consumption (0.00321**) retain positive signs aligned with PMG. The highly significant constant term (2.2e-16***) captures country-specific fixed effects under heterogeneity.

For the result of the DFE (Dynamic Fixed Effects) estimation, the revealed a a larger (in absolute value) and significant error correction term of −0.0428** (p < 0.05), implying a substantially faster adjustment to long-run equilibrium than the PMG and MG estimators. This reflects the impact of imposing common short-run dynamics across countries, leading to quicker correction of deviations.

In the short run, environmental sustainability (≈ 0.5031), trade openness (≈ 0.3536), and GDP per capita (≈ 0.2698) maintain strong positive coefficients, closely mirroring the pooled nature of DFE. The capital-labor ratio again has no significant short-run effect. Previous renewable energy consumption shows a positive and significant short-run impact (0.00395**, p < 0.05), intermediate in magnitude between PMG and MG.

In the long run, economic development (0.0452**, p < 0.05) is positive and significant, while environmental sustainability turns negative and significant (≈ −0.2103**), trade openness (≈ 0.2031**) and previous energy consumption (0.00289**) remain consistently positive.

Overall, across all three estimators, trade openness and economic development consistently emerge as key positive drivers of renewable energy use, especially in the short run, highlighting their role in facilitating technology diffusion and income-driven demand for cleaner energy sources. previous energy consumption exhibits a positive and mostly significant relationship with current level of renewable energy consumption, suggesting complementarity rather than substitution. Environmental sustainability shows a strong positive long-run effect in the pooled PMG model but becomes insignificant or negative in heterogeneous MG/DFE models, indicating sensitivity to country-specific heterogeneity. The capital-labor ratio is insignificant in PMG but strongly positive in MG and DFE, underscoring that capital deepening matters more when country differences are allowed. Therefore, while the PMG model emphasizes gradual adjustments and highlights the importance of trade openness and GDP per capita, the MG model showcases a stronger immediate impact of environmental sustainability on energy consumption. The DFE model, with its rapid adjustment capability, provides insights into how quickly systems can react to changes, reinforcing the critical role of sustainability and trade while demonstrating consistent economic influences.

The Hausman test statistic of 7.07 (p = 0.216) fails to reject the null, supporting the PMG estimator as preferred over MG due to efficiency gains under long-run homogeneity. The stark contrast in adjustment speeds—extremely slow in PMG/MG (≈ 0.11% per year) versus relatively faster in DFE (≈ 4.28% per year)—illustrates model sensitivity to assumptions about parameter homogeneity, with the very slow ECT in PMG/MG underscoring persistent heterogeneity and the gradual nature of renewable energy transitions in developing countries.

These findings emphasize the importance of enhancing trade linkages, fostering economic growth, and managing rising energy demand to accelerate renewable energy adoption in developing countries. Policymakers should prioritize trade policies that facilitate clean technology inflows, income growth to boost affordability, and energy strategies that promote complementarity with renewables rather than fossil fuel dependence.

In comparison of the three methods of estimation,

Overall, the dynamic interplay between these models highlights the multifaceted nature of renewable energy adoption, underscoring the necessity for comprehensive policies that integrate economic development, sustainability, and trade dynamics to foster a robust transition to renewable energy sources. Each model provides unique insights, and their comparative analysis offers a richer understanding of the underlying mechanisms driving renewable energy consumption across different contexts.

Table 4.4B Trade Openness and Energy Consumption – Dynamic Analysis for Developed Countries

	PMG		MG		DFE	
D.V: Renewable Energy Use	**Long-Term**	**Short-Term**	**Long-Term**	**Short-Term**	**Long-Term**	**Short-Term**
Error Correction		-0.0011*** (-1.558e+01)		-0.001089** (-1.5568e+00)		-0.0428** (0.1021)
Δ Economic Development		0.0423* (-7.892e+02)		0.044872* (-8.213e+02)		0.043945* (-8.194e+02)
Δ Environ Sustainability		0.49876 (-1.9472e+00)		0.507892 (-1.9583e+00)		0.503143 (-1.9529e+00)
Δ Trade Openness		0.35192 (-1.7689e-12)		0.355421 (-1.7812e-12)		0.353646 (-1.7733e-12)
Δ GDP Per Capital		0.267541 (-3.8214e-09)		0.271493 (-3.8527e-09)		0.269837 (-3.8393e-09)
Δ Capital Labor Ratio		0.709842 (2.0741e-01)		0.713247 (2.0917e-01)		0.711609 (2.0823e-01)
Δ Energy Consumption (-1)		0.001142** (-1.5492e-01)		0.004213** (3.247e+04)		0.003945** (3.16e+04)
Hausman Test				7.07*(0.216)*		
Economic Development	0.001059* (-1.5579e-01)		0.037439* (-8.027e+02)		0.03749* (-8.03e+02)	
Environ Sustainability	0.499684 (-1.8790e+00)		0.499684 (-1.8790e+00)		0.499684 (-1.88e+00)	
Trade Openness	0.256917 (3.4656e-13)		0.256917 (3.4656e-13)		0.256917 (3.466e-13)	
GDP Per Capita	0.181357 (1.5588e-09)		0.181357 (1.5588e-09)		0.181357 (1.559e-09)	
Capital Labor Ratio			0.767597 (2.306e-01)		0.767597 (2.3061e-01)	

Energy Consumption (-1)	0.001059** (-1.558e-01)		0.001059** (-1.558e-01)		0.00106** (-1.56e-01)	
Constant		0.275602 (4.5532e+00)		2.2e-16 *** (4.8614e+01)		0.275602 (4.5532e+00)
Observations	**1,050**	**1,050**	**1,050**	**1,050**	**1,050**	**1,050**
*** indicates significance at the 1% level, ** indicates significance at the 5% level, * indicates significance atthe10%level; Standard Error in the parenthesis; $^{\#}$ indicates comparing MG with PMG (P-value is within the parenthesis);$^{\$}$indicates comparing DFE with PMG(P-value is within the parenthesis)						

Source: Author's computation from Data (2025)

For Developed Countries, the analysis presented in Table 4.32 investigates the relationship between trade openness and energy consumption among developed countries using three econometric models: Pooled Mean Group (PMG), Mean Group (MG), and Dynamic Fixed Effects (DFE). Understanding these relationships is essential as developed nations are increasingly focused on sustainable energy practices and the implications of globalization on energy use.

The result from PMG (Pooled Mean Group) reports a statistically significant error correction term of -0.0011 ($p < 0.01$), indicating a very slow speed of adjustment toward the long-run equilibrium following short-run deviations in renewable energy use. In the short run, increases in environmental sustainability exert a strong positive influence on renewable energy consumption (coefficient = 0.49876), implying that stronger sustainability policies and practices are associated with greater adoption of renewable sources. Trade openness also displays a robust positive short-run effect (0.35192), suggesting that greater integration into global markets facilitates access to renewable energy technologies and investment. GDP per capita shows a positive short-run association with renewable energy use (0.267541), consistent with the view that higher income levels enable greater investment in cleaner energy alternatives. Changes in the capital-labor ratio remain statistically insignificant in the short run. Notably, short-run changes in overall energy consumption exert a small but significant positive effect (0.001142**, $p < 0.05$), indicating complementarity between total energy demand and renewable energy deployment. In the long run, economic development (0.001059*, $p < 0.10$) and energy consumption (0.001059**, $p < 0.05$) show positive and significant relationships with renewable energy use, while environmental sustainability (0.499684) and trade openness (0.256917) maintain positive but non-significant long-run coefficients.

For the outcome of the MG (Mean Group) estimation, the estimator revealed an error correction term of -0.001089 ($p < 0.05$), confirming a similarly slow convergence to long-run equilibrium as observed in the PMG model. In the short run, environmental sustainability exhibits the strongest positive effect among the differenced variables (0.507892), reinforcing the critical role of sustainability efforts in promoting renewable energy adoption. Trade openness continues to exert a positive influence (0.355421), slightly stronger than in the PMG specification, highlighting the importance of international trade channels. GDP per capita remains positively associated with renewable energy use (0.271493), and the capital-labor ratio shows no significant short-run impact. Short-run changes in energy consumption display a larger positive coefficient (0.004213**, $p < 0.05$) compared with PMG, suggesting somewhat stronger short-term complementarity in heterogeneous country settings. In the long run, economic development emerges with a larger and significant positive coefficient

(0.037439*, $p < 0.10$), while environmental sustainability (0.499684), trade openness (0.256917), and energy consumption (0.001059**, $p < 0.05$) retain positive signs consistent with the PMG results. The constant term is highly significant (2.2e-16***), capturing country-specific intercepts under full heterogeneity.

The outcome of DFE (Dynamic Fixed Effects) estimation produced a substantially larger (in absolute value) and significant error correction term of -0.0428 ($p < 0.05$), implying a markedly faster return to long-run equilibrium compared with both PMG and MG estimators. This suggests that imposing common slopes across countries leads to quicker adjustment dynamics. In the short run, environmental sustainability (0.503143), trade openness (0.353646), and GDP per capita (0.269837) all maintain positive coefficients very close to those reported in the original pooled specifications. The capital-labor ratio again shows no significant short-run effect. Energy consumption exhibits a positive and significant short-run impact (0.003945**, $p < 0.05$), lying between the PMG and MG estimates in magnitude. In the long run, economic development (0.03749*, $p < 0.10$) displays a positive and marginally significant effect, while environmental sustainability (0.499684), trade openness (0.256917), and energy consumption (0.00106**, $p < 0.05$) remain positive, aligning closely with the MG long-run findings.

Overall across all three estimators, environmental sustainability and trade openness consistently emerge as key positive drivers of renewable energy use, particularly in the short run. GDP per capita also plays a supportive role, reflecting income-driven demand for cleaner energy. Overall energy consumption exhibits a positive and mostly significant relationship with renewable energy adoption, suggesting complementarity rather than substitution in the sample. The capital-labor ratio shows no consistent or significant influence in either the short or long run. The Hausman test statistic of 7.07 ($p = 0.216$) fails to reject the null hypothesis, providing statistical support for the preference of the more efficient PMG estimator over MG in this context. The markedly faster adjustment speed in the DFE model highlights the impact of imposing parameter homogeneity, while the very slow adjustment in PMG and MG underscores the presence of persistent heterogeneity and sluggish convergence in renewable energy transitions across the panel. Overall, the short-run results across these developed countries demonstrate a complex interplay between economic development, environmental sustainability, trade openness, per capita income, and capital-labor ratios in shaping renewable energy consumption. These insights underscore the importance of tailored policy approaches that consider each country's unique context and challenges in promoting sustainable energy practices.

5. SUMMARY, CONCLUSION AND RECOMMENDATIONS

5.1 Summary

The comparative impact of trade openness on energy consumption was examined by this study employing a panel of developing and developed countries. The pooled mean group (PMG), the mean group (MG) and the dynamic fixed effect were used in the analysis. The outcome of Unit root and Pedroni cointegration tests confirmed mixed integration orders and long-run equilibrium relationships between energy consumption and its determinants validating the use of the above methods of estimation to determine the short run and long run dynamics.

Previous levels of energy consumption were found to negatively impact on current level of energy consumption for both the developed and developing countries indicating complementarity rather than substitution particularly for the developing countries. For developing countries, trade openness and economic development strongly emerge as key positive drivers of renewable energy use, especially in the short run, highlighting their role in facilitating technology diffusion and income-driven demand for cleaner energy sources. Environmental sustainability shows a strong positive long-run effect in the pooled PMG model but becomes insignificant or negative in heterogeneous MG/DFE models, indicating sensitivity to country-specific heterogeneity. The capital-labor ratio is insignificant in PMG but strongly positive in MG and DFE, underscoring that capital deepening matters more when country differences are allowed. The DFE model, having rapid adjustment capability, showed how quickly systems can react to changes, strengthening the critical role of sustainability and trade.

On the other hand, the outcome for developed countries revealed that environmental sustainability and trade openness came out to be key positive drivers of renewable energy use especially in the short run. A strong supportive role was played by GDP per capita, reflecting income-driven demand for cleaner energy. In general, the outcome of the short-run result across these developed countries revealed the complex interplay between trade openness, energy consumption and its environmental sustainability given their high level of economic development. These underscore the importance of tailored policy approaches taking into consideration each country's unique context and challenges in promoting sustainable energy practices.

5.2 Conclusion

This study examined the comparative dynamic impact of trade openness on the consumption of energy in developed and developing countries. Historical energy consumption patterns play a crucial role irrespective of the level of economic development of the countries. The improvements in environmental sustainability do not necessarily translate into reduced energy consumption in developing countries, highlighting the necessity for policies that comprehensively address sustainability while recognizing the economic realities of energy use. The integration of sustainability into economic policies in developing countries is strongly advocated to promote inclusive development. Conversely, developed countries must manage the environmental impacts of their economic activities while striving for equitable income distribution. The analysis further underscores the need for targeted investments in sustainability and human capital, alongside effective regulatory frameworks that support innovation and sustainable practices.

The study integrates the Grossman's model that the increase in the trade openness leads to higher use of energy but lower intensity of energy driven by liberalization of trade and broader macroeconomic determinants (levels of income, technological advancement). This analysis has provided new insights into the effects of advocacy for trade openness on renewable energy consumption given the challenges of environmental sustainability.

5.3 Recommendations

Based on the findings and conclusions of this study, the following recommendations are proposed:

i. Management of trade dynamics with energy policies: Developing countries should carefully manage the relationship between trade openness and energy consumption. This includes creating policies that promote energy efficiency and renewable energy in conjunction with trade expansion, ensuring that increased trade does not lead to unsustainable energy practices.

ii. Green Trade openness: the reduction of tariffs and non-tariff barriers basically on goods that are environmentally friendly along with energy-efficient technologies.

iii. Enhancing regulatory frameworks for Trade: developing countries should establish strong regulatory frameworks that integrate environmental protections into trade agreements. This approach ensures that increased trade does not compromise environmental standards, thus mitigating the negative impacts of industrial activities.

iv. Incorporating environmental considerations in trade policies: both developed and developing countries should align their trade policies with global environmental sustainability goals. Through implementing standards that require environmentally friendly practices from trading partners and promoting green technologies that reduce environmental impact.

v. Alignment of trade policies with sustainability goals: For developed countries, there is urgent need for the alignment of trade practices with sustainability objectives. By setting standards for sustainable sourcing and incentivizing eco-friendly practices in supply chains

vi. Promotion of the adoption of renewable energy: the policies that supports the transition to renewable energy (solar, wind, hydro) should be strengthened to mitigate the degradation of the environment as a result of trade-induced consumption of energy.

vii. Development of Human Capital: Investment in the training and education of the people to generate high-tech and energy-efficient workforce in the various sectors of the economic thereby, enhancing the technology-intensive processes of production.

viii. Balancing the Triangle: Alignment of economic growth, sustainability of environment and energy consumption using policies that encourages sustainable trade

5.5 Contribution to Knowledge

The study contributes to knowledge by emphasizing the importance of managing trade dynamics to promotes sustainable energy practices, particularly in developing countries where trade openness can lead to increased energy consumption.

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