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Macroeconomic Determinants of Energy Consumption in BRICS+ Countries: Evidence from a Pooled Mean Group Autoregressive Distributed Lag Panel Approach

Lobna Abid*, Mariam Hamrouni

Laboratory of Probabilty and Statistics, Higher Institute of Business Administration of Sfax (ISAAS), University of Sfax, Tunisia.
*Email: lobnabid@yahoo.fr

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ABSTRACT

Against the backdrop of shifting global energy balances, this study analyzes energy consumption within the BRICS+ countries, using a panel of eight countries that combines the founding members (Brazil, Russia, India, China, and South Africa) with three newly admitted members (Egypt, Iran, and Saudi Arabia). The objective is to quantify the impacts of financial development, economic growth, trade openness, and urbanization on energy demand. Covering the 1990-2021 period, the empirical analysis leverages data from the World Bank and the IMF. Following unit root and cointegration testing, the Pooled Mean Group (PMG-ARDL) model is employed to simultaneously estimate homogeneous long-run relationships and heterogeneous short-run dynamics. The analysis is further enriched by the Dumitrescu-Hurlin panel causality tests. The empirical findings reveal that, in the long run, financial development, economic growth, and trade openness significantly stimulate energy consumption, with economic growth emerging as the most influential driver. Conversely, urbanization exerts a positive but statistically insignificant effect. In the short run, only economic growth and financial development actively influence energy demand. These results underscore the critical importance of fostering green finance, achieving energy-growth decoupling, promoting sustainable trade policies, and implementing efficient urban planning to effectively reconcile economic expansion with energy sustainability.

Keywords: Energy Consumption, BRICS, Financial Development, Economic Growth, Trade Openness, Urbanization
JEL Classifications: Q43, Q41, O47, F18

1. INTRODUCTION

Energy has become a fundamental pillar of economic development and social welfare in the modern world. As economies expand, industrial production intensifies, urban populations grow, and international trade deepens, the demand for energy increases substantially. While energy consumption supports economic growth and improvements in living standards, it also raises important concerns regarding energy security, environmental sustainability, and climate change mitigation. Understanding the factors that drive energy consumption has therefore become a major concern for policymakers and researchers seeking to achieve sustainable development objectives.

In recent decades, emerging economies have played an increasingly prominent role in global energy markets. Among them, the BRICS countries—Brazil, Russia, India, China, and South Africa—have become major contributors to global economic growth and energy demand. Collectively, these economies account for a significant share of world population, industrial output, and energy consumption. Their rapid economic expansion, industrialization processes, and urban development have considerably increased pressure on energy resources and environmental systems. More recently, the enlargement of the BRICS bloc into BRICS+ has further enhanced its economic and geopolitical importance. The inclusion of new members such as Egypt, Ethiopia, Iran, Saudi Arabia, and the United Arab Emirates has expanded the group's

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economic diversity and strengthened its influence on global energy production, consumption, and trade flows.

The growing importance of BRICS+ countries in the global energy landscape has intensified interest in identifying the determinants of energy consumption within these economies. Existing theoretical and empirical studies suggest that energy demand is influenced by several macroeconomic factors, including economic growth, financial development, trade openness, and urbanization. Economic growth generally stimulates energy consumption through increased industrial activity, infrastructure development, and household demand. Financial development may affect energy use by facilitating access to credit, encouraging investment, and supporting technological innovation. Trade openness can influence energy consumption through greater production specialization, international integration, and technology transfer. Likewise, urbanization may alter energy demand patterns by changing transportation systems, housing needs, and industrial structures.

Despite the extensive literature on the energy-growth nexus and the determinants of energy demand, several research gaps remain. First, most previous studies have focused on individual countries, regional groups, or the original BRICS economies, while empirical evidence on the newly expanded BRICS+ framework remains scarce. Second, existing research often examines only one or two determinants of energy consumption, neglecting the simultaneous interaction among financial development, economic growth, trade openness, and urbanization. Third, the majority of empirical investigations do not adequately distinguish between short-run dynamics and long-run equilibrium relationships, despite the possibility that macroeconomic variables may affect energy consumption differently over time.

Given these limitations, a comprehensive analysis of energy consumption determinants within the BRICS+ economies is both timely and necessary. The expansion of the BRICS bloc has created a heterogeneous group of countries characterized by different levels of economic development, financial sophistication, energy dependence, and demographic structures. Consequently, investigating the drivers of energy consumption in this new framework can provide valuable insights into the challenges and opportunities associated with sustainable energy management in emerging economies.

The present study aims to examine the effects of financial development, economic growth, trade openness, and urbanization on energy consumption in a panel of BRICS+ countries over the period 1990-2021. To achieve this objective, the study employs the Pooled Mean Group Autoregressive Distributed Lag (PMG-ARDL) approach, which allows for the estimation of both long-run equilibrium relationships and short-run adjustment dynamics while accounting for heterogeneity across countries. In addition, the Dumitrescu–Hurlin panel causality test is applied to explore the direction of causality among the variables.

This study contributes to the literature in several important ways. First, it provides one of the earliest empirical investigations of the determinants of energy consumption within the expanded BRICS+ framework, thereby extending the scope of previous studies beyond the original BRICS countries. Second, it adopts a comprehensive approach by simultaneously examining the roles of financial development, economic growth, trade openness, and urbanization. Third, by employing the PMG-ARDL methodology, the study distinguishes between short-run and long-run effects, offering a more nuanced understanding of energy demand dynamics. Finally, the findings generate important policy implications regarding green finance, sustainable trade strategies, energy efficiency, and urban planning in the context of the energy transition.

The remainder of this paper is organized as follows. Section 2 presents the theoretical framework and develops the research hypotheses. Section 3 reviews the empirical literature. Section 4 presents the data, the econometric methodology and the empirical results. Finally, Section 5 concludes the study, outlines the main policy implications and proposes directions for future research.

2. LITERATURE REVIEW AND HYPOTHESES DEVELOPMENT

2.1. Theoretical Framework

Understanding the determinants of energy consumption requires a comprehensive theoretical framework that integrates economic, financial, trade, and demographic perspectives. The relationship between energy consumption and its macroeconomic drivers has been extensively examined in both theoretical and empirical studies. This section discusses the principal theories underpinning the relationships between energy consumption, economic growth, financial development, trade openness, and urbanization, thereby providing the conceptual foundation for the empirical analysis.

2.1.1. Energy consumption and economic growth

The relationship between energy consumption and economic growth is primarily explained by the Neoclassical Growth Theory and the Energy-Led Growth Hypothesis. According to the Neoclassical Growth Theory developed by Solow (1956), economic growth results from the accumulation of capital, labor, and technological progress. Although energy was not explicitly incorporated into the original model, subsequent extensions recognized energy as a critical production input that enhances productivity and supports economic activity. As economies industrialize and expand their productive capacities, energy demand tends to increase in parallel with output growth.

The Energy-Led Growth Hypothesis further emphasizes the central role of energy in the production process. This perspective argues that energy is an indispensable factor of production alongside capital and labor, implying that energy consumption directly contributes to economic growth. Higher levels of economic activity stimulate industrial production, transportation services, infrastructure development, and household consumption, all of which require substantial energy inputs. From this theoretical standpoint, economic growth is expected to increase energy demand, particularly in emerging economies where industrialization and urban expansion remain highly energy-intensive.

2.1.2. Financial development and energy consumption

The relationship between financial development and energy consumption can be explained through the Financial Intermediation Theory. Financial Intermediation Theory, developed by scholars such as Gurley and Shaw (1960), McKinnon (1973), and Levine (1997), argues that well-developed financial systems improve the allocation of resources by mobilizing savings, facilitating investment, reducing transaction costs, and expanding access to credit. Financial institutions play a crucial role in channeling financial resources toward productive sectors of the economy.

Through these mechanisms, financial development can influence energy consumption in several ways. First, greater access to credit enables firms to expand production capacity and invest in new technologies, thereby increasing energy demand. Second, financial deepening allows households to finance the acquisition of durable goods such as automobiles, air conditioners, and household appliances, which are generally energy-intensive. Third, improved financial markets may attract foreign investment and stimulate industrial development, further raising energy consumption.

Therefore, financial development is generally expected to exert a positive influence on energy demand, particularly in developing and emerging economies characterized by rapid industrial and financial expansion.

2.1.3. Trade openness and energy consumption

The relationship between trade openness and energy consumption is largely grounded in the Trade-Led Growth Theory. Trade-led growth theory posits that international trade promotes economic growth by enhancing specialization, improving resource allocation, facilitating technology transfer, and expanding market access. Through participation in global value chains, countries can increase production efficiency and stimulate industrial development.

Trade openness may affect energy consumption through several transmission channels. On the one hand, increased trade activity stimulates manufacturing production, transportation services, logistics operations, and export-oriented industries, all of which require substantial energy inputs. This mechanism is commonly referred to as the scale effect, whereby economic expansion resulting from trade liberalization increases energy demand.

On the other hand, trade openness may facilitate the diffusion of advanced technologies and energy-efficient production methods. This technology effect can reduce energy intensity and partially offset the increase in energy consumption associated with economic expansion.

For emerging economies such as the BRICS+ countries, where industrial development and export-oriented activities remain major drivers of economic growth, the scale effect is generally expected to dominate. Consequently, trade openness is anticipated to increase energy consumption.

2.1.4. Urbanization and energy demand

The relationship between urbanization and energy consumption is primarily explained by Urban Economics Theory.

Urban Economics Theory emphasizes that population concentration and urban expansion fundamentally transform patterns of economic activity, infrastructure development, transportation systems, and household behavior. As populations migrate from rural to urban areas, demand for housing, public services, transportation networks, and industrial facilities increases substantially.

Urbanization influences energy consumption through multiple channels. Expanding urban infrastructure requires considerable energy for construction, transportation, and public services. Rising household incomes and changing lifestyles associated with urban living often lead to greater ownership of energy-intensive appliances and increased residential energy use. Furthermore, urban industrial clusters generally consume large quantities of energy to sustain production activities.

Although urban density may generate efficiency gains through economies of scale and improved infrastructure utilization, the overall effect of urbanization in developing economies is often associated with higher energy demand due to rapid population growth and expanding economic activity. Consequently, urbanization is expected to exert a positive influence on energy consumption within the BRICS+ economies.

2.2. Hypotheses Development

Based on the theoretical arguments presented above, the following hypotheses are formulated:

- H_1: Financial development has a positive and significant effect on energy consumption in BRICS+ countries
- H_2: Economic growth has a positive and significant effect on energy consumption in BRICS+ countries
- H_3: Trade openness has a positive and significant effect on energy consumption in BRICS+ countries
- H_4: Urbanization has a positive and significant effect on energy consumption in BRICS+ countries.

3. EMPIRICAL LITERATURE REVIEW

A large body of empirical work has examined the macroeconomic drivers of energy demand. Early studies established that energy use responds to income, prices and technology (Berndt and Wood, 1975; Bohi, 1981; Espey and Espey, 2004), while endogenous growth models emphasize the roles of innovation and natural resources in long-run output (Jones, 1995; Barbier, 1999). This section reviews the main empirical findings for each determinant considered in this study.

3.1. Energy Consumption and Economic Growth

Panel studies generally confirm a strong long-run association between output and energy use in emerging and developing economies (Lee and Chang, 2008; Tsaurai, 2021). For the BRICS countries, Shahbaz et al. (2018) document asymmetric effects of globalization and economic growth on energy consumption, Raza et al. (2024) confirm the energy–growth linkage using disaggregated

energy data, and Anser et al. (2024) analyse the joint dynamics of energy consumption, technological innovation and economic growth within a GMM panel VAR framework. However, the Environmental Kuznets Curve literature (Grossman and Krueger, 1991; Stern, 2004) and studies on rebound effects (Sorrell, 2014) indicate that rising income and efficiency gains do not automatically translate into lower energy use.

3.2. Financial Development and Energy Consumption

The finance–growth literature shows that deeper and more efficient financial systems stimulate investment and output (King and Levine, 1993; Levine and Zervos, 1998; Merton and Bodie, 2004; Ang and McKibbin, 2007), which may in turn raise energy demand. Empirically, Danish et al. (2018) find a significant link between financial development and energy consumption in the Next-11 countries, Ahmed (2017) revisits the role of financial development in the energy–growth–trade nexus of the BRICS economies, and Le (2020) examines how financial development, institutions, government expenditure and trade openness shape the energy–growth nexus.

3.3. Trade Openness and Energy Consumption

Trade can raise energy use through scale effects or reduce it through composition and technique effects (Grossman and Krueger, 1991). Empirical evidence for emerging economies mostly points to a positive net effect: Shahbaz et al. (2018) show that globalization influences energy consumption in the BRICS region, and Koengkan (2018) finds a positive impact of trade openness on energy consumption in the Andean Community countries.

3.4. Urbanization and Energy Demand

Jones (1991) shows that urbanization increases energy use in developing countries, and Seto et al. (2012) forecast a rapid expansion of urban areas by 2030 with substantial environmental consequences. For the BRICS countries, Voumik and Sultana (2022) examine the joint effects of urbanization, industrialization, electrification and renewable energy on the environment. Conversely, Morikawa (2012) shows that higher population density improves the efficiency of energy use in service establishments.

Overall, the empirical literature remains largely focused on individual countries, regional groups or the original BRICS members, and rarely examines financial development, economic growth, trade openness and urbanization simultaneously within the enlarged BRICS+ group. The present study aims to fill this gap.

4. DATA, METHODOLOGY AND RESULTS

4.1. Data Description

This study investigates the determinants of energy consumption in the BRICS+ countries over the period 1990-2021. The empirical analysis is based on an annual balanced panel dataset covering eight countries: Brazil, Russia, India, China, South Africa, Egypt, Iran, and Saudi Arabia. These countries were selected due to their increasing role in global energy markets, their heterogeneous economic structures, and their growing influence on global economic and environmental dynamics.

The study period (1990-2021) is chosen to capture major structural transformations, including financial liberalization, trade globalization, rapid industrialization, and the ongoing energy transition. This period also allows for sufficient temporal variation to examine both short-run dynamics and long-run equilibrium relationships among the variables.

The data used in this study are collected from internationally recognized databases. Energy consumption and macroeconomic variables are obtained from the World Bank's World Development Indicators (WDI), while financial development indicators are sourced from the International Monetary Fund (IMF) Financial Development Index database. The combination of these reliable sources ensures data consistency and comparability across countries and over time.

4.2. Variables Definition

The empirical model includes one dependent variable and four key explanatory variables. All variables are transformed into natural logarithms to reduce heteroscedasticity, improve normality, and allow elasticity-based interpretation of the estimated coefficients. Table 1 summarizes the definition, measurement and source of each variable.

The dependent variable, energy consumption (lnEC), captures total per capita energy use and reflects the overall energy demand of an economy.

Financial development (lnFD) reflects the depth, access, and efficiency of financial systems, which may influence energy demand through investment and consumption channels.

Economic growth (lnGDP) represents the level of economic development and is expected to be a major driver of energy consumption through industrial activity, infrastructure development, and income effects.

Trade openness (lnTRADE) measures the degree of integration into the global economy and captures the influence of international trade on production and energy demand.

Urbanization (lnPop) reflects structural demographic changes associated with urban population growth, which may alter energy consumption patterns through infrastructure expansion and lifestyle changes.

4.3. Econometric Model

The empirical relationship between energy consumption and its determinants is specified as follows:

Table 1: Definition of variables

Variable	Definition	Source
lnEC	Natural log of total energy consumption per capita in kg of oil equivalent	World Bank (WDI)
lnFD	Natural log of financial development index	IMF
lnGDP	Natural log of GDP per capita in constant 2015 US dollars	World Bank (WDI)
lnTrade	Natural log of trade openness, measured as exports plus imports over GDP	World Bank (WDI)
lnPop	Natural log of urban population share	World Bank (WDI)

$$\text{Ln}(EC_{it}) = \alpha_0 + \alpha_1 \ln(FD_{it}) + \alpha_2 \ln GDP_{it} + \alpha_3 lnPOP_{it} + \alpha_4 lntrade_{it} + \varepsilon_{it} \quad (1)$$

where i denotes the country and t denotes the year, α0 is the constant term and εit is the error term, with:

ln EC_{it}: Represents the total energy consumption of country i at time t
ln FD_{it}: Denotes financial development
ln GDP_{it}: Real GDP
ln POP_{it}: represents urbanization, measured by the urban population share
ln $trade_{it}$: Trade openness of country i at time t
ε_{it}: Is the error term.

4.4. Preliminary Tests

Before estimating the long-run and short-run relationships using the PMG-ARDL approach, a series of preliminary econometric tests are conducted to ensure the robustness and validity of the empirical results. These tests are essential in panel data analysis, particularly in macroeconomic frameworks characterized by heterogeneity and cross-sectional dependence, as is the case for BRICS+ countries.

4.4.1. Descriptive statistics

The first step in the empirical analysis involves examining the descriptive statistics of all variables. This allows for a preliminary assessment of the distribution, central tendency, and dispersion of the data across countries and over time. In particular, measures such as the mean, standard deviation, minimum, and maximum values provide insights into the heterogeneity of energy consumption and its determinants within the BRICS+ panel. High variability across variables is expected, given the structural differences in economic development, financial systems, and energy profiles among the countries under study.

The descriptive statistics reported in Table 2 show substantial variation across the panel, especially for energy consumption and GDP per capita. The mean of lnEC is 7.47, with a minimum of 5.78 and a maximum of 8.98, indicating wide heterogeneity in energy use across countries and years. The mean of lnFD is −0.92, while lnGDP, lnTrade, and lnPop also display meaningful dispersion, reflecting structural differences within BRICS+.

4.4.2. Correlation matrix

A correlation analysis is performed to identify the pairwise relationships between the explanatory variables and to provide an initial indication of potential associations. This step also helps in detecting possible multicollinearity problems at a preliminary level. Although correlation coefficients do not imply causality, they are useful for understanding the direction and strength of linear relationships among variables such as economic growth, financial development, trade openness, and urbanization.

The correlation matrix reported in Table 3 shows a strong positive association between energy consumption and GDP per capita, as well as between GDP per capita and urban population. As confirmed by the variance inflation factors in Table 4, which are below the conventional threshold, indicating that multicollinearity is not severe and that coefficient estimates are reliable.

4.4.3. Multicollinearity test (VIF)

To formally assess the presence of multicollinearity, the Variance Inflation Factor (VIF) test is applied. Multicollinearity can distort the estimation of coefficients and reduce the reliability of statistical inference. A VIF value >10 is generally considered indicative of severe multicollinearity. The results of this test ensure that the explanatory variables included in the model do not exhibit excessive linear dependence, allowing for reliable and unbiased coefficient estimation.

The VIF evaluation reported in Table 4 confirms the absence of concerning multicollinearity within the estimated model. The mean VIF is 3.83, well below the critical threshold of 10. Among the explanatory variables, GDP (VIF = 6.93) and urbanization (VIF = 5.92) show moderate correlation with the other variables, while trade openness (VIF = 1.41) and financial development (VIF = 1.08) present no issues. These results confirm that the model is robust and that the estimated coefficients can be reliably interpreted.

4.4.4. Cross-sectional dependence tests

Given the macroeconomic nature of the dataset and the economic interdependence among BRICS+ countries, the presence of cross-sectional dependence is highly likely. Ignoring this issue may lead to biased and inconsistent estimations. To address this issue, several complementary tests are employed: Pesaran's CD test (2004; 2007): used to detect general cross-sectional dependence in panel data models; Frees test (1995; 2004): A non-parametric test based on rank correlation, robust to distributional assumptions and Friedman test (1937): A non-parametric test based on rank statistics, useful for detecting dependence without

Table 2: Descriptive statistics

Variable	Obs	Mean	Std.dev	Min	Max
lnEC	256	7.469714	0.8814936	5.780447	8.984616
lnFD	256	−0.92117267	0.2896979	−1.687399	−0.3945252
lnGDP	256	8.474396	0.9128989	6.276452	10.17655
lntrade	256	3.756123	0.3843235	2.718396	4.705712
lnpop	256	4.0355571	0.3625273	3.24052	4.469545

Table 3: Correlation among the different variables

	lnEC	lnFD	lnGDP	lnTrade	lnpop
lnEC	1.0000				
lnFD	0.2294	1.0000			
lnGDP	**0.8736**	0.2621	1.0000		
lnTrade	0.5842	0.0633	0.4201	1.0000	
lnpop	**0.7946**	0.2345	**0.8969**	0.2293	1.0000

Table 4: Multicollinearity test

Variable	VIF	1/VIF
lnGDP	6.93	0.144366
lnpop	5.92	0.169003
lntrade	1.41	0.709811
lnFD	1.08	0.928149
Mean VIF		3.83

strong parametric assumptions. Rejecting the null hypothesis of cross-sectional independence confirms the presence of significant interdependencies among countries, justifying the use of second-generation econometric techniques.

To account for potential cross-sectional correlation among the panel units, the cross-sectional dependence tests of Frees (1995) and Friedman (1937) were applied. The results of these tests are presented in Table 5.

The findings indicate that the null hypothesis of no cross-sectional dependence across units is rejected at various significance levels. This implies that the observations are not independent; a shock affecting a given country could have spillover effects on others, thereby revealing a pronounced interdependence among the panel units.

The conclusions derived from both tests, as reported below, confirm this interpretation. Both the Frees (1995) and Friedman (1937) tests are highly significant (P = 0.0000), demonstrating the existence of cross-sectional dependence across the panel series. Consequently, these results justify incorporating this interdependence into the subsequent econometric analyses.

4.4.5. Panel unit root tests

Before estimating the model, it is essential to determine the stationarity properties of the variables to avoid spurious regression problems. To this end, both first-generation and second-generation panel unit root tests are employed: Levin et al. (LLC, 2002): assumes common unit root process across cross-sections; Im et al. (IPS, 2003): Allows for heterogeneity in the autoregressive coefficients; and Cross-sectionally augmented IPS (CIPS, Pesaran, 2007): Accounts for cross-sectional dependence and provides more robust results in macro panels. These complementary tests ensure a robust assessment of the integration order of the variables, which is crucial for the validity of the PMG-ARDL estimation strategy.

In our case, the Levin, Lin, and Chu (LLC) test was applied to examine the stationarity of the panel variables. Table 6 presents the complete set of obtained results.

The results indicate that the majority of the variables are non-stationary in levels (with the exception of *lntrade*, which is I(0)) but become stationary after first differencing (I(1)). These findings justify the use of econometric methods capable of simultaneously handling variables integrated of different orders, such as the PMG-ARDL model. Furthermore, they underscore the importance of conducting a cointegration test to examine the long-run relationships among the variables.

Table 5: Results of cross-sectional dependence tests

Test applied	Statistic	P-value
Frees' test	2.016	0.0000
Friedman's test	43.318	0.0000

4.4.6. Panel cointegration tests

After confirming the integration properties of the variables, panel cointegration tests are conducted to examine the existence of a long-run equilibrium relationship among energy consumption and its determinants.

The following tests are applied: Kao (1999) test: Based on the Engle-Granger two-step procedure, assumes homogeneous cointegration relationships across cross-sections. Pedroni (1999; 2004) test: allows for heterogeneity in cointegrating vectors and intercepts, making it more flexible for heterogeneous panels and Westerlund (2007) test is a powerful error-correction-based approach that explicitly accounts for cross-sectional dependence and provides robust inference in macro panels. The rejection of the null hypothesis of no cointegration across these tests confirms the existence of a stable long-run relationship among the variables, thereby validating the use of the PMG-ARDL framework for estimation.

The results of the Kao (1999) panel cointegration test are presented in Table 7.

The ADF t statistic (−2.7621) is significant at the 1% level (P = 0.0029), allowing for the rejection of the null hypothesis of no cointegration. These results confirm the existence of a stable, long-run relationship among energy consumption, financial development, economic growth, trade openness, and urbanization in the studied countries.

4.5. PMG-ARDL Estimation Strategy and results

To investigate the dynamic relationship between energy consumption and its determinants in BRICS+ countries, this study employs the Panel Autoregressive Distributed Lag (ARDL) framework developed by Pesaran et al. (1999). This methodology is particularly suitable for heterogeneous panels with variables integrated of order I(0) and I(1), as confirmed by the unit root tests. It also allows the simultaneous estimation of both short-run dynamics and long-run equilibrium relationships.

4.5.1. Comparison among the PMG, MG, and DFE models

To identify the most suitable model for estimating the relationship between energy consumption and its determinants, two Hausman specification tests were conducted. The first compared the PMG model with the DFE model, while the second focused on the comparison between the PMG and MG models.

Table 6: Panel unit root test results

Variables	LLC statistic (level)	P-value (level)	LLC statistic (1st difference)	P-value (1st difference)	Order of integration
lnEC	−1.3390	0.0903	−4.0131	0.0000	I (1)
lnFD	−2.4887	0.0064	−5.7996	0.0000	I (1)
lnGDP	−2.4003	0.0082	−3.8630	0.0001	I (1)
lntrade	−2.3566	0.0092	−13.4941	0.0000	I (1)
lnpop	−5.7828	0.0000	−11.0558	0.0000	I (0)

The PMG–DFE test yielded a statistic of Chi-square (4) = 5.43 (P = 0.2458), which is statistically insignificant at the 5% level. Consequently, the null hypothesis of no systematic differences between the estimators cannot be rejected, suggesting long-run parameter homogeneity across the countries. Similarly, the PMG–MG comparison produced a statistic of Chi-square (4) = 2.77 (P = 0.5967), confirming that the differences between these two estimators are not statistically significant. The results of the robustness tests comparing the alternative models are presented in Table 8.

The convergence of these results supports the selection of the PMG model as the most appropriate specification. The latter offers a balanced compromise between long-run relationship homogeneity and short-run dynamic heterogeneity. It thus captures a common long-run trajectory between energy consumption and its structural determinants (growth, financial development, trade openness, and population) while accounting for country-specific idiosyncrasies in the short run. Furthermore, the higher log-likelihood of the PMG model (546.33 compared to 537.99 for the DFE) confirms its econometric superiority, establishing it as the preferred model.

4.5.2. Interpretation of the PMG-ARDL model

Table 9 presents the estimated short- and long-run coefficients. The robustness of the model is confirmed by the error correction term (ECT) coefficient, which is negative and statistically significant across all conventional significance levels.

The error correction coefficient is estimated at −0.173 (P < 0.05), confirming the existence of a stable, long-run relationship between energy consumption and its determinants. The negative and significant value indicates that any temporary short-run disequilibrium is gradually corrected, drawing the system back toward its long-run equilibrium path. The adjustment speed of approximately 17.3%/year suggests that an exogenous shock affecting energy consumption is absorbed over an average period of 5-6 years, reflecting moderate inertia within the BRICS+ energy systems.

Table 7: Kao Panel cointegration test results

Test	ADF t-statistic	P-value
Kao residual cointegration test	−2.7621	0.0029

Source: Authors' calculations

Table 8: Comparative table of the models: PMG, MG, and DFE

Specification Test	Chi-square (df)	Prob >Chi-square	Decision H_0
PMG versus DFE	5.43 (4)	0.2458	Do not reject H_0
PMG versus MG	2.77 (4)	0.5967	Do not reject H_0

Table 9: Results of the PMG-ARDL model

Variables	Coefficients	Standard error	P-value
Long term			
lnFD	0.341217***	0.0809489	0.0000
lnGDP	0.6695053***	0.0918718	0.0000
lntrade	0.1194209*	0.0622763	0.055
lnPOP	0.6898229	0.5281243	0.191
Short term			
ECT	−0.1727436**	0.0722319	0.017
ΔlnFD	0.0484166**	0.0233048	0.038
ΔlnGDP	0.4798143***	0.1441242	0.001
Δlntrade	0.0388129*	0.0234139	0.097
ΔlnPOP	5.179627	4.671503	0.268
Constant	−0.2318846***	0.0796297	0.004

From an economic and policy perspective, these findings underscore the importance of incorporating long-run dynamics into energy policy design. Short-run adjustments—whether deriving from variations in GDP, trade openness, or population—do not immediately result in significant shifts in energy consumption but rather diffuse progressively over time. Consequently, energy planning strategies must be designed within a long-term framework to ensure the stability, efficiency, and sustainability of the energy system.

Within our expanded sample of eight BRICS+ countries, the empirical findings demonstrate that several macroeconomic and financial factors significantly affect energy consumption, carrying important economic and policy implications. Expanding the scope to include the broader BRICS+ bloc better captures the economic, energetic, and institutional diversity of these emerging economies, thereby offering a more comprehensive perspective than analyses restricted to the five original BRICS members.

4.5.2.1. Long-run results

4.5.2.1.1. Financial development and energy consumption

Expanding the sample to eight BRICS+ countries allows for a better capture of the economic, energetic, and institutional diversity among emerging economies, thereby offering a more comprehensive perspective than studies restricted to the five original BRICS members. Within this framework, financial development exerts a positive and statistically significant effect on energy consumption (coefficient = 0.341, P < 0.01). This impact is driven by eased credit access for economic agents (both households and firms), which stimulates productive investment, the acquisition of consumer durables, and industrial expansion, ultimately increasing energy demand.

The inclusion of additional countries (Egypt, Iran, and Saudi Arabia) accounts for a wider variety of consumption patterns and financial structures, thus reinforcing the robustness and generalizability of the findings. These results align with the empirical work of Fu et al. (2022) for China, Ma and Fu (2020) for a global sample of 120 countries, and Al-Mulali and Lee (2013) for the GCC countries. Policy-wise, these findings underscore the necessity of redirecting financial development toward green investments, promoting energy efficiency, and supporting the adoption of clean technologies to harmonize economic growth with environmental sustainability across these heterogeneous economies.

4.5.2.1.2. Economic growth and energy consumption

Economic growth exerts a positive and statistically significant effect on energy consumption (coefficient = 0.669, P < 0.01). This relationship is driven by the pivotal role of economic activity in fueling energy demand: expanding industrial production,

accelerated urbanization, and rising living standards stimulate increased energy utilization across both households and firms.

Expanding the sample to include the BRICS+ countries represents a major contribution, as it captures a broader spectrum of economic, industrial, and energy heterogeneity than observed in the initial BRICS bloc. Incorporating economies at different stages of development and with varied energy structures provides a more comprehensive and nuanced perspective on the link between economic growth and energy consumption. These findings corroborate the conclusions of Lefatsa and Nubong (2025) for SADC countries and Raza et al. (2024) for BRICS countries, while enriching the literature by accounting for the expanded BRICS+ framework.

4.5.2.1.3. Trade openness and energy consumption

Trade openness exerts a positive effect on energy consumption, which is significant at the 10% level in the long run (coefficient = 0.119, P-value = 0.055) and remains marginally significant in the short run (coefficient = 0.039, P-value = 0.097). In the short run, this relationship reflects the immediate impact of intensifying trade and integration into global value chains on the energy demand of firms and households. In the long run, this positive effect strengthens, reflecting the durable influence of trade openness on industrial expansion, export growth, and productive diversification, all of which require an increased energy supply.

The expansion to the BRICS+ countries allows for a better apprehension of the diversity in industrial and energy structures, offering a more complete view of the dynamics between international trade and energy consumption. These results confirm the observations of Koengkan (2018) for the Andean Community and Han et al. (2022) for China, while highlighting the necessity of accompanying trade openness with energy efficiency policies and a transition toward renewable energy sources.

4.5.2.1.4. Population and energy consumption

Energy consumption exhibits a positive but statistically insignificant relationship with population (coefficient = 0.689, P = 0.19). This suggests that while demographic growth tends to increase energy demand—particularly for domestic and industrial needs—population size alone does not robustly explain the variations in energy consumption. Other structural factors, such as economic development, urbanization, and energy efficiency, play a more preponderant role in the energy dynamics of BRICS+ countries.

Integrating the eight BRICS+ nations allows for a broader grasp of economic, industrial, and energy diversity, providing a more comprehensive perspective than analyses focused on a single country or the original five BRICS nations. This finding contrasts with studies by Muzayanah et al. (2022) in Indonesia, Zarco-Periñán et al. (2021) in Spain, and Audi and Ali (2016) in Lebanon, which demonstrated a positive and significant relationship between population and energy consumption. It also differs from the work of Ma et al. (2024) and Wang et al. (2024) in China, as well as Morikawa (2012) in Japan, who observed a moderating effect of population density on energy consumption.

4.5.2.1.5. Short-run dynamics and transitory adjustments

Having established the long-run determinants of energy consumption in BRICS+ countries, it is essential to examine the short-run dynamics to understand transitory adjustments and the immediate responses of the explanatory variables. This approach provides a complementary perspective, allowing for the distinction between long-lasting effects and temporary impacts, thereby identifying immediate leverage points for economic and energy policymakers.

The short-run empirical analysis of energy consumption in BRICS+ countries reveals a clear hierarchy among determinants. Economic growth and financial development emerge as the primary drivers, whereas trade openness and urbanization play a more secondary or lagged role.

4.5.2.2. Short-run results

4.5.2.2.1. Economic growth (lnGDP)

Economic growth emerges as the most influential and statistically significant determinant of short-run energy consumption, with a coefficient of 0.480 ($P < 0.01$). This relationship is driven by the development model of the BRICS+ countries, which is characterized by rapid industrialization and energy-intensive urbanization. Empirically, any cyclical acceleration in economic activity generates an immediate and substantial strain on energy demand. This strong dependence underscores the necessity of implementing proactive energy efficiency policies to decouple—even partially—economic growth from energy consumption during expansionary phases.

4.5.2.2.2. Financial development (lnFD)

Financial development also exerts a positive and statistically significant effect on energy consumption. In the BRICS+ nations, which are characterized by rapidly expanding financial systems, broadened credit access facilitates corporate investments and household expenditures, thereby stimulating energy demand. The results indicate that credit expansion translates into an almost immediate increase in energy consumption, making the financial sector an important channel of cyclical transmission.

4.5.2.2.3. Trade openness (lnTrade)

Trade openness exhibits a positive effect that is marginally significant at the 10% level (coefficient = 0.039; P approx = 0.097). Theoretically, intensifying trade stimulates energy-intensive industrial production, a defining feature of the BRICS+ footprint in global value chains. However, the effects of this trade integration fully materialize only with a certain time lag. The marginal significance of the coefficient indicates that in the short run, trade openness is not a primary driver of energy consumption variations, as its influence is outpaced by domestic growth and credit dynamics.

4.5.2.2.4. Urbanization (lnPop)

The urbanization variable does not display a statistically significant effect on short-run energy consumption ($P = 0.268$). This lack of significance reflects the structural nature of urbanization processes: profound transformations in infrastructure and lifestyles require a long time horizon to substantively alter energy demand. For the BRICS+ countries, despite their rapid urban growth, this result indicates that the energetic impact of urbanization belongs to long-run trends rather than short-run cyclical shocks.

Table 10: Dumitrescu and Hurlin (2012) causality test results

H_0 hypothesis	W-bar statistic	Z-bar statistic	P-value	Decision
Financial development (FD) does not Granger-cause energy consumption (EC)	4.8021	7.6042	0.0000	Reject H_0
Economic growth (GDP) does not Granger-cause energy consumption (EC)	3.4216	4.8432	0.0000	Reject H_0
Trade openness (TRADE) does not Granger-cause energy consumption (EC)	2.2759	2.5517	0.0107	Reject H_0
Population (POP) does not Granger-cause energy consumption (EC)	5.3969	8.7938	0.0000	Reject H_0

Source: Authors' calculations

The short-run analysis for the expanded BRICS+ sample demonstrates that immediate fluctuations in energy consumption are primarily dictated by economic growth and credit expansion. These findings converge with the empirical work of Shahbaz et al. (2018), and Caglar et al. (2022), yielding several strategic implications:

- Energy-growth decoupling: The high elasticity of energy consumption relative to economic growth necessitates the implementation of proactive conservation and energy efficiency policies, including stringent industrial performance standards and building thermal retrofits.
- Channelling finance toward transition (Green finance): The significant impact of financial development suggests the utility of integrating climate objectives into macroprudential regulation. This can be achieved through incentives for financing sustainable energy projects and tighter requirements for funding fossil-fuel assets.
- Sustainable urban planning: Although urbanization yields no immediate effect, it remains a major long-run structural factor. Spatial planning policies must anticipate future needs by incorporating sustainable urban development principles, such as decarbonized public transit and the integration of renewable energy sources into municipal infrastructure.

Consequently, managing energy demand in the BRICS+ countries requires an integrated approach that acts simultaneously on cyclical levers (economic cycles and credit expansion) and structural drivers (urban planning and industrial policy) to guarantee a sustainable development pathway.

4.6. Dumitrescu–Hurlin Panel Causality Test

To complement the PMG-ARDL long-run and short-run analysis, the Dumitrescu and Hurlin (2012) panel causality test is applied to investigate the direction of causality among variables. This test is particularly suitable for heterogeneous panels with potential cross-sectional dependence.

Unlike traditional causality tests, it allows for heterogeneity in causal relationships across countries while testing the null hypothesis that no Granger causality exists for all cross-sectional units.

The test is applied to examine the causal relationships between financial development and energy consumption; economic growth and energy consumption; trade openness and energy consumption and urbanization and energy consumption. The results provide additional insight into whether macroeconomic variables not only influence energy consumption in equilibrium but also drive its temporal evolution. The results are reported in Table 10.

To examine the causal relationships among the variables within the panel of BRICS+ countries over the 1990-2021 period, we applied the heterogeneous panel causality test developed by Dumitrescu and Hurlin (2012). This test is particularly well-suited for panels characterized by parameter heterogeneity and cross-sectional dependence, both of which are pervasive features in macroeconomic data. It evaluates the null hypothesis of the absence of Granger causality for all countries in the panel, against the alternative hypothesis that a causal relationship exists for at least one subgroup of countries.

- Financial development → Energy consumption: The null hypothesis is rejected at the 1% significance level, indicating that the expansion of the financial sector stimulates energy consumption by financing industrial and infrastructural investments.
    - Economic growth → Energy consumption: A significant unidirectional causality running from GDP to energy consumption is observed, confirming that economic growth constitutes a direct driver of energy demand within the BRICS+ countries.
    - Trade openness → Energy consumption: Trade openness also exerts a causal influence, reflecting the effect of integration into global value chains on industrial production and energy demand.
- Population → Energy consumption: Demographic growth significantly influences energy consumption, capturing the expansion of residential and tertiary sector requirements.

The results of the Dumitrescu and Hurlin test demonstrate that energy consumption within the BRICS+ sample is multifaceted. It is driven not only by economic growth, but also by financial development, trade openness, and demographic shifts. These findings offer critical insights for the formulation of public policies aimed at reconciling economic development with the energy transition across these strategic economies.

5. CONCLUSION

This study investigates the relationship between energy consumption and its macroeconomic determinants—financial development, economic growth, trade openness, and urbanization—in a panel of BRICS+ countries over the period 1990-2021 using the PMG-ARDL framework.

The empirical results reveal the existence of a stable long-run relationship among the variables. In the long run, economic growth, financial development, and trade openness significantly increase energy consumption, with economic growth emerging as the dominant driver. Urbanization shows a positive but statistically insignificant effect. In the short run, economic growth and financial

development remain the main determinants of energy demand, while trade openness and urbanization exert weaker or insignificant effects. The error correction term confirms the existence of a long-run equilibrium toward which the system converges.

This study contributes to the existing literature in several ways. First, it provides one of the earliest empirical analyses focusing on the expanded BRICS+ framework, thereby extending the scope of previous studies that mainly concentrate on the original BRICS economies. Second, it integrates simultaneously four key macroeconomic determinants—economic growth, financial development, trade openness, and urbanization—within a unified dynamic framework, allowing for a more comprehensive understanding of energy consumption drivers.

Third, it applies a robust econometric methodology (PMG-ARDL) that distinguishes between short-run dynamics and long-run equilibrium relationships while accounting for heterogeneity across countries. Finally, the study incorporates cross-sectional dependence and causality analysis, enhancing the robustness and reliability of the empirical findings.

5.1. Policy Recommendations

The findings of this study provide important policy implications for BRICS+ countries.

- First, the strong impact of economic growth and financial development on energy consumption highlights the need to promote green growth strategies, ensuring that economic expansion is decoupled from excessive energy use.
- Second, financial systems should be reoriented toward green finance mechanisms, encouraging investment in renewable energy projects, energy-efficient technologies, and low-carbon infrastructure.
- Third, trade openness policies should be accompanied by environmental regulations that promote clean technology transfer and reduce the energy intensity of production and global value chain participation.
- Fourth, although urbanization does not show a significant short-run effect, it remains a critical long-term driver. Therefore, policymakers should adopt sustainable urban planning strategies, including energy-efficient buildings, smart cities, and sustainable transport systems.

Despite its contributions, this study has several limitations.

- The analysis is based on a relatively limited sample of eight BRICS+ countries, which may restrict the generalizability of the results
- The study uses aggregate energy consumption, without distinguishing between renewable and non-renewable energy sources, which may mask important structural differences
- Environmental indicators such as CO_2 emissions, carbon intensity, or ecological impact are not included in the model, limiting the analysis of environmental sustainability.

5.2. Future Research Directions

Future research could extend this study in several directions.

- Incorporating renewable energy consumption to better understand the transition toward cleaner energy systems
- Including CO_2 emissions and environmental degradation indicators to assess the environmental consequences of macroeconomic drivers
- Examining the role of green finance and sustainable financial development in shaping energy demand
- Investigating the ecological footprint as a more comprehensive measure of environmental pressure
- Extending the analysis to include post-2021 climate policies and post-pandemic structural changes, which may significantly reshape energy consumption patterns in BRICS+ economies.

Overall, this study demonstrates that energy consumption in BRICS+ countries is primarily driven by macroeconomic expansion and financial deepening, highlighting the urgent need for integrated policies that align economic growth with sustainable energy transition objectives.

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