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Innovation, Economic Growth and Energy Intensity: A Comparative Analysis of Developed and Developing Countries

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Abstract

This study examines the relationships between innovation, economic growth, and energy intensity in developing and developed countries. Annual panel data for 50 developing and 34 developed countries over 2008–2022 are analysed using separate two-step System Generalized Method of Moments models. Innovation is measured by the total number of resident and non-resident patent applications, while real GDP per capita serves as a proxy for economic growth. Both variables are significantly and negatively associated with energy intensity in both groups. The estimated reduction associated with economic growth is greater in developed countries, whereas that associated with innovation is greater in developing countries. Energy intensity exhibits persistence in both groups, with more gradual adjustment in the developed-country estimates. Among the control variables, urbanization is positively associated with energy intensity in both samples, trade openness displays contrasting relationships, and foreign direct investment is statistically insignificant. These findings highlight the relevance of technological improvement, capital renewal and energy-efficient infrastructure for reducing energy requirements per unit of output across different development settings.

Keywords: Energy intensity, innovation, economic growth, urbanization, trade openness, foreign direct investment.

1. Introduction

Maintaining economic growth in both developing and developed economies while reducing the energy required to produce a given level of output is a key policy issue. There is a possibility that growth will increase energy use, and innovation and structural change can enhance the energy performance of production. Energy intensity is a measure of the energy consumed per unit of economic activity. A decrease may indicate better energy efficiency or a greater energy shift in the activity, but not necessarily indicate decreased energy consumption or carbon emissions. It is thus crucial to understand what factors are

connected with lower energy intensity when assessing the capacity of economies to accommodate growth while enhancing their energy performance (Voigt et al., 2014; Deichmann et al., 2018).

It is a relationship that is driven by innovation and economic growth. Higher incomes can provide resources to invest in more efficient capital, and innovation can increase productivity in machinery, production processes, and energy management. These mechanisms are in line with Endogenous Growth Theory that places an emphasis on knowledge accumulation and technological progress as sources of productivity (Romer, 1990). But new knowledge doesn't necessarily lead to the adoption of energy-saving technologies. Likewise, the economy could grow despite greater energy efficiency. The other way around is also true: economic growth may require more energy even if production becomes more efficient. The association of innovation with economic growth, in terms of energy intensity, thus embodies the interplay among technological progress, capital renewal, and the reshaping of economic activity.

These relationships may vary across developing and developed countries. Economies have varying production configurations, technology and opportunities for replacement of less efficient capital. The needs for industrial and infrastructural development can grow in line with the developing economy, but so can the opportunities for more efficient production processes. Established innovation systems can be beneficial for developed economies, even if they involve a certain degree of slow adjustments linked with long-lived capital and infrastructure. Prior studies have reported on differences in energy-intensive patterns and the impact of technology and structural shifts in economies (Voigt et al., 2014; Deichmann et al., 2018). The variation suggests that it may be worthwhile to consider the two country groups separately, and not to assume that the same coefficients on innovation and the economic-growth proxy apply across all economies.

The central empirical question is whether innovation and economic growth are linked to lower energy intensity in both developing and developed countries, and how these relationships differ between the two groups. Previous research offers evidence on income and energy intensity, green innovation and knowledge spillovers (Deichmann et al., 2018; Wurlod & Noailly, 2018; Sun et al., 2021). However, they have different innovation measures, units of analysis and energy outcomes. Green patents represent a specific kind of patent, while the number of patents applied for is a more general indicator of patenting; energy-efficiency indicators and aggregate energy intensity measure different things, but they are related. These measures differ in how they interpret innovation across development groups.

The present research builds on this literature and explores innovation and per capita real GDP within a shared dynamic specification of aggregate energy intensity for the developing and developed countries. The estimated associations and persistence can be compared between the two samples, based on consistent variable definitions and a common observation period. In addition to evidence from specialized innovation indicators, the total

number of resident and non-resident patent applications reflects overall patenting activity. The analysis focuses on how this overall measure relates to national energy intensity.

In response to this question, the impact of innovation and economic growth on energy intensity in developing and developed countries is investigated. Data on the annual time series of 50 developing and 34 developed countries are analyzed by applying two-step System Generalized Method of Moments (SGMM) models separately. The number of resident and non-resident patent applications is used as an indicator of innovation, and real GDP per capita is used to measure the proxy for economic growth. Several control variables are also included, such as urbanization, trade openness and foreign direct investment. The dynamic specification accounts for persistence in energy intensity, and the estimator addresses potential endogeneity of the regressors, given the required instrument assumptions.

The study investigates the relationship of each of these two factors with energy intensity for both groups of countries, looking for a negative correlation. This is because the explanatory-variable coefficients and the persistence parameter are separable and can be different from one sample to the next. The comparison provides evidence of its relevance to technology adoption, investment policy, and energy policy. This is a descriptive interpretation of the cross-group differences within the framework of this estimation.

The remainder of the paper is organized as follows. The empirical literature is reviewed in Section 2. The theoretical and conceptual framework is presented in Section 3. The data and methodology are discussed in Section 4. The results are presented and discussed in Section 5. The conclusion, policy implications and limitations are presented in Section 6.

2. Literature Review

2.1 Innovation and Energy Intensity

Innovation has the potential to lower energy intensity through gains in production technology and with the use of energy efficient capital equipment, as well as in the diffusion of knowledge. But empirical evidence is sensitive to measures of innovation. Patents, green patents, R&D expenditure, researchers and technology networks represent various aspects and stages of innovative activity. As a result, it is not an appropriate comparison to equate their energy intensity impact estimates.

Literature on innovation and energy intensity is generally based on a patent approach and confirms the impact of innovation on reducing energy intensity. Wurlod and Noailly (2018) found using sectoral data for OECD countries that green innovation decreased energy intensity in most industrial sectors. Hille and Lambernd (2020) also found that the relationship between patent applications and total energy intensity of provinces in South Korea was very negative. Sun et al. (2021) also found that the technological innovation and knowledge spillovers enhanced the energy efficiency of the highly innovative countries. Overall the results indicate that both the generation and dissemination of

technological knowledge can be used to enhance energy performance. However, the measures of innovation and the dependent variables vary among the studies. Environmental innovation is identified by green patents, whereas total patents are used to identify innovative activity in general, and energy efficiency is different to energy intensity. However, differences in these make it difficult to directly compare the estimated effects.

Alternative indicators of innovation are less consistent. Hille and Lambernd (2020) reported that patent applications were strongly correlated with reduction in energy intensity, but the negative correlation of the R&D expenditures was non-statistically significant. The same findings were reported by Saudi et al. (2019) which also indicated that the association with energy intensity varied by patent, R&D spending and high-technology exports in Indonesia. Huang et al. (2022) also identified two types of technologies: energy-conservation and energy-substitution technologies, and showed that the impacts of the technologies on energy intensity are dependent on technical attributes and absorptive capacity. So, the literature implies that innovation should not be considered as a one-size-fits-all process. Energy intensity can be influenced by innovation inputs, outputs, and certain technological uses, in various ways.

More recently, the importance of knowledge networks and the technological context has been highlighted. Li et al. (2026) showed that the key determinants of lower urban energy intensity in China were to have stronger positions in innovation networks, which indicates the importance of knowledge openness, technological complexity, and connectivity as important channels. There is also related evidence indicating that development of renewable energy can also lead to reduced energy intensity depending on the level of renewable energy development (Yu et al., 2022). While these studies expand the technological definition of energy intensity, the measures taken at the city level, regional level or technology level cannot be directly compared to national aggregate patent activity.

In general, the results of the existing studies are in line with this energy-intensity reducing effect of innovation but the evidence depends on the indicator of innovation, the level of aggregation and the economic context. The current evidence is focused on OECD economies, China, South Korea or specific developing countries. So far, there is little comparative evidence linking more general innovative activity (total number of patent applications) to effects on energy intensity in developed and developing economies. This limitation allows them to break down the innovation-energy intensity relationship for the two groups of countries.

2.2 Economic Growth and Energy Intensity

The scale effect is coupled with the technological and structural effect in the relationship between economic growth and energy intensity. Economic growth can have an impact on energy demand by raising production volumes, transportation needs, building and infrastructure demand. Concurrently, a higher income stream can help drive technology upgrading, the replacement of less efficient capital and structural shift towards more energy-efficient activities. It is therefore essential to understand whether technological and

production progress can keep up with the additional energy needs required to grow the economy or whether there is a net connection between economic growth and energy intensity.

The general pattern of the empirical evidence from across the world is that income has a negative relationship with energy intensity, although this relationship is stronger in some countries than in others. For 137 economies, Deichmann et al. (2018) also demonstrate a negative correlation between income growth and energy intensity change, and that the energy intensity reduction slows down after a certain income. Similarly, Voigt et al. (2014) identified technology and structural change as the driving forces behind changes in energy intensity in the main economies. The results indicate that the income-energy intensity relationship is not just a scale effect, but is tightly linked to technology and economic structure changes as countries evolve.

This negative relationship is supported by more direct empirical evidence. Even after controlling for trends in energy intensity, energy prices, taxes, and persistence, Mahmood and Ahmad (2018) concluded that there was a significant negative association between economic growth and energy intensity in European countries. Díaz et al. (2019) also found that reductions in energy intensity were linked to greater GDP per capita growth in a substantially larger sample of 134 countries and with the use of dynamic panel methods, such as system GMM. In spite of variations in samples and model specification, the findings of these studies are consistent that economic growth can be achieved while decreasing energy intensity.

However, from a regional perspective, there is evidence that the relationship can vary with economic development. The negative direct, spillover and total effects of GDP per capita on energy intensity suggested that it is in inverse relationships with energy intensity in cities in Guangdong; the positive squared income term suggested that the reduction effect of GDP per capita on energy intensity will change with the increase of income. Similarly, Hille and Lambernd (2020) revealed that the income-related technological impacts result in a decline of total energy intensity in South Korea, especially in the case of oil and electricity. The results here confirm the importance of technological upgrading, but also indicate that the income effect may not be the same at various stages of development.

The findings from previous studies on the overall trend of the relationship between economic growth and energy intensity are mostly negative, but the extent and the mechanism of the relationship vary by country and income level. Much evidence reviewed is limited in scope to large amalgamated samples or specific countries and regions, with a lack of direct evidence on whether the relationship is systematically different in developed and developing economies. It is significant, therefore, to compare these groups for their technological potential, their method of production and their possibilities for substitution of energy-intensive capital, since these could be very different.

2.3 Urbanization, Trade Openness and Foreign Direct Investment

Besides innovation and economic growth, factors like structural and international economic factors could affect energy intensity. Improved energy efficiency in cities can result from a higher concentration of people and economic activity, and more energy is needed in cities for infrastructure, transportation, and buildings. To show the relevance of urbanization to explaining changes in energy intensity, Yan (2015) applied the data from Chinese provinces. The results from one country, provincial level setting, however, do not necessarily reflect the relationship in economies with different urban structures. The impacts of innovation and economic growth are therefore measured taking into account the control factor of urbanisation.

The impact of openness to trade is also mixed, as trade can trade via different channels. Openness could lead to higher energy consumption through production expansion and energy transportation while also allowing the use of energy efficient technologies, capital goods, and technical knowledge. Sohag et al. (2015) concluded that energy consumption went up with trade openness, but it went down with innovation in Malaysia. Their dependent variable, however, was energy use, as opposed to energy intensity, so it would be hard to compare directly with studies interested in how energy is being used in relation to economic output. Contrary to this, Fallah Jelodar and Sadeghi (2023) found evidence on the effects of trade openness on energy intensity in some developing countries, which was at the cost of importing technologies and improving production efficiency. The contrasting evidence suggests that the impact of trade openness depends on whether the production-expansion or technology transfer effects dominate. It is also warranted to analyze its relationship individually for the developed and developing economies.

Evidence of FDI is even less conclusive. Kasimov et al. (2023) employed two-step GMM with 97 developing countries, and the results indicated that FDI was positively correlated with energy intensity, but the interaction of FDI and technology was negatively correlated with energy intensity. The findings indicate that the energy impact of FDI is as a result of the ability of the host country to absorb and make use of the transferred technology. While Naimoglu et al. (2024) did report a negative long-run coefficient of FDI for India, they were able to achieve statistical significance only under DOLS, and not under FMOLS or CCR. Additionally, Hübler and Keller (2010) did not discover any significant evidence of a decrease in energy intensity due to FDI inflows to developing economies. So, the literature is inconclusive about the direct relationship between FDI and energy intensity reductions.

The mixed results of the FDI findings is important, as they reflect aggregate FDI inflows, which reflect investment in industries with widely varying energy requirements, not just energy-efficient technology transfers. Likewise, urbanization and trade may have an energy increasing or energy saving impact. These variables are thus more appropriately considered as structural controls in the current analysis than as the main control variables. Their addition allows the identification of the relationship between innovation and

economic growth, and between energy intensity and economic integration and economic structure.

2.4 Synthesis and Research Contribution

There is strong existing literature to support the relationship of technological advancements and economic development with energy intensity change, but some gaps exist. First, the relationship between innovation and the intensity of use of innovation energy is sensitive to the way in which innovation is measured. Different dimensions of technological change are captured in different measures of technological change, such as green patents, R&D expenditure, total patents, technology-specific innovations and innovation networks, and have yielded different empirical results. However, there are generally positive trends in energy intensity in the patent-based data, while results from R&D investments and other innovation indicators are mixed. Second, while there is a general trend of falling energy intensity in economic growth, strong evidence suggests that the relationship between them is also dependent on income levels, technological progress and structural transformation.

Another constraint is the focus of previous research on a single country, specific geographic area, specific industry or a combination of countries. These methods are useful in terms of providing evidence but are not explicit on the relationship between innovation and economic growth and its impact on energy intensity between developed and developing economies. This distinction is crucial as the technological capabilities, economic structures, capital stocks, and ability to take up and spread energy-efficient technologies are different among the two groups. Furthermore, urbanization and openness to trade and FDI are contradictory in some ways and hence have to be accounted for when looking for the key relationships.

In the present study these limitations are overcome by considering innovation and economic growth in a common dynamic framework, and by explicit comparisons between developed and developing countries. The measures of innovation are total patent applications, whereas the measures of economic growth are real GDP per capita; urbanization, trade openness and FDI are included as control variables. The analysis is over 50 developing countries and 34 developed countries over 2008-2022 and takes into account the persistence of energy intensity by using a dynamic panel specification. This comparative method enables the study to evaluate the direction and strength of the relationship between innovation, economic growth, and energy intensity across the two sets of development countries, and thus generate evidence that cannot be readily found in single-country, regional, and pooled-sample studies.

3. Theoretical and Conceptual Framework

The study is based on the Endogenous Growth Theory. It provides an account of how knowledge accumulation, research and technological advances can help sustain productivity improvements (Romer, 1990). When applied to energy intensity, this

approach implies that with better production practices and capital usage, output can grow while the amount of energy used grows less than proportionately.

Machinery, production processes, and energy management are potential areas of innovation that can impact energy intensity. The dissemination of knowledge can also help to promote the use of more efficient technologies. The channels encourage a negative relationship between innovation and energy intensity, and acknowledge that the relationship between the invention and its relevance and application determines the outcome. The annual patent applications reflect a flow of patenting activity rather than an accumulation of knowledge, and they don't directly reflect performance in energy savings.

Economic growth can influence energy intensity through capital renewal and structural transformation. Expanding productive capacity can support investment in efficient equipment and shifts towards less energy-intensive activities, while industrial and infrastructure expansion can increase energy requirements. The expected relationship reflects the balance between these processes. A negative coefficient on real GDP per capita is consistent with improvements in technology and production structure accompanying economic growth.

The empirical model looks at the independent effects of innovation and real GDP per capita on energy intensity. Urbanization, trade openness and FDI are included because they may affect infrastructure demand, production patterns and access to technology. Figure 1 summarises the hypothesised relationships between these variables and energy intensity.

The study hypothesises that innovation and real GDP per capita are negatively associated with energy intensity in both groups of countries. Urbanization may raise energy intensity when additional infrastructure and transport requirements outweigh efficiency gains. The expected signs of trade openness and FDI remain ambiguous because technology transfer and the expansion of energy-intensive activities may operate simultaneously.

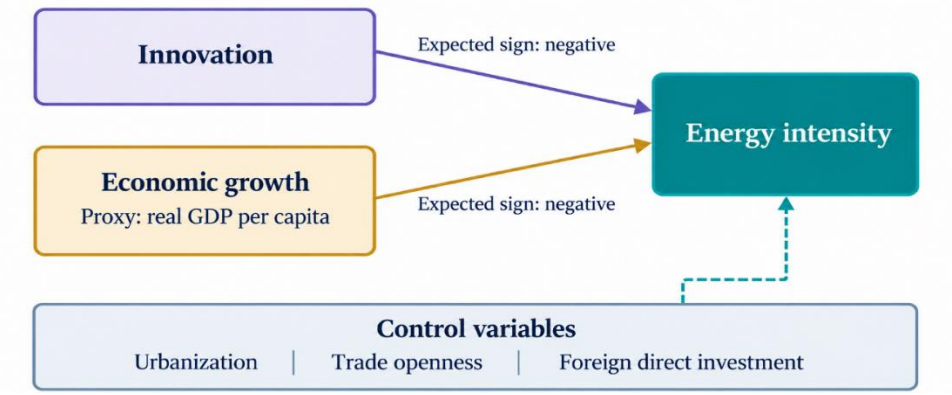

Figure 1: Conceptual Framework

4. Data and Methodology

4.1 Research Design and Sample

The study uses secondary annual panel data for 2008–2022. Under the World Bank income classification used for the analysis, low-income, lower-middle-income and upper-middle-income economies are combined into the developing-country group, while high-income economies constitute the developed-country group. These are operational definitions for this study. The classification source is the 2024–2025 release (Metreau et al., 2024). Subject to data availability, the final sample comprises 50 developing and 34 developed countries.

The two country groups are estimated separately using the same explanatory variables and observation period. The sample comprises 50 developing and 34 developed countries over 2008–2022, with country coverage determined by data availability. Observations vary across variables, resulting in unbalanced panels. Table 2 reports the available observations for each variable, while the System GMM estimation samples comprise 655 observations for developing countries and 442 for developed countries. The estimation samples reflect the availability of the variables and lagged observations required by the dynamic specification.

The macroeconomic indicators are obtained from the World Development Indicators database, with patent-application data originating from the World Intellectual Property Organization. Series are merged by country and year. Table 1 defines the variables, measurement units, transformations and source of the data collection.

Table 1: Variable Definitions and Data Sources

Variable	Measurement	Transformation	Source
ENI	Primary energy supply per unit of GDP; MJ per 2021 PPP dollar	Natural log	WDI
GDPC	Real GDP per capita; constant 2015 US dollars	Natural log	WDI
INV	Resident plus non-resident patent applications; annual count	Natural log	WDI / WIPO
URB	Urban population; % of total population	Natural log	WDI
TOP	Exports plus imports; % of GDP	Natural log	WDI
FDI	Net FDI inflows; % of GDP	Inverse hyperbolic sine	WDI

Note: WDI = World Development Indicators; WIPO = World Intellectual Property Organization; PPP = purchasing power parity; MJ = megajoule.

4.2 Variable Measurement and Transformations

Energy intensity measures the amount of primary energy required to produce one unit of economic output. The study uses the World Development Indicators measure expressed in megajoules per 2021 purchasing-power-parity dollar of GDP. A higher value means that an economy requires more energy to generate the same level of output. It is an aggregate indicator influenced by both energy-use efficiency and production structure. Energy intensity is the dependent variable and is expressed in natural logarithms.

Economic growth is represented by real GDP per capita in constant 2015 US dollars. This measures inflation-adjusted output per person. Because the model uses its logged level, the estimated coefficient concerns proportional differences in real GDP per capita, rather than a percentage-point change in the annual GDP growth rate.

Innovation is measured by the annual sum of resident and non-resident patent applications filed in a country. Resident applications originate from domestic applicants and non-resident applications from foreign applicants. Their sum provides a broad proxy for patenting activity but does not distinguish energy-related inventions or establish commercial adoption. The sum is expressed in natural logarithms.

Urbanization is measured as the urban population share, expressed as a percentage of total population. It captures the relative size of the urban population rather than population density or the efficiency of urban infrastructure. Its natural logarithm is included as a control.

Trade openness measures the value of exports and imports of goods and services relative to GDP. It reflects the depth of an economy's integration. This percentage is included in the natural log form.

Foreign direct investment is calculated as net inflows of foreign direct investment as a percentage of GDP. When disinvestment exceeds new investments, the series can take on negative values. The inverse hyperbolic sine transformation is therefore used; it is defined for positive, zero, and negative values. Does not need to take the natural log of the negative FDI observations (Burbidge et al., 1988).

$$\boldsymbol{ihsFDI_{it}} = \mathbf{asinh}(\boldsymbol{FDI_{it}}) = \mathbf{ln}\left(\boldsymbol{FDI_{it}} + \sqrt{\boldsymbol{FDI_{it}^2} + \mathbf{1}}\right) \qquad (4.1)$$

Each indicator continues to be measured in its traditional units: real GDP per capita is in constant 2015 U.S. dollars, energy intensity is in units per 2021 PPP dollar of GDP, and FDI and trade openness are percentages of GDP. The transformations of the variables are shown in Table 1 and correspond to coefficient interpretations.

The dynamic model provides short-run elasticity interpretations for the logged explanatory variables. The coefficient of IHS-transformed FDI is interpreted in the context of the IHS transformation and is not an ordinary log–log elasticity coefficient. Note: Logged values can be negative, even though the raw values were positive and less than one.

4.3 Dynamic Specification and Estimation

The model focuses on the effects of economic growth and innovation on energy intensity. Urbanization, trade openness and foreign direct investment are included as control variables. The dynamic specification is:

$$\ln ENI_{it} = \alpha + \rho \ln ENI_{i,t-1} + \beta_1 \ln GDPC_{it} + \beta_2 \ln INV_{it} + \beta_3 \ln URB_{it} + \beta_4 \ln TOP_{it} + \beta_5 ihsFDI_{it} + \mu_i + \varepsilon_{it} \quad (4.2)$$

In Equation (4.2), lnENI denotes the natural logarithm of energy intensity, lnGDPC denotes the natural logarithm of real GDP per capita, and lnINV denotes the natural logarithm of the annual sum of resident and non-resident patent applications. The control variables lnURB and lnTOP represent the natural logarithms of the urban population share and trade openness, respectively, while ihsFDI represents the inverse hyperbolic sine transformation of net FDI inflows as a percentage of GDP.

The subscripts (i)and (t) refer to countries and years. The parameter (ρ) reflects persistence in energy intensity; (μ_i) denotes unobserved, time-invariant country characteristics; and (ε_{it}) denotes the idiosyncratic disturbance. The coefficients for the explanatory variables are short-run elasticities. The coefficient on ihsFDI measures the response to a change in transformed FDI and is not an ordinary log–log elasticity. No long-run multipliers are estimated here.

Energy intensity may adjust gradually because production technologies and infrastructure are long-lived. A lagged dependent variable represents this persistence. In a dynamic fixed-effects model, the transformed lagged dependent variable is correlated with the transformed error, creating finite-sample bias when the time dimension is short (Nickell, 1981). Innovation and real GDP per capita may also be endogenous because of reverse causality or omitted time-varying influences. These considerations motivate dynamic instrumental-variable estimation, subject to the required moment conditions.

Two-step System GMM combines a first-differenced equation instrumented with appropriate lagged levels and a level equation instrumented with appropriate lagged differences (Arellano & Bover, 1995; Blundell & Bond, 1998). The additional level moment conditions require restrictions beyond those of difference GMM. The reported specifications use 33 instruments for developing countries and 19 for developed countries. Arellano–Bond tests assess serial correlation in the differenced residuals, while the Hansen test evaluates the joint overidentifying restrictions (Arellano & Bond, 1991). First-order correlation is generally expected after differencing; the AR(2) test should not reject the relevant restriction on second-order correlation. Non-rejection by the Hansen test does not establish that every identifying assumption holds. Instrument counts are reported because excessive instruments can weaken specification tests (Roodman, 2009).

4.4 Preliminary Diagnostics

Descriptive statistics summarizes available observations, while pairwise correlations describe unconditional associations. Variance inflation factors assess multicollinearity among the regressors. The Breusch–Pagan LM and Hausman tests examine country-specific effects and the static fixed-effects versus random-effects comparison. Modified Wald and Wooldridge tests assess heteroskedasticity and serial correlation, respectively. Cross-sectional dependence is tested using the Pesaran (2004) test. These diagnostics describe the error structure and country-specific characteristics of the panels, while the Arellano–Bond and Hansen tests assess the serial correlation and overidentifying restrictions of the estimated system GMM models.

5. Results and Discussion

This section explores the link between innovation, economic growth, and energy intensity for the two country groups. Two-step System GMM estimates are contextualized with descriptive statistics, correlations, and panel diagnostics. The discussion compares the findings with theoretical expectations and what is known in the literature, and clearly separates findings that are associated with mechanisms from those that are not tested.

5.1 Descriptive Statistics

This subsection summarizes the distribution of variables for developed and developing countries. The number of observations, mean, standard deviation, minimum, and maximum are reported in Table 2 for each variable. These statistics offer an initial comparison of the two groups and context for the subsequent empirical analysis.

Table 2: Descriptive Statistics

Variable	Obs.	Mean	Std. dev.	Min.	Max.
Developing Countries					
lnENI	730	1.471	0.476	0.293	2.745
lnGDPC	750	8.217	0.798	5.899	9.812
lnINV	722	6.562	2.239	1.099	14.334
lnURB	750	3.978	0.374	2.790	4.559
lnTOP	745	4.136	0.467	3.096	5.229
ihsFDI	750	1.646	0.888	−4.309	4.475
Developed Countries					
lnENI	508	1.276	0.409	0.157	2.750
lnGDPC	510	10.460	0.533	9.259	11.616
lnINV	476	7.804	2.591	1.099	13.340
lnURB	510	4.349	0.164	3.907	4.605
lnTOP	510	4.566	0.610	3.153	6.093
ihsFDI	510	1.546	1.804	−6.663	6.761

Note: ln denotes the natural logarithm. Variable definitions follow Table 1; ihsFDI denotes inverse-hyperbolic-sine-transformed FDI. Counts reflect available observations for each variable.

Table 2 shows a higher mean of logged energy intensity in developing countries (1.471) than in developed countries (1.276). Its standard deviation is also greater, at 0.476 compared with 0.409. These statistics indicate a higher mean and greater dispersion in the observed developing-country sample, but do not identify the technological or structural factors responsible.

Developed countries have a higher mean of logged real GDP per capita (10.460 compared with 8.217) and a higher mean of logged patent applications (7.804 compared with 6.562). These values describe income and recorded patenting activity in the observed samples. They do not directly measure research quality, commercial adoption or the energy relevance of inventions. The standard deviations of logged patent applications, 2.591 and 2.239 respectively, also indicate considerable dispersion within each group.

Developed countries also have higher means of logged urbanization (4.349 versus 3.978) and trade openness (4.566 versus 4.136). IHS-transformed FDI varies substantially in both samples, with greater dispersion in developed countries. Its negative minimum values are admissible under the IHS transformation. These descriptive differences do not establish causal effects or statistically significant differences between the groups.

5.2 Correlation Analysis

In this subsection, the nature (direction and strength) of the pairwise linear relationships between the study variables in developing and developed countries is reviewed. The correlation results in Table 3 provide a preliminary indication of the relationship between the explanatory variables used in the analysis and energy intensity for each group. These correlations describe unconditional relationships and do not establish causality.

Table 3: Correlation Matrix

Variable	lnENI	lnGDPC	lnINV	lnURB	lnTOP	ihsFDI
Developing Countries						
lnENI	1					
lnGDPC	−0.4595	1				
lnINV	−0.0676	0.4423	1			
lnURB	−0.2135	0.7543	0.3000	1		
lnTOP	0.0797	0.0966	−0.1513	0.0982	1	
ihsFDI	0.0342	0.0447	−0.1645	0.0800	0.3874	1
Developed Countries						
lnENI	1					
lnGDPC	−0.1104	1				
lnINV	−0.0510	0.3875	1			
lnURB	−0.0573	0.6794	0.4603	1		
lnTOP	−0.3161	−0.0153	−0.4813	0.0110	1	
ihsFDI	−0.1342	−0.0855	−0.1511	0.0226	0.2574	1

Table 3 reports unconditional pairwise correlations. Energy intensity is negatively correlated with real GDP per capita in developing countries (r = -0.4595) and developed countries (r = -0.1104). Its correlation with innovation is also negative in both groups, although small in magnitude (r = -0.0676 and -0.0510). These signs are directionally consistent with the proposed energy-saving roles of structural transformation accompanying economic growth and innovation, but their small or moderate magnitudes show that the relationships cannot be understood from bivariate association alone.

GDP per capita and urbanization have the largest pairwise correlation among the regressors in each group: 0.7543 in developing countries and 0.6794 in developed countries. Trade openness is weakly positively correlated with energy intensity in developing countries and negatively correlated in developed countries. The subsequent multivariate analysis examines these associations conditional on the other regressors and lagged energy intensity. The VIF assessment complements the pairwise correlations by examining the joint linear dependence among the explanatory variables.

5.3 Multicollinearity Assessment

This subsection evaluates multicollinearity among explanatory variables in both developing and developed countries. Table 4 shows the variance inflation factor (VIF) and tolerance values for all of the regressors. These measures assess whether strong linear relationships among the explanatory variables may inflate standard errors and reduce the precision of the estimated coefficients.

Table 4: Variance Inflation Factors

Variable	Developing VIF	Developing 1/VIF	Developed VIF	Developed 1/VIF
lnGDPC	2.87	0.348573	1.897	0.527
lnURB	2.52	0.396271	2.179	0.459
lnINV	1.34	0.748772	1.876	0.533
lnTOP	1.22	0.818717	1.545	0.647
ihsFDI	1.20	0.831205	1.104	0.906
Mean VIF	1.83	-	1.72	-

Table 4 provides no indication of severe multicollinearity among the included regressors. Mean VIF values are 1.83 for developing countries and 1.72 for developed countries. The largest VIF is 2.87 for lnGDPC in developing countries and 2.179 for lnURB in developed countries. These values are below conventional thresholds of 5 and 10, supporting the joint inclusion of the explanatory variables.

5.4 Panel Diagnostic Tests

This subsection presents the panel diagnostic tests for the developing- and developed-country samples. Table 5 reports the results of the Breusch–Pagan LM, Hausman, modified Wald, Wooldridge, and Pesaran CD tests. These tests assess country-specific effects, the

choice between static fixed- and random-effects specifications, heteroskedasticity, serial correlation, and cross-sectional dependence, providing context for the subsequent dynamic panel analysis.

Table 5: Panel Diagnostic Tests

Test	Developing Statistic	P-value	Developed Statistic	P-value
Breusch–Pagan LM	4279.01	<0.001	2597.59	<0.001
Hausman	19.12	0.0018	97.60	<0.001
Modified Wald	5382.31	<0.001	1053.46	<0.001
Wooldridge	111.628	<0.001	38.694	<0.001
Pesaran CD	−0.870	0.3841	20.521	<0.001

The Breusch–Pagan LM test rejects the pooled OLS null in both samples, supporting the presence of country-specific effects. The Hausman test is also significant in developing countries ($p = 0.0018$) and developed countries ($p < 0.001$), favouring fixed effects within the static-panel comparison. These results support accounting for unobserved country heterogeneity.

The modified Wald and Wooldridge tests reject homoskedasticity and the absence of first-order serial correlation in both samples. The Pesaran CD test does not reject cross-sectional independence in developing countries ($p = 0.3841$), but indicates cross-sectional dependence in developed countries ($p < 0.001$). Common shocks and cross-country linkages offer possible explanations, although the test does not identify their sources.

The diagnostics identify country-specific effects, heteroskedasticity and serial correlation in both groups. Dynamic persistence and potential endogeneity provide the motivation for System GMM, while the significant developed-country CD result qualifies inference for that sample. Model-specific instrument assumptions remain central to the interpretation of the estimates.

5.5 Two-step System GMM Estimates

Table 6 presents the two-step System GMM coefficients, standard errors and specification tests for the two samples. The coefficients describe conditional short-run relationships. The discussion considers persistence, the principal explanatory variables and the controls in relation to the theoretical framework and previous research.

Table 6: Two-Step System GMM Regression Results

Variable	Developing Countries	Developed Countries
L.lnENI	0.626***	0.891***
	(0.0592)	(0.0457)
lnGDPC	−0.172***	−0.456***
	(0.0283)	(0.132)
lnINV	−0.0840***	−0.0531***
	(0.0148)	(0.0183)
lnURB	0.163**	2.631***
	(0.0815)	(0.679)
lnTOP	0.0360**	−0.163***
	(0.0169)	(0.0568)
ihsFDI	−0.00310	−0.0113
	(0.00257)	(0.00680)
Constant	1.715***	−5.410***
	(0.395)	(1.557)
Observations	655	442
Country groups	50	34
Instruments	33	19
AR(1) p-value	<0.001	0.002
AR(2) p-value	0.262	0.420
Hansen p-value	0.440	0.274

Note: Standard errors are in parentheses.
*** p < 0.01; ** p < 0.05; * p < 0.10.
L. denotes the one-period lag. Coefficients on logged explanatory variables are conditional short-run elasticities; the IHS-transformed FDI coefficient is not.

Energy intensity is persistent in both country groups, with lagged dependent-variable coefficients of 0.626 for developing countries and 0.891 for developed countries, both significant at the 1% level. The higher persistence estimate in developed countries indicates more gradual adjustment in energy intensity, consistent with the long service lives of industrial equipment, buildings and transport infrastructure. The lower estimate in developing countries indicates that the association between previous and current energy intensity diminishes more quickly within the estimated model. These findings highlight the importance of sustained capital renewal and technological improvements in reducing energy requirements per unit of output.

Economic growth, measured by real GDP per capita, is negatively associated with energy intensity in both country groups at the 1% significance level. A 1% increase in real GDP per capita is associated with a 0.172% reduction in energy intensity in developing countries and a 0.456% reduction in developed countries, holding other factors constant. The estimates indicate a more pronounced reduction in energy requirements per unit of output in developed economies, consistent with capital renewal, improvements in production

efficiency and structural shifts towards less energy-intensive activities. In developing economies, the energy requirements of industrial and infrastructure expansion may partly offset these improvements, contributing to the smaller estimated reduction. This interpretation accords with the technological and structural explanations discussed by Voigt et al. (2014) and Deichmann et al. (2018), and with Endogenous Growth Theory, which emphasizes knowledge accumulation and technological progress as sources of productivity improvement.

Innovation is negatively associated with energy intensity in both country groups at the 1% significance level. A 1% increase in total patent applications is associated with a 0.0840% reduction in energy intensity in developing countries and a 0.0531% reduction in developed countries, holding other factors constant. A greater estimated reduction in developing economies corresponds to the possibilities for technological catch-up and the replacement of inefficient equipment and production processes, while improvements in developed economies may be more incremental due to comparatively advanced production technologies. The results confirm the hypothesised negative relationship and are consistent with the Endogenous Growth Theory, which stresses that knowledge accumulation and technological progress are sources of productivity improvement. They are also aligned with the general findings on innovation and energy performance presented by Wurlod and Noailly (2018) and Sun et al. (2021), but are broadened to cover all resident and non-resident patent applications, not just green innovation or energy-efficiency results.

Among the control variables, urbanization is positively associated with energy intensity in both country groups, with coefficients of 0.163 for developing countries and 2.631 for developed countries, significant at the 5% and 1% levels, respectively. In developing countries, a one per cent growth in the share of the urban population is followed by a 0.163% growth in energy intensity, and in developed countries by a 2.631% growth in energy intensity, holding innovation, economic growth, and other regressors constant. The relationship is consistent with the energy needs of buildings, transport, and urban infrastructure exceeding the efficiency gains in the sample period. The inclusion addresses the urbanization–energy intensity literature examined by Yan (2015), and the differences in urbanization when estimating the relationships between innovation, economic growth and energy intensity.

In developing countries, the coefficient of trade openness is positive, while it is negative in developed countries. A 1% increase in the trade-to-GDP ratio is associated with a 0.0360% increase in energy intensity in developing countries and a 0.163% reduction in developed countries, significant at the 5% and 1% levels, respectively. These contrasting relationships are consistent with differences in the energy requirements of traded production and access to efficient technologies. This means that trade openness would have an additional dimension of production and international integration, which is controlled

for. Sohag et al. (2015) provide similar evidence on trade and energy consumption, but not on energy intensity.

Foreign direct investment is included to capture direct investment transactions and their potential technological effects. In developing countries, it is −0.00310; in developed countries, it is −0.0113. The coefficients are negative but are not statistically significant at conventional levels. The estimates show little evidence of an independent relationship between aggregate FDI inflows and energy intensity when controlling for growth and other regressors. Within individual industries, the sectoral structure and technological effects of investment could mask inter-industry links, which is consistent with the overall evidence provided by Hübler and Keller (2010). The coefficients are not the standard per cent elasticities for FDI because they are transformed using the inverse hyperbolic sine.

The specification tests provide supporting evidence for the reported moment restrictions. The Arellano–Bond AR(1) test is significant in both samples, as expected for first-differenced errors. The AR(2) test does not reject the absence of second-order serial correlation, with p-values of 0.262 and 0.420 for developing and developed countries, respectively. The Hansen test does not reject the joint overidentifying restrictions, with corresponding p-values of 0.440 and 0.274. Instrument counts are 33 for 50 developing countries and 19 for 34 developed countries.

Estimates depend on the dynamic specification and instrument assumptions. Cross-sectional dependence in the developed-country sample limits statistical inference, particularly the interpretation of its substantial urbanization elasticity. Comparisons between the two groups indicate differences in estimated relationships, not statistically established differences in population coefficients. Capital renewal, technological adoption, and production composition may explain these patterns, but their individual contributions are beyond the scope of the aggregate specification.

Overall, innovation and economic growth are associated with lower energy intensity in both country groups. The estimated reduction associated with economic growth is greater in developed economies, whereas the reduction associated with innovation is greater in developing economies. These patterns are consistent with differences in opportunities for technological improvement and structural transformation. Among the control variables, urbanization is positively associated with energy intensity, trade openness displays contrasting relationships, and FDI is statistically insignificant.

6. Conclusion

This study examines the relationships between innovation, economic growth, and energy intensity in 50 developing and 34 developed countries over 2008–2022 using separate two-step System GMM models. Energy intensity is persistent in both groups, with more gradual adjustment in the developed-country estimates. Innovation and economic growth, measured by real GDP per capita, are negatively and significantly associated with energy

intensity in both samples. These findings are consistent with technological improvement, capital renewal and structural changes that reduce energy requirements per unit of output.

The estimated relationship between economic growth and lower energy intensity is more pronounced in developed countries, whereas the relationship between innovation and lower energy intensity is more pronounced in developing countries. Among the control variables, urbanization is positively associated with energy intensity in both samples, trade openness has contrasting signs, and FDI is statistically insignificant. The findings highlight differences in the estimated relationships across development settings, subject to the model's assumptions and the limitations discussed below.

6.1 Policy Implications

The negative coefficients on the economic-growth proxy support the integration of energy-efficiency objectives into growth and investment planning. Technology adoption, relevant skills and the replacement of inefficient equipment are potential priorities. Research grants, tax incentives and public procurement could support these objectives, with their design informed by the energy performance and adoption prospects of the technologies concerned.

The negative coefficient on real GDP per capita supports the integration of energy-efficiency objectives into growth and investment planning. Access to finance and appropriate performance standards may facilitate the adoption of efficient capital in developing countries. The higher persistence estimate in developed countries is consistent with the relevance of sustained programmes for upgrading buildings, transport and industrial equipment.

The positive urbanization coefficients direct attention to the energy implications of urban expansion. Building-efficiency standards, public transport and coordinated infrastructure planning are policy options consistent with the observed relationships. Evaluation of these options requires evidence on their costs and effectiveness beyond the national-level associations estimated here.

The opposite trade coefficients suggest that energy policy should consider the production and technology content of trade. Access to efficient imported equipment and cleaner production processes may be particularly relevant where openness is associated with higher energy intensity. Given the insignificant aggregate FDI coefficients, assessment of investment by sector and technology content would provide a more informative basis for energy policy than investment volume alone.

6.2 Limitations and Future Research

The 2008–2022 observation period is relatively short for examining long-term energy and infrastructure transitions. The panels are unbalanced, and differences in data availability may affect the composition of the estimation samples. Aggregate country-level data also conceal variation across sectors, regions and firms.

Total patent applications provide a broad proxy for patenting activity but do not identify energy-related inventions or establish commercial adoption. The measure also combines resident and non-resident applications, whose contributions cannot be distinguished by the present specification. Future research could use energy-specific patents, green patents and direct technology-adoption measures to examine more clearly defined channels.

The comparison between developing and developed countries is based on separately estimated coefficients; formal tests of coefficient equality would be required to establish statistically significant differences between the groups. Future research could extend the analysis through cross-group comparison tests and nonlinear specifications. Energy prices, human capital, governance and other omitted factors may also influence energy intensity and the explanatory variables, limiting the identification of specific transmission mechanisms.

The choice of instruments and moment restrictions are crucial for estimating the system GMM. The reported AR(2) and Hansen tests neither demonstrate instrument strength nor rule out all sources of bias. The developed-country specification still faces the issue of cross-sectional dependence, and the high persistence needs further exploration. Sensitivity analyses could use alternative instruments and specifications that capture common shocks to assess whether the results are stable. The estimates are therefore only suggestive dynamic-panel relationships, and should not be interpreted as causal effects of the policy interventions.

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Declaration of AI Use

AI-assisted tools were used only for language refinement, grammar correction, sentence restructuring, and improving readability during manuscript preparation. They were not used to collect data, execute the statistical analyses, generate numerical results, or make substantive scientific judgments about the findings.

Data Availability

The data will be made available from the corresponding author upon reasonable request.

Declaration of Conflict of Interest

The authors declare no financial competing interests relevant to this study.

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