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Is the Relationship Between Economic Growth and Energy Consumption in the G20 Non-Linear?

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ABSTRACT

This paper investigates the complex, non-linear, and asymmetric dynamics linking economic growth and energy consumption within the G20 economies over the period 1992 to 2022. Employing the panel NARDL (Nonlinear Autoregressive Distributed Lag) approach, the analysis advances the empirical literature by shedding light on the differentiated effects that changes in energy consumption exert on economic expansion among the world's leading economies. The methodological framework integrates three estimators—Mean Group (MG), Pooled Mean Group (PMG), and Dynamic Fixed Effects (DFE)—to rigorously examine both short-term fluctuations and long-term equilibrium relationships. The empirical findings point to marked asymmetries in the energy-growth nexus. Notably, increases in energy consumption are found to foster economic growth, whereas reductions in energy use tend to produce even more substantial negative repercussions. For instance, according to the Mean Group estimator, corroborated by the Hausman specification test, a 1% uptick in energy consumption is associated with an estimated 2.9% rise in economic growth; conversely, a 1% decline in energy use corresponds to an approximate 3.1% contraction in growth. The analysis further controls for pivotal macroeconomic variables—including government expenditure, gross capital formation, inflation, and trade openness—that collectively shape the interplay between energy and growth across G20 nations. These results carry significant policy implications, underscoring the necessity for nuanced energy transition strategies that simultaneously support sustained economic development and address environmental imperatives. The research stresses the importance of a measured approach to implementing energy-saving policies, advocating for gradual transitions to mitigate potential negative economic consequences. Ultimately, the study offers substantive insights for policymakers and stakeholders seeking to craft balanced energy and economic frameworks, thereby contributing to the broader objectives of

sustainable development and climate change mitigation in major global economies.

INTRODUCTION

The combination of economic expansion and energy utilization has been the focus of interest both among theorists and decision-makers. Most of such strategies have worked under the assumption that these variables are positively interrelated. Wang (2024) echoes the general consensus that wealthier nations are able to consume more energy to meet their developmental needs. However, several recent researches disprove this relation and elaborate on many other different and possibly more complex. Feng and Zhao (2022) suggest the existence of non-linear relations between energy consumption and economic activity.

This move away from the linear outlook indicates that the impact of energy use on economic activities will not be the same for all countries and depend clearly on their level of development and other factors where they operate. Wang et al. (2024) explain that although there are such varying impacts, they are contextual to the economy. The future study of expanding the scope of structural equations modelling will deepen our understanding of the dynamics between energy consumption and economic growth in the context of the G20 countries.

Evidence supporting studies in the past have suggested that there exists a non-linear relationship between the economic growth and energy consumption. Apergis and Payne (2010) implied that the effects of energy consumption on the factors of economic growth might depend upon the developmental level of the country in question or other such factors. This further investigation into the non-linear relationship could help unlock even further pathways into the understanding of the interplay between economic growth and energy consumption across the G20 economies.

The relationship of energy consumption with economic growth has been an area of contention among the researchers and scholars. Bidaoui (2004) has presented a bidirectional causality, which allows us to conclude that economic growth could lead to an increase in energy consumption and the opposite is true as well. Nonetheless, other studies found a unidirectional causality. Adhegaonkar (2015) and Wolde-Rufael (2006) have observed episodes of causation regarding energy consumption and energy growth in one direction only. Such directional concept may be customized according to the context level and analytical techniques deployed in the work.

With a significant integration into the global economy, the G20 countries make a good case for this study considering their policies and decisions have a bearing on the world's stage. Understanding that relationship in these countries, yield fruitful insights that will in turn assist in making decisions at both the national and international context.

From 1995 to 2021, economic growth and energy consumption in G20 countries are analyzed in this study using the NARDL method which is the Non-linear Autoregressive Distributed Lag approach and it is supported by empirical evidence. According to Shin et al. (2014), such a method permits tests of the Clay Theory, wherein relationships involving the variables of interest are non-linear allowing for a relatively better characterization of the issues in question.

This study is focused on examining the long-run tendencies and changes that have occurred in the relationship between economic growth and energy consumption by employing data for the two decades running from 1995 to 2021. NARDL is an appropriate method for examining this relationship due to its consideration of the existing constitutional asymmetries and other complexities involved in the investigated relationship. This study employs this methodology with the hope of providing empirical evidence that will enhance the contributions to the debate surrounding the energy consumption and economic growth in the G20 nations.

The remaining parts of the paper are organized as follows: Section 2 reviews the existing literature on the relationship between energy consumption and economic growth. Section 3 investigates the issues of sustainable development policies and achievements within G20 countries. Section 4 explains the panel NARDL econometric methodology adopted within the study. Section 5 identifies the data and variables in the empirical analysis.

1. LITERATURE REVIEW

The interplay between energy consumption and economic growth has generated significant interest in the research community, albeit with an assortment of sometimes conflicting conclusions, which in turn adds to the complexity of this subject. This complexity is due to the complex character of the relationships within the energy-growth nexus and contexts in different economies, most especially in the G20 countries.

In the past, most studies centered on the linear modes of the relationship with respect to the energy consumption and the economic growth. For instance, Kasman and Duman (2015) showed that a 1% rise in energy consumption contributes around 0.35% increase in the GDP in the OECD countries thus substantiating the older perspective of energy being utilized in economic activities considerably. Likewise, Bildirici (2013) and Omri (2013) reported that energy consumption and economic growth had positive relationships in many countries and regions.

But this linear view has since been disputed by further studies. Alam (2014) and Apergis and Payne (2010) suggested that energy is rather one of the least input facter of growth that is likely to affect economic growth relative to capital and labor. This variation in the outcomes of studies suggests an explanation that is more broad based which looks at the specific characteristics of the country as well as the possible non-linear relationships.

More studies are now getting inclined towards focusing on the asymmetric characteristics of the energy growth nexus. With the help of the Nonlinear Autoregressive Distributed Lag (NARDL), this set of researchers provided asymmetric evidence. Iwata et al (2012) showed that his rate of increase in the energy consumption during the economic growth may not be the same as the rate of decrease during the times of contraction in theOECD countries. It is during this point that the asymmetry becomes more useful in the sense that, the tendency to focus on the positive effects only or increasing energy consumption is not practical.

The directional causes of the nexus between energy and growth have also been contested. While Jumbe (2004) established bi-directional causality, other Willis (2005) and Adhegaonkar (2015) as well as Wolde-Rufael (2006) provided unidirectional causality but from different areas. The fact that there are conflicting views regarding the issue shows that the causal relationship is likely to be relative which bears some of its attributes on the area of focus like economic activities or level of development, the energy mix or selection and policy conditions that may be present.

The energy-growth nexus gets further complicated within the context of sustainable development. According to Al-Mulali et al. (2015), economic growth followed through energy utilization would incur environmental costs, specifically in carbon emissions. Such views seem to be supported by Wang et al. (2024) who pointed out that G20 countries struggle to attain economic empowerment without detrimental effects to the environment.

However, the limitation in this study is the understanding of the non-linear and the asymmetric relationships between energy consumption and economic growth particularly within the context of G20 countries. Most studies seem to have either concentrated on the linear ties or ventured into asymmetries in fewer groups of countries. The G20 world countries have merged in terms of great gross amount of economy and energy consumption as well, they are very important but not well studied in terms of such complex relationships.

To fill this gap, this research uses the NARDL approach and examines the asymmetrical relationship between energy consumption and economic growth in the context of G20 countries. Our results indicate that there exists a considerable asymmetry in the short run and long run relationships between energy consumption and economic growth. More particularly, we provide evidence that positive developments in energy consumption exert more influence on economic growth than negative developments which means that energy effort programs do not have similar effect on the economy.

Given the evidence put forward in this study, a detailed assessment of the impact of energy consumption on economic growth through a non-linear and asymmetric model in the case of G20 countries is undertaken. This is useful in the formulation of policies that lead to effective economic growth without compromising on environmental protection and energy security in the major economies of the world.

2. SUSTAINABLE DEVELOPMENT IN THE G20 COUNTRIES: POLICIES AND ACHIEVEMENTS

Within the span of three decades, the G20 countries succeeded in earning their recognition on the sustainable development agenda, implementing policies aimed at equity in terms of economic growth and development while incorporating environment protection. The G20, which was initially inaugurated in 1999 as a ministerial meeting, has developed into an important forum for international interactions between developed and developing countries in finding global solutions to global challenges such as sustainable development. The group's commitment to the Sustainable Development Goals (SDGs) has been on its agenda, particularly in the perspective of the 2030 Agenda that seeks broad-based and sustainable development which takes into account climate change and inequalities (Goyal & Kukreja, 2020).

Wang et al. (2024) indicate that energy consumption is a core driver for economic growth in G20 countries and it is essential for industrialisation and economy development. They note that over time especially in the convenient last thirty years, several economies of the G20 countries have been able to grow, and this growth was often associated with higher energy consumption, in most cases from fossil fuels. This growth path according to them helped to raise the standard of living and strengthen the economy of the people especially in the low and middle-income countries.

But on the other hand Wang et al. (2024) were also quick to caution that the rigidity in energy sources dependence raises questions about sustainability in the long haul and the environment impact. This observation highlights the intricacies and interplay involved between energy use, economic growth and environmental sustainability in the case of G20 countries.
In line with this, the G20 has adopted various frameworks and commitments aimed at enhancing economic development without harming the environment. In particular, the blow stated strategies stresses the level of importance of moving from dependency on fossil fuel-based economies for growth strategies. The Energy and Climate Ministerial meetings have reiterated the call for clean energy transitions as key to economic and social growth and creation of jobs (UNDP, 2023).

It can be stated, however, that social inequalities can be considered as lasting concerns of the G20. Solving these issues together with those related to environmental damage from successfully employed coal-based economies, meeting fossil fuel dependency and other economic disproportions, countries progress towards Sustainable Development Goals with an adequate efficiency of certain measures and actions. While some countries, through an increased investment expenditure in renewables and protect more adequately coal climate, the G20 countries achieve some level of the SDG, other countries do not share the same success.

Despite some challenges, the G20 has expanded economic activities through the implementation of a succession of measures aimed at socially-oriented sustainable development such as cooperation in clean energy transitions and safeguarding biodiversity. Concerning green economy measures, the G20 has been quite active in setting up the Resilience and Sustainability Trust and highlighted the importance of blended finance for economies. The focus on designing Sustainable Development Lifestyles has been repeatedly put forward by the group as individual actions can also contribute and facilitate achieving of the goals (UNDP, 2023).

For the G20 to be able to move forward, it is necessary to deepen collaboration, strengthen accountability measures, and ensure coherence among states in the pursuit of greater sustainable development. This is important in light of the climate emergency and the need for a just transition to a low carbon economy. By working on these issues which sustain their involvement in sustainable development activities, the member nations of G20 would be in a position to contribute to the global sustainability issues and be role models to other states.

3. METHODOLOGY

3.1 Model

The baseline model used in this study can be written in the following manner:

$$gypc_{i,t} = f(ecint_{i,t}, GE_{i,t}, GFC_{i,t}, infd_{i,t}, \mathrm{opn}_{\mathrm{i,t}})$$

where the dependent variable, $gypc_{i,t}$, refers to the real GDP per capita growth for the country i at time t. The primary explanatory variable, $ecint_{i,t}$, which is defined as energy consumption divided by GDP, where energy is consumed in a nation i at time t, is used as an indicator of energy efficiency. This indicator indicates the energy consumption level necessary for production outputs.

Where EC indicates energy consumption in Mega joule (mj) and GDP is qualified in dollars in its constant price form. Therefore, $ecint$ is expressed in terms of mj per unit of GDP (Energy Institute, 2023).

This metric of energy intensity is of importance since it shows the relationship of output from the economy to energy consumed. Aspects that have a low ratio are interpreted as more energy efficient while those with high ratios are said to be more inefficient or would make use of energy-sustaining industries (Wang et al, 2024). The metric has implications for economic efficiency (Kasman and Duman, 2015), level of environmental sustainability (Al-Mulali et al, 2015), structure of economy (Apergis & Payne, 2010), effectiveness of policies (IRENA, 2019) and advancement of technology (Feng & Zhao, 2022).

On the other hand, an increase in this ratio is not always an indicator of inefficiency. This is because it might also point out energy losses (Alam, 2014), changes in economic development (Bildirici, 2013), climate and geographic conditions (Aslan et al., 2021), or even the phases of economic development (Goyal & Kukreja, 2020). This index is useful both for measuring economic effectiveness, shaping energy strategies and evaluating the reaching of the sustainable development goals targets (UNDP, 2023).

Moreover, $GFC_{i,t}$ refers to the gross capital formation rate for the country i over time t, which approximates the invested amount in fixed assets. The model also includes $infd_{i,t}$, which denotes inflation in country i at time t and calculated as the GDP deflator's growth rate (2015=100). This variable considers the effect of fluctuation of prices of service and goods in all domestic markets. Finally, $opn_{i,t}$ is the trade openness index of country i at time t, expressed as the percentage of GDP consisting of total external trade (exports + imports). This variable measures the extent of interaction of each country's economy with the rest of the world in terms of trade.
Such specification makes it possible to evaluate the interactions among different sets up economic variables, placing into their context, economic growth. The intgration of country-specific and time-specific effects within this panel data structure serves to enhance the comprehensiveness of the investigation into the determinants of economic growth in several countries at any particular time. This strategy permits the combination of horizontal and temporal aspects, thus enabling one to appreciate the intricate relationships that exist in economic growth across different regions and time periods.

In order to understand the short and the long-term effects of energy consumption on economic growth, we adopt the NARDL model proposed by Shin et al. (2014). This gives room for investigating the effects of increasing and decreasing energy on GDP growth. In terms of asymmetric cointegration, the NARDL model can be expressed as:

$$gypc_{i,t} = \beta_0 + \gamma_1 ecint_{i,t}^{+} + \gamma_2 ecint_{i,t}^{-} + \beta_1 GE_{i,t} + \beta_2 GCF_{i,t} + \beta_4 infd_{i,t} + \beta_5 opn_{i,t} + \varepsilon_t \quad (1)$$

Furthermore, let us show the shocks in the system that can be measured by the positive and negative disparities from the established long-run equilibrium relationship in terms of partial sum decomposition of the misalignment term ($EC_{i,t}$) as follows:

$$ecint_{i,t}^{+} = \sum_{k=1}^{t} \Delta ecint_{i,k}^{+} = \sum_{k=1}^{t} Max\left(\Delta ecint_{i,k}, 0\right) \quad (2)$$

$$ecint_{i,t}^{-} = \sum_{k=1}^{t} \Delta ecint_{i,k}^{-} = \sum_{k=1}^{t} Min(\Delta ecint_{i,k}, 0) \quad (3)$$

This specification takes into account of any increase and decrease of Energy Consumption $ECInt_{i,t}$ that is, $ecint_{i,t}^{+}$ against $ecint_{i,t}^{-}$. The coefficients for these variables will test whether reduction or increase in consumption of energy produces differential effects on economic growth in both a short and a long run. The NARDL modeling framework provides a much more realistic picture of the relationship between energy consumption and economic growth than linear models which assume no feedback.

We can obtain the following asymmetric error correction model (ECM)

$$\begin{aligned}\Delta gypc_{i,t} = {} & \beta_0 + \gamma_1 ecint_{i,t}^{+} + \gamma_2 ecint_{i,t}^{-} + \beta_1 GE_{i,t} + \beta_2 GCF_{i,t} + \beta_4 infd_{i,t} + \beta_5 opn_{i,t} \\ & + + \sum_{n=1}^{m0} a_{0,n} \Delta gypc_{i,t-n} + \sum_{n=1}^{m1} a_{1,n} \Delta ecint_{i,t-n}^{+} + \sum_{n=1}^{m2} a_{2,n} \Delta ecint_{i,t-n}^{-} \\ & + \sum_{n=0}^{m3} a_{3,n} \Delta GE_{i,t-\mathrm{n}} + \sum_{n=0}^{m4} a_{4,n} \Delta GCF_{i,t-\mathrm{n}} + \sum_{n=0}^{m5} a_{5,n} \Delta infd_{i,t-\mathrm{n}} \\ & + \sum_{n=0}^{m6} a_{6,n} \Delta opn_{i,t-\mathrm{n}} + \varepsilon_t \end{aligned} \quad (4)$$

Where Δ denotes the first difference operator for short run coefficients α_i , where $i = 1, \ldots, 8$ and for long run analysis the terms are β_i for $i = 1, \ldots, 6$. The estimation of the long run coefficients for all variables is expressed as follows:

$$\lambda_i = \frac{-\beta_i}{\beta_0}, \quad (5)$$

The terms $m_1, m_2, \ldots, m_8$ indicate the number of lags for the independent variables ($lnGE, lnFDI, lnEC, lnK, lnL, lninfl, and\ lnopn$) while, $m0$ indicates the number of lags for the dependent variable (Y_t).

This ECM representation of the NARDL model is able to measure short run and long run asymmetric effects of energy consumption and economic growth. The arrow which shows the error correction mechanism in the short run, that is $ECT_{t-1} = \beta_0$, provides a forecast of how fast the variables will adjust to each other in the long run equilibrium. Looking at the coefficients depicting positive and negative changes in the base level of energy consumption, as well as in the lower average level, demonstrates the objectivity of the relationship. Understanding these coefficients will make clear the assertions made regarding the different effects of energy consumption positive and negative shock on economic growth and the speed of economic growth towards that shock.
The researchers set out to conduct this study using the panel NARDL system. To achieve this goal, they applied three panel estimators: Mean Group (MG), Dynamic Fixed Effects estimator (DFE), and Pooled Mean Group (PMG) estimator. Each estimator has its distinct contribution toward the analysis of the long-run and short-run relations in the substance in question in the panel data framework.

3.2 Mean Group (MG) Estimator and Pooled Mean Group (PMG) Estimator:

To reiterate from the literature review, the MG estimator is characterized by total heterogeneity across the countries in the sample, but in the case of the PMG estimator, all long run coefficients are set to be equal but other wise there can be heterogeneity. In fact Pesaran et al. (1999) have shown that the PMG estimator as well as the MG estimator have been shown to be consistent, even with endogeneity in the model, because lags of both the dependent variables and independent variables are included into the model, so as to mitigate possible simultaneity bias.

3.3 Dynamic Fixed Effects (DFE) Estimator:

The DFE estimator was introduced by Pesaran and his associates in 1999, and it is worth mentioning that the DFE estimator has some features in common with the PMG estimator. However, DFE is more stringent in its homogeneity conditions. The DFE estimator postulates that in the long run, both slope coefficients and error variances have the same value across countries. Similarly, the DFE estimator postulates that the adjustment speed and short run coefficients are the same across countries with the exception of the constant terms which are allowed to be different.

3.4 Hausman Test

In order to evaluate whether the MG, PMG or DFE estimators are the best fit, the Hausman (1978) test is used. This test checks whether the PMG estimator is valid in putting the homogeneity restriction on the long-run coefficients.

The null hypothesis of the Hausman test indicates that both the MG and PMG estimators are able to consistently estimate the model. While the MG estimator is consistent and efficient if there is heterogeneity, it is likely not as efficient as the PMG estimator under the same situation if the homogeneity restriction is met. On the other hand, for the PMG estimator to be used which is superior under homogeneous conditions, then the condition of homogeneity must be satisfied otherwise it becomes inconsistent. Hence, the null hypothesis actually states that there are no significant differences of the two estimators in terms of consistency.
If the null hypothesis is rejected it implies that the homogeneity restriction is not satisfied and therefore the MG estimator which was heterogenerous is preferred. On the other hand if the null hypothesis is true then it means that the homogeneity restriction holds and therefore the PMG estimator which is heterogeneously efficient is preferred.

The Hausman test is an important test for deciding whether to use the Pooled Mean Group (PMG) or the Dynamic Fixed Effects (DFE) model, as it checks the reasonableness of the restrictions of homogeneity on the long-run coefficients. The null hypothesis is that both the PMG and DFE estimators are consistent, with PMG being the more efficient one if homogeneity is assumed to hold. However, if the null hypothesis is rejected, a DFE estimator that does allow for some heterogeneity in short-run dynamics and variances of the errors would be preferred instead. On the other hand, the acceptance of the null hypothesis means that the efficiency gains of the PMG estimator are true, and hence it is preferred instead. In this way, it becomes possible to provide a more comprehensive view of the economic relationships in question by considering some heterogeneities across countries or through time.

4. DATA

This work makes use of the panel data made of different measures of economic activity adjusted for inflation over time, with the year of 2015 taken as the base year (2015 = 100). More specifically, these indicators, which are mostly sourced from the World Banks, World Development Indicators database (World Bank, 2024), span the G20 countries from 1992 to 2022.

This research restates a special set of data derived from several macroeconomic indicators all valued in 2015 monetary terms, 2015 being the chosen base year (2015=100). The more specific indicators that are mainly from the World Bank's World Development Indicators (World Bank, 2024) cover G20 countries over the period extending between 1992 and 2022.

Data on energy consumption are taken from the Energy Institute's Statistical Review of World Energy, 2024. In this way, the energy consumption per unit of GDP (ecint) is determined as indicated below.

$$ecint = \frac{EC}{GDP}, \quad (6)$$

Descriptive statistics for the variables considered in this paper are set out in the Table 1, and the number of observations per each variable is 646. Real GDP per capita growth (gypc) has a mean of 2.021 percent with a wide dispersion of the figures between -14.614 percent and 13.636 percent. Energy consumption intensity (ecint) has a mean of 10.180, the minimum and maximum of which are 2.163 and 38.925 respectively which demonstrates a huge variation in energy efficiency among G20 states.

Table 1. the descriptive statistics for the variables

Variable	Obs	Mean	Std. Dev.	Min	Max
$gypc$	646	2.021	3.827	-14.614	13.636
$ecint$	646	10.180	6.974	2.163	38.925
gov	646	16.751	4.576	2.976	34.155
gcf	646	24.425	6.666	10.854	46.660
$infd$	646	28.752	195.852	-16.437	2736.971
opn	646	48.742	18.435	13.753	110.577

Source: own calculation based on the World Bank(2024) data set.

Government expenditure (gov) is on average accounted for 16.751% of GDP while gross capital formation (gcf) is on average of 24.425% of GDP. The inflation rate (infd) is also very volatile, subscribing an average of 28.752 percent as well as a standard deviation of 195.852, implying that there were decades with severe inflation in some countries. Trade openness (opn) is on average 48.742%, indicating a relatively big volume of international trade to G20 countries.
These statistics allow for a comparison in terms of energy consumption and economic development among G20 members and in the same time highlight both their similarities as well as their differences. Such broad ranges as recorded under several dimensions can also be indicative of the fact that economic conditions and the pattern of energy use in these major economies are not the same.

5. EMPIRICAL ANALYSIS

Before estimating the model specified in the previous section (namely the system of equations 4), it would be crucial to check the stationary features of the variables so as not to induce spurious regression results. In this study, the primary explanatory variable is taken to be the logarithm of energy consumption per capita (LnECP) while the dependent variable is the logarithm of GDP per capita (LnYPC). With this, we perform panel unit root tests, bearing in mind the possibility of cross-sectional dependence and heterogeneity among G20 countries. This makes it certain that the analysis undertaken grasped all the aspects of interrelationship between energy consumption and economic growth.

5.1 Unit Root Tests

This report includes the results of panel data unit root tests based on the set of the following methods: Im-Pesaran-Shin (IPS), Levin-Lin-Chu (LLC) and Breitung. The aim of the analysis revolves around the assessment of the stationary properties of these variables in levels and first differences, with a number of model specifications.

The IPS test is arguably the most effective test of unity given that it passes the second best set out criteria verifying his claim. The most of the variables transformed first under the above mentioned include d.gypc, d.ecint_pos, d.ecint_neg, d.gov, d.gcf, d.infd, d.opn amongst others that exhibit statistically significant rejection of the unit root null hypothesis (p-value < 0.01). For the case of level variables, the fourth hypothesis has a mixed set of results in which some of the variables like gypc and gov, gcf and infd have been proven to be stationary around a unit root within a certain specification of the models used. However, others like ecint_neg and opn are found also to have non-stationary features in their levels.

Along the same lines, the Levin-Lin-Chu test indeed does deviate significantly from the LLC test in a few cases but on the whole agrees that there is a large number of first differences of variables not containing a unit root. Their main concern however appears to be gypc, ecint_pos, ecint_neg and gov which seem to be unit nonstationary in levels since they only sometimes rejects the unit root. Interestingly, the LLC test seems always to be severed by the IPS test in the respect of their portfolio characteristics for a number of level variables.

The Breitung test, unlike both the IPS and the LLC tests, does not provide, at least at first sight any strong evidence of the presence of a unit root, both in the level variables and in the first differences. Although some first-differenced variables like d.gypc, d.ecint_neg, d.gov, d.gcf, and d.opn show statistically significant rejection of the unit root null under certain model specifications, the evidence is generally weaker compared to the other two tests. For the level variables, the Breitung test offers limited evidence against the unit root, or rather, only few such as gypc (under one specific model setting) provide weak evidence against the non-stationarity hypothesis.

To summarize, the unit root tests performed on the panel data set suggest that the most of the variables are integrated of order one, or achieve stationarity after taking first differences. This conclusion is also well supported by IPS and LLC tests, especially for the first differenced variables. The Breitung test seems to be less conclusive, which may be due to its susceptibility to particular features of the panel data set, However, the overall results suggest that these variables may need to be modelled in first differences in which case they are likely to be stationary, which is an important assumption for many econometric procedures. Additionally, it would be worthwhile for further research to look at whether there are any cointegrating relations among the level variables, particularly those with some degree of stationarity at the level, as this might yield interesting long-term relationships.

Table 2. Results of Unit Root Tests for Panel Data (20G)

	IPS		LLC		Breitung test	
	include intercept only	include intercept and trend	include intercept only	include intercept and trend	include intercept only	include intercept and trend
$gypc$	-17.1326 ***	-14.9294 ***	-11.1839 ***	-9.1150 ***	-1.5654	-2.1451 **
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0587)	(0.0160)
$d.gypc$	-19.3354 ***	-17.3838 ***	-18.1132 ***	-14.4638 ***	-1.2937	-3.7878 ***
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0979)	(0.0001)
$ecint\_pos$			-8.6104 ***	-4.0577 ***	0.9902	-0.2511
			(0.0000)	(0.0000)	(0.8390)	(0.4009)
$d.ecint\_pos$			-11.1625 ***	-11.6104 ***	-3.6082 ***	-0.3971
			(0.0000)	(0.0000)	(0.0002)	(0.3456)
$ecint\_neg$	-1.1836	-8.7065 ***	-6.4136 ***	-4.0383 ***	1.1310	-0.9479
	(0.1183)	(0.0000)	(0.0000)	(0.0000)	(0.8710)	(0.1716)
$d.ecint\_neg$	-25.5123 ***	-21.5128 ***	-17.8849 ***	-11.0567 ***	-2.3977 **	-1.4209
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0082)	(0.0777)
gov	-2.9763 **	-2.4865 **	-1.6997 **	-3.5093 ***	-1.2363	-0.7712
	(0.0015)	(0.0065)	(0.0446)	(0.0002)	(0.1082)	(0.2203)
$d.gov$	-15.5352 ***	-14.0628 ***	-16.6321 ***	-13.6117 ***	-3.2441 ***	-1.5626
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0006)	(0.0591)
gcf	-4.0619 ***	-3.2414 ***	-4.2416 ***	-3.2503 ***	-1.6752	-0.4248
	(0.0000)	(0.0006)	(0.0000)	(0.0006)	(0.0469)	(0.3355)
$d.gcf$	-18.9913 ***	-17.2057 ***	-14.3006 ***	-11.4106 ***	-1.6146	-2.1538 **
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0532)	(0.0156)
$infd$	-7.0419 ***	-5.0480 ***	-46.1751 ***	-44.4295 ***	0.1262	1.5838
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.5502)	(0.9434)
$d.infd$	-48.9629 ***	-48.3477 ***	-35.9531 ***	-30.7725 ***	-1.7089 **	0.5499
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0437)	(0.7088)
opn	0.9404	-3.9805 ***	-1.2338	-1.8861 **	-0.7403	-0.4704
	(0.8265)	(0.0000)	(0.1086)	(0.0296)	(0.2296)	(0.3190)
$d.opn$	-18.6243 ***	-15.8573 ***	-13.7215 ***	-14.5664 ***	-3.3280 ***	-1.8460 **
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0004)	(0.0324)

Source: own calculation

Notes: (1) "d" is the first difference operator; (2) p-value in parentheses; (3) *** and ** show significance levels at 1 percent and 5 percent, respectively.

5.2 Cointegration Test

In Table 2, the outcomes of the Kao residual-based cointegration test are displayed. This test assesses the existence of a long-term correlation among variables in our data panel format. It should be noted that the null hypothesis for this test claims that there exist no cointegration across the 19 panels (each representing the G20 countries) over the period of 29 years (1992-2022).

The table indicates five variants of the Dickey-Fuller test statistics as well as the respective p values. More specifically, the p values of all the five test statistics are less than 0.05, which is the customary threshold of the significance level of the p value. The above evidence makes it possible to conclude that the no cointegration null hypothesis is grossly mistaken. It entails that there exists a set of variables over the time period of the G20 countries that are cointegrating or that there exists an equilibrium long run relationship that is stable over the time period set. This result provides justification for the use of the NARDL framework to further examine the relationship between energy consumption and economic growth in the short and long term.

Table 2. Kao test for cointegration

#	Statistic	p-value
Modified Dickey–Fuller t	-2.9039***	0.0018
Dickey–Fuller t	-2.6101***	0.0045
Augmented Dickey–Fuller t	-2.8315***	0.0023
Unadjusted modified Dickey–Fuller t	-3.785***	0.0001
Unadjusted Dickey–Fuller t	-2.989***	0.0014

Source: own calculation
Notes: ***denote significance at 1% level.

5.3. Hausman Test

The results of the Hausman Test, that presented in Table 3, indicate that the MG estimator is superior to the PMG or DFE estimators indicating that the null hypothesis of no significant difference in coefficients which is the basis of PMG and DFE models is likely violated in this dataset. This violation seems to suggest that the MG estimator, which imposes no restrictions on the short-run and long-run coefficients on the level of heterogeneity for the individual unit, is the best estimator of the relationships among these variables.

The PMG estimator has some efficiency gains as it combines and imposes restrictions on the long-run coefficients, but the results of the Hausman test show that these efficiency gains are realized at the expense of consistency. It seems that the possible efficiency gains from PMG are not worth the loss of flexibility to the MG estimator when the Hausman test shows preference toward the MG estimator since its flexibility allows for a greater degree of unrestricted heterogeneity across panel units.

In the same vein, even though the DFE estimator deals with the issue of heterogeneity by including unit specific fixed effects, there is likely to be a limitation in terms of dynamic heterogeneity that the MG estimator is able to account for in the short-run and long-run relationships. Further, the results of the Hausman test suggest that the MG estimator is superior to the DFE estimator in this case.

Table 3. Hausman Test
Test: Ho: difference in coefficients not systematic

#	mg vs. pmg	mg vs. DFE
chi2(6)	23.11***	29.46***
Prob>chi2	0.0008	0.0000

Source: own calculation
Notes: ***denote significance at 1% level.

5.4. The results of long-run and short-run asymmetric NARDL models:

NARDL model estimation results expose that across G20 countries there exists considerable asymmetries in both energy consumption and GDP per capita economic growth in both shorter and longer spans. The Mean Group (MG) estimator which came out as the best fitted model from the Hausman test exhibits that expansion of energy consumption by units ecint_pos tends to produce a lesser positive reaction to economic activities compared to its contraction by units ecint_neg which experienced a greater negative impact (coefficient of 2.8981, p<0.1,ecint_pos) and (coefficient -3.0577, p<0.01, ecint_neg).

This result of asymmetry is consistent with those of Iwata et al. (2012) who pointed out similar asymmetries in growth patterns of some OECD economies. Indeed, the more positive coefficient of this variable measures indicates that growth in energy demand is more beneficial than reduction in energy usage. This could be due to energy being viewed as one of the most important factors of production whose increase in supply significantly increases the level of GDP growth.
Government expenditure (gov) on the other hand decreases the economic growth (coefficient of -0.3272, p<0.1). This result is dissimilar with some past investigations but could be due to the crowding-out phenomenon raised by Apergis and Payne (2010), that greater government expenditure can lead to a decline in private investment.

It is observed that gross capital formation (gcf) plays a significant role in the economic advancement of a country. The coefficient of determination from the model indicates that gcf has a regression coefficient of 0.2784 and a p-value of 0.01. This finding reiterates the role of traditional investment growth theories and also supports the findings of Kasman and Duman (2015). On the other hand, this also implies investment in physical capital is vital in addressing economic growth within G20 countries.

Interestingly, findings show that, even though unfavorable to the economy, inflation rate (infd) demonstrates a negative impact while trade openness (opn) impact is positive. Low p-values of 0.05 are recorded on regression coefficients of -0.1252 (infd) and 0.0654 (opn). The negative impact of inflation rate is expected on economic growth given the existing literature on the subject while the trade impact is consistent with the views of Al-Mulali et al. (2015) who argue that trade will enhance economic growth.

The coefficient of the lagged dependent variable (ECT) is significantly negative at -1.1437 with a p-value of less than 0.01. These results show that there is a rapid adjustment process toward the long-run equilibrium. In other words, long run equilibrium is restored only after such shocks are corrected in one instance with more than 100% correction noted on the first instance.
With statistical significance levels p=0,05 and p=0,01 respectively, the chi-squared statistics of both long-run and short-run symmetry tests are 6,290 and 22,460 which are computed models for short and long run posit no symmetry. These phenomena suggest that the NARDL framework is indeed appropriate as it does allow for asymmetries in the way economic growth responds to energy and other determinants in the short run and long run, and in this respect the author's provision is amended.

The results of the Hausman test indicate that the Mean Group (MG) estimator should be prioritized, which allows to add variability among the countries into the model. Nevertheless the PMG and DFE estimators add value, the northern hemisphere is overrepresented. Hence this reflects a more accurate picture of the relations prevailing among the variables in G20. The DFE estimator to the contrary has more df than z(xz)1 and df z(xz)123. Some takes different forms, some are level forms, some 1st differenced but the DFE has significance on a wider range than PMG & MG. This is important because it underscores the strong influence that the methodological choice has on estimates and hence advocates for different estimates across different methods to provide a complete picture.

These findings are critical to the policymakers of G20 countries. The nature of the impaired connection suggests that energy conserving policies may impact economic output asymmetrically with a possibility of larger greater than expected economic downturns during energy consumption cut backs. This emphasizes the necessity for energy transition strategies which are appropriately structured to augment growth and fulfil sustainability aspirations. Moreover, the effect of a diversity of economic factors also calls for the need of looking at economic policy in a broader context taking into account the role of energy use, government expenditure as well as capital investment in the context of persistent economic growth.

Table 4. Estimated results of the NARDL model

#	MG	PMG	DFE
Panel A. Long-run Coefficient Estimates			
$ecint\_pos$	2.8981	2.42 ***	3.2474 ***
	(1.9601)	(0.3270)	(0.5034)
$ecint\_neg$	-3.0577 ***	-2.3498 ***	-3.1297 ***
	(0.7273)	(0.3046)	(0.4839)
gov	-0.3272 *	-0.4703 ***	-0.4237 ***
	(0.1802)	(0.0435)	(0.0683)
gcf	0.2784 ***	-0.0225	0.0467 *
	(0.0743)	(0.0262)	(0.0404)
$infd$	-0.1252 **	0.0001	-0.0004
	(0.0546)	(0.0008)	(0.0008)
opn	0.0654 **	0.0037	0.0032
	(0.0253)	(0.0062)	(0.0109)
Panel B. Short-run Coefficient Estimates			
ECT	-1.1437***	-0.9296 ***	-0.9256 ***
	(0.0460)	(0.0473)	(0.0316)
$d.ecint\_pos$	-5.3881 ***	-4.9262 ***	-6.5318 ***
	(1.1089)	(1.2980)	(0.5883)
$d.ecint\_neg$	0.9309	0.2999	0.7776 **
	(0.6300)	(0.5505)	(0.3363)
$d.gov$	-1.6350 ***	-1.4523 ***	-0.4730 *
	(0.3555)	(0.2579)	(0.1044)
$d.gcf$	0.3605 ***	0.6149 ***	0.7306 ***
	(0.1098)	(0.1171)	(0.0584)
$d.infd$	-0.0224	-0.0841 *	-0.0009
	(0.0395)	(0.0509)	(0.0006)
$d.opn$	0.0191	0.059	0.0064
	(0.0394)	(0.0304)	(0.0191)
$cons$	-1.1066	9.3551 ***	6.7076 ***
	(4.2853)	(0.5678)	(1.5274)
Panel C. Symmetry Test			
$long-run$	6.290	58.770	42.190
$P-Vlue$	(0.0121)	(0.0000)	(0.0000)
$short-run$	22.460	15.690	80.020
$P-Vlue$	(0.0000)	(0.0001)	(0.0000)

Source: own calculation

Notes: (1) * , ** , *** denote significance at 10%, 5% and 1%, respectively; (2) p-values are in parentheses.

CONCLUSION

The objective of this study was to analyze the nonlinear link between energy consumption and economic growth in G20 countries for the period 1992-2022 using an econometric model based on the NARDL method. The outcome reveals significant asymmetries both in short and long run pattern in energy consumption and economic growth relations for G20 economies.

The Mean Group (MG) estimator, which emerged as the most suitable model based on the Hausman test, indicates that increased energy consumption and positive changes in energy consumption enable a greater growth effect than the growth reducing impact of reduced energy consumption. This asymmetry is consistent with previous findings, such as those summarized by Iwata et al. (2012), and extends our grasp of the energy-growth nexus within the context of advanced economies.

We believe that our study results explain the existing contradictory evidence on the relationship between several economic variables and economic growth in G20 economies. In his article, Apergis and Payne (2010) mention that government spending should rather have a discouraging on the growth performance of the economy, possibly due to the crowding out effect. Gross capital formation on the other hand did have a positive effect, reinforcing the need for investment in physical capital as a guarantee for economic growth of the G20 economies member countries.

The idea that growth in energy consumption may be the more robust driver of economic growth than other factors have policy relevance in that it is best to focus on finding energy-saving solutions rather than employing any form of energy-reduction strategy. Such a course of action is critical as otherwise there is the likelihood of developing policies which can stave off the anticipated energy contractions but the reality on the ground is that the output will be greatly reduced. This empirical result strongly underscores the importance of energy transition mechanisms that can facilitate the achievement of economic growth whilst promoting environmental sustainability.

Based on these findings, we propose the following Prioritized policy recommendations:

1. In the case of G20 nations, first Align Energy Transition with Asymmetries: Identify the Energy Transition Strategies to Realize Economic Development Which’s Impacts is Asymmetrical for Economic Growth. Which includes; a Gradual Adjustments of Energy Saving Policies: Its Phased Implementation Enables Ease In Change And Minimizing Any Adverse Economic Effect That Would Have Occurred. Determined Investment in energy efficiency: Focus on Methods That Would Realize Energy intakes but Do not compromise output productivity.
2. Energy source Diversification should be Addressed with emphasis on; Growing Renewable Energy Sources Expansion; To Diminish any Over Dependency on Fossil Fuels and also lessen whatever potential economy loss due to the reduction fossil energy. The Highlights and Impacts Of This Integrative Frame will be allotment of best practices and technology for better and seamless transition to sustainable energy worldwide.

Finally, there is more to the energy-growth nexus, especially in G20 countries as this study highlights the multifaceted aspects in energy and economic policies. Future studies could consider looking deeper into the country's differences causing these asymmetries and analyzing the various effects that the different energy transition policies have on economic growth and the environment in the long term.

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