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Does energy diversification cause an economic slowdown? Evidence from a newly constructed energy diversification index

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ABSTRACT

This study introduces a new measure of energy diversification. We explore it's impact on economic development across the panels of low-income, high-income, European Union (EU), the Organization for Economic Co-operation and Development (OECD), and G20 countries. The study uses data from 1995 to 2018 and utilizes Nonlinear Panel Autoregressive Distributed Lag (NPARDL) method. Our findings show that the major economies (including G20) realize positive economic growth with increasing long-run energy diversification. However, some countries (e.g., OECD and G20) experience negative economic growth due to energy diversification in the short term. The results also disclose that energy diversification does not favor economic growth in low-income economies, both short and long terms. Therefore, more precautionary measures should be taken while diversifying energy sources.

1. Introduction

Energy has been an important production input since the early 1850s, thanks to the industrial revolution. Energy has also been a significant factor in explaining economic growth, especially since the 1950s (Ellabban et al., 2014; Sadorsky, 2009a; Stern and Kander, 2012). However, each country uses different energy sources with a different share. This issue is tagged as the "energy mix." Energy diversification adds different energy sources into the energy mix (portfolio). In other words, it is defined as increasing the share of energy sources to lessen the dependence on a single energy source (Stirling, 2010). Energy concentration means that a country relies heavily on a single energy resource. The energy mix has different policy implications on climate change, economic performance, and the energy indicators, such as carbon intensity, energy efficiency, energy intensity, energy security, and energy transition (Rubio-Varas and Muñoz-Delgado, 2019; Vivoda, 2019).

Energy resources are not equally distributed around the world. Some countries have productivity and opportunity cost advantages in some forms of energy production (Muller and Yan, 2018). Ricardo's model of comparative advantage predicts that countries with different factors of production specialize in different economic activities following the relative productivity differences (Costinot and Donaldson, 2012). Therefore, the countries, which have a comparative advantage on energy products, should specialize in energy products in line with Ricardo's model of comparative advantage. These countries are expected to get higher welfare gains from international trade (i.e., exporting energy-based products), reaching higher economic growth rates. Several countries (e.g., Bahrain, Brunei Darussalam, Kuwait, Qatar, and Saudi Arabia) have experienced a strong economic performance by exporting energy-based products since the 1970s (Matallah, 2020). These economies have also been classified as "high-income economies" (the World Bank's definition) due to their strong economic performance exporting energy-based products.

However, things did not go well for all energy-exporting economies. Some countries with a large share of energy-based products in total merchandise exports (e.g., Algeria, Angola, Azerbaijan, Libya, Nigeria, and Venezuela) did not enjoy solid economic growth. In other words, their economic performances have been volatile (Kireyev, 2021). Over and above, some countries have faced unstable demand for energy, geopolitical concerns, uncertainties related to electricity, oil, and natural gas supplies (Cohen et al., 2011; Stirling, 1994). Therefore, it is observed that specialization in the specific energy-based product (even though there is a comparative advantage) does not guarantee that energy production is beneficial for economic growth.

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Various developed and developing economies have attempted to diversify their economic structure and energy sources at this stage. Diversification is crucial in creating a sustainable economy and economic growth and mitigating the negative effects of external shocks on economic performance (Can and Gozgor, 2018; Gozgor and Can, 2017; Kireyev, 2021; Mania and Rieber, 2019). Diversification promotes economic growth performance, decreasing output volatility (Mobarak, 2005). For instance, even Saudi Arabia announced an economic diversification program (Strategic Vision 2030) due to the rising energy prices and their effects on fiscal and financial uncertainty (Albassam, 2015). The economic aspect of this program targets to increase non-oil exporting to 50% of total exports by enhancing manufacturing equipment and ammunition (Matallah, 2020).

Energy diversification can be important in several aspects. Firstly, it promotes productivity by increasing the technology level. Energy still plays a significant role in economic activity (Känzig, 2021). However, technological change has been the dominant factor in driving economic growth since the 1990s (McMillan and Rodrik, 2011). Thanks to technological progress in energy production, various low-income and developing economies have attempted to diversify their energy sources from fossil fuels to renewables, especially since the 1990s (Gallagher, 2006). The recent studies (Paramati et al., 2021; Paramati et al. (2022); Shahbaz et al., 2019) also state that green technologies have played an important role in increasing energy efficiency and reducing carbon emissions. This issue is also in line with the historical developments. Many countries have enjoyed transforming from one energy source to another, e.g., from firewood to coal and coal to fossil fuels (Allen, 2012; Fouquet, 2016; Fouquet and Pearson, 2012; Rubio and Folchi, 2012). Therefore, the historical developments suggest that the transformation from fossil fuels to renewable energy can increase economic performance due to technological improvements.

Secondly, various countries have lacked significant fossil-fuel energy sources. Most developing and developed countries have negligible oil and natural gas reserves and production. These countries have to import energy-based products from the rest of the world to use them in the production process. However, energy prices have been highly volatile, especially since the 2000s (Ross, 2012). Therefore, the costs of energy imports can be changed year by year. This issue makes energy-importer countries fragile to uncertainty shocks related to energy prices, energy supplies, and geopolitical issues. Particularly, the concept of energy mix concentration instead of energy diversification is considered an early warning indicator of vulnerability (Rubio-Varas and Muñoz-Delgado, 2019).

On the other hand, the volatility of energy prices is also vital for energy exporters. It makes these countries vulnerable to uncertainty shocks related to energy markets (Adedoyin and Zakari, 2020). For example, most energy-exporter economies have favored the commodity price boom from 2002 to 2007 due to increasing global energy demand (especially from China and India). The oil prices hit the peak of US$147 per barrel in July 2008. However, it plunged to US$34 in December 2008 due to the Global Financial Crisis of 2008–9 (Ross, 2012).

Similarly, due to the uncertainty related to the COVID-19 pandemic, the Brent Crude fell below US$20 on April 21, 2020. The West Texas Intermediate (WTI) Crude futures contract declined to below $0 for the first time in history (Corbet et al., 2020). There are also significant fluctuations in other carbon-based energy prices, such as coal and natural gas. Overall, the energy-based products can lead to the terms-of-trade and uncertainty shocks, which harm the economic performance of all groups of countries, including developing and advanced countries, or energy-importers and energy-exporters.

Thirdly, energy diversification can alleviate the "resource curse" outcomes, such as the low quality of institutions due to the authoritarian regimes (Allcott and Keniston, 2018; Van der Ploeg, 2011; Venables, 2016). Energy diversification can also decrease domestic turmoil and geopolitical risks, including challenges to energy security (Sovacool, 2011; Vivoda, 2019). Energy diversification can also help mitigate the effect of uncertainties related to oil and gas supplies due to the decline of the conflicts. However, during the periods of structural changes in energy sources, countries (especially developing countries) can experience weaker economic performances due to structural and functional changes in their economic system (Rubio-Varas and Muñoz-Delgado, 2019).

Fourthly, energy diversification can mitigate the spillover impact of energy prices on food prices and decrease domestic conflicts and violence due to price spikes and volatility (Bellemare, 2015).

Finally, global warming due to greenhouse gas emissions is the main reason for climate change. Therefore, many countries are in the energy transition process, called the "low carbon energy system." Several papers have defined energy diversification as an important driver of de-carbonization and greenhouse gas reductions to achieve sustainable economic growth and slow down climate change (De Freitas and Kaneko, 2011; Pearson and Foxon, 2012). Energy diversification by raising the level of investments in renewables is expected to decrease greenhouse gas emissions from fossil fuels. Therefore, it will help slow down the negative outcomes of climate change and achieve sustainable economic growth.

Given these backdrops, this paper proposes a new measure of energy source diversification. Our measure is comparable across 64 countries, and it covers the period from 1995 to 2018. After defining this new measure, we analyze the impact of energy diversification on economic development across the panel datasets of low-income, high-income, EU, OECD, and G20 countries. Our main purpose of using different panels of sample countries is to investigate and understand the nexus between energy diversification and economic output.

The contributions of the paper are as follows. We introduce a novel measure of energy diversification. Previous papers have focused on the level of energy consumption or the sub-levels of different energy sources relative to total energy consumption (e.g., Yilanci et al., 2021). We introduce a comparable measure of the energy mix across countries at different income levels and the regions from 1995 to 2018. Therefore, it adds an important value to the empirical literature.

At this point, Rubio-Varas and Muñoz-Delgado's (2019) approach is the one that is close to our paper. The authors measure the concentration of energy mixes (so-called the Energy Mix Concentration Index-EMCI) for eight European countries. Then, they show that small economies experience quicker energy transitions in the long run. Using the same index (EMCI), Akrofi (2021) compares the energy diversification pattern in 10 African economies from 2000 to 2017.

Our analysis deviates from Rubio-Varas and Muñoz-Delgado (2019) and Akrofi (2021) and contributes to the current literature in various ways. First, we focus on 64 developing and developed countries in all regions rather than specific countries in one region, such as Africa or Europe. Second, we introduce a new measure of energy diversification and analyze its impact on economic development. Previous papers have only provided a comparative analysis of energy diversification across the countries over time. Third, we utilize various estimation procedures, including the NPARDL, to obtain both short-run and long-run effects of energy diversification on economic development. Understanding the short-run and long-run impacts of energy diversification on economic growth is crucial for policy design. It helps to see how the economic growth responds to the structural changes in the energy mix, i.e., from fossil fuel-based to renewable energy sources. It is important to note that the countries may experience a slowdown in their economic growth in the short run but will see the positive benefits of energy diversification in the long run.

At this juncture, our results indicate that energy diversification does not favor economic development in the short run. In other words, the reduction in energy diversification boosts economic activities in the low-income, the OECD, and the G20 countries in the short run. However, energy diversification has no negative consequences on economic development across the country groups, except for the low-income countries in the long run. Therefore, we suggest it is important to separate the effects of energy diversification in the short- and long runs.

The rest of this paper is organized as follows. Section 2 reviews the previous papers in the literature. Section 3 explains the index of energy consumption diversification, the empirical setup, the data, and the econometric methodology. Section 4 discusses the empirical results and provides the robustness checks with policy implications. Finally, Section 5 concludes the paper.

2. Literature review

Developing and developed economies use traditional energy sources, such as coal, crude oil, and petroleum, to achieve higher economic development. Still, this issue negatively affects both environment and human health. Therefore, countries at different income levels consider different restrictions on fossil fuel energy as there could be a trade-off between economic development and environmental degradation. However, environmental degradation significantly leads to climate change. It will also negatively affect economic growth in a specific region, such as Africa (Baarsch et al., 2020; Zakari and Khan, 2022). Therefore, policymakers seek alternative energy sources to mitigate CO_2 emissions. Given this backdrop, our paper proposes a new indicator of the energy mix, which is the index of energy sources diversification.

Many papers have investigated the relationship between alternative energy sources and economic development with time-series and panel datasets by utilizing different econometric techniques (e.g., Bhattacharya et al., 2017; Bhattacharya et al., 2016; Gozgor, 2018; Gozgor et al., 2018; Paramati et al., 2017, 2018; Yilanci et al., 2021). Previous papers have provided mixed empirical results, categorized into four main results: the conservation, the feedback, the growth, and the neutrality hypotheses (Apergis and Payne, 2010). The *conservation hypothesis* indicates a causality from economic growth to energy indicators. Regarding our case, countries will seek alternative energy sources when they grow. The *growth hypothesis* implies a positive relationship between energy indicators and economic growth. Therefore, alternative energy sources lead to higher economic growth, according to the growth hypothesis. At this stage, our paper tests the validity of the growth hypothesis for the effects of energy diversification on economic growth. The *feedback hypothesis* highlights an interrelationship between energy indicators and economic growth, meaning economic performance and alternative energy sources drive each other. Finally, the *neutrality hypothesis* proposes no significant causal relationship between economic growth and energy indicators. Therefore, alternating energy sources do not change economic performance and vice versa (Apergis and Payne, 2009). There is no consensus on which hypothesis is valid in which countries. The results depend on the choice of the econometric methodology and the sample. Meanwhile, this issue opens up space for new research work.

There are two additional hypotheses on the relationship between energy mix and economic performance: the energy ladder hypothesis and the Jevons' paradox (effect). The energy ladder hypothesis proposes that increased economic performance leads to higher energy source quality, promoting energy efficiency and environmental quality (Stern, 2010; Van der Kroon et al., 2013). Therefore, according to the energy ladder hypothesis, there is unidirectional and positive causality from economic performance (measured by per capita income) to increasing energy sources diversification over time. Countries diversify their energy mix with higher quality energy sources as they become richer. Environmental unfriendly energy sources (e.g., coal) will not remain in the energy portfolio (Rubio-Varas and Muñoz-Delgado, 2019).[1]

The validity of the energy ladder hypothesis has been empirically tested. For instance, Burke (2013) uses the panel data of 134 countries from 1960 to 2010. The author finds that economic development leads to a significant energy transmission from biomass to fossil fuels and then from fossil fuels to primary electricity. However, as discussed in the introduction, countries have different comparative advantages in energy sources, production costs, and energy consumption. Therefore, the relationship between energy diversification and economic performance can occur in different directions (i.e., from energy diversification to economic development) due to the energy supply and demand dynamics.

There is limited empirical evidence on energy source diversification. Most of the papers in the energy literature have provided anecdotal evidence on energy diversification (see, e.g., Templet, 1999). For instance, regarding empirical papers, Rubio-Varas and Muñoz-Delgado (2019) measure the energy mixes of France, Germany, Italy, the Netherlands, Portugal, Spain, Sweden, and the United Kingdom. The authors find that small economies (Portugal and Sweden) tend to experience quicker energy transitions from 1800 to the 2010s. This evidence is in line with the findings of previous papers by Henriques and Sharp (2016), Marcotullio and Schulz (2007), and Rubio and Folchi (2012), which find that large energy consumer economies have different dynamics from small energy consumers regarding the energy diversification and energy transition patterns.[2] At this stage, our methodology is closed to the approach of Rubio-Varas and Muñoz-Delgado (2019). Akrofi (2021) also uses the EMCI method of Rubio-Varas and Muñoz-Delgado (2019) and examines the energy diversification trends in Africa's top ten economies from 2000 to 2017. The author observes that Kenya and Morocco are the two most energy-diversified countries in the region.

It is also important to note that energy diversification may not promote economic performance according to Jevons' paradox (effect). According to the Jevons' paradox, technological progress or government policy increases energy source diversification. Still, it may reduce crucial energy sources (e.g., coal). Thus, economic performance will not increase due to decreasing demand for traditional energy sources. We expect the validity of the Jevons' paradox in the short run.

3. Data and methodology

3.1. The index of energy consumption diversification

The variety of energy sources has increased since the 1990s. However, this issue does not automatically imply that all the countries follow similar energy diversification patterns or use similar energy sources (Akrofi, 2021). Therefore, we introduce a comparable index to measure energy mixes (portfolio) and analyze the diversification pattern in different countries over decades. The energy portfolio diversification is expected to occur from traditional sources of energy (fossil fuels) to new sources of energy (renewables). Therefore, there is a feedback mechanism between transition in energy mixes and energy source diversification.

We calculate the index of energy source diversification for the countries using the Statistical Review of World Energy dataset of British Petroleum (2021) over 1995–2018. We follow the Herfindahl–Hirschman export market diversification index (World Bank, 2013: 26). Specifically, we adopt and calculate the Herfindahl–Hirschman to the energy diversification index, as such:

[1] However, the “energy stacking” hypothesis proposed by Masera et al. (2000) suggests that environment unfriendly energy sources (e.g., coal) will not completely disappear. They will remain with an insignificant share in the energy mix.

[2] Marcotullio and Schulz (2007) focus on the United States and 28 developing and developed countries. Rubio and Folchi (2012) focus on the data from 20 Latin American countries. Henriques and Sharp (2016) use the data from Denmark. These papers demonstrate a quicker transition of energy sources in the small energy consumer economies.

$$\frac{\sum_{j=1}^{n_i}\left(\frac{x_{it}}{X_{it}}\right)^2 - \frac{1}{n_i}}{1-\frac{1}{n_i}} \quad (1)$$

In Eq. (1), X_{it} is the total primary energy consumption (million tons oil equivalent) in country i in time t, x_{it} is the energy consumption from different energy sources (coal, hydroelectric, natural gas, nuclear energy, oil, and renewable) in country i in time t, and n_i is the number of energy sources in country i. Note that if a country consumes energy from only a single source (i.e., $n_i = 1$, and there is a full energy concentration and no diversification), we will not be able to calculate the index. The value of "0" means that a country's primary energy consumption is equally diversified among the related six energy sources.

Therefore, our energy diversification index can measure whether the energy portfolios of different countries have become more diversified or not. Besides, we can measure whether some countries followed similar diversification patterns or not. We can also compare the energy diversification levels and analyze whether they converge across different periods. Our index also helps us determine the starting date of the energy diversification process and compare them across different countries.

3.2. Empirical model setup

We then focus on the classical growth models, such as the Solow growth model, which indicates capital and labor are the main determinants of economic growth (see, e.g., Romer, 1990):

$$Y = f(K, L) \quad (2)$$

Where Y is the economic growth, K is capital, and L is labor. Then, following the endogenous growth models, we include the role of economic openness or globalization (GLB)[3] (see, e.g., Grossman and Helpman, 2015):

$$Y = f(K, L, GLB) \quad (3)$$

We extend the growth model in Eq. (3) by including the energy diversification (ED), and our new model can be written as follows:

$$Y = f(K, L, GLB, ED) \quad (4)$$

We estimate this model via various estimation techniques, and the estimated model in logarithmic form can be written for panel datasets, as such:

$$lnY_{it} = a_0 + a_1 lnK_{it} + a_2 lnL_{it} + a_3 lnGLB_{it} + a_4 lnED_{it} + \varepsilon_{it} \quad (5)$$

Y_{it} is the economic growth $K_{it}$is the capital, $L_{it}$is the labor, $GLB_{it}$is the globalization, $ED_{it}$is the energy diversification, i indicates country, t indicates the time, and$\varepsilon_{it}$is the error term.

We also estimate the following model with the NPARDL estimation technique to analyze the asymmetric effects of energy diversification on economic growth both in the short-run and long-run:

$$\Delta GDP_{i,t} = \beta_0 + \beta_1 X_{i,t} + \beta_2 ECT_{i,t} + \rho GDP_{i,t-1} + \theta^+ ED^+_{i,t-1} + \theta^- ED^-_{i,t-1} + \sum_{i=1}^{p-1}\varphi_i \Delta GDP_{i,t-k} + \sum_{i=0}^{q}\pi_i^+ \Delta ED^+_{i,t-k} + \sum_{i=0}^{q}\pi_i^- \Delta ED^-_{i,t-k} + \mu_{i,t} \quad (6)$$

In Eq. (6),$\Delta GDP_{i,\ t}$ is the economic growth, $X_{i,\ t}$represents the control variables, $ECT_{i,\ t}$ is the error correction term, $GDP_{i,\ t-1}$ is the long-run asymmetric impact, ${ED_{i,\ t-1}}^+$ is the long-run positive impact of energy diversification, ${ED_{i,\ t-1}}^-$ is the long-run negative impact of energy diversification, $\Delta GDP_{i,\ t-k}$ is the short-run asymmetric impact,${\Delta ED_{i,\ t-k}}^+$ is the short-run positive impact of energy diversification, ${\Delta ED_{i,\ t-k}}^-$ is the short-run negative impact of energy diversification. $\mu_{i,\ t}$ represents the error term.

3.3. Data

Economic growth is measured by the gross domestic product (GDP) and per capita GDP with the constant 2010 US$ prices. Capital is measured by gross capital formation (constant 2010 US$), and labor is the total labor force. These data are obtained from the World Development Indicators of the World Bank (2022). We consider the KOF Overall Globalization index, and the related data are obtained from Gygli et al. (2019). Finally, as discussed in Section 3.1., we calculate the index of energy diversification, and the related data are obtained from the energy consumption series of British Petroleum (2021).

Our sample coverage is from 1995 to 2018 and 64 countries. The selected sample countries come from different income groups and regions, such as the low-income, high-income, EU, OECD member, and G20 countries. The list of countries in the sample is provided in Appendix I. All the variables are expressed in natural logarithms, as recommended by previous studies (Paramati et al., 2016; Paramati et al., 2017).

3.4. Econometric methodology

We utilize various panel data estimation techniques to obtain the short-run and long-run parameters. First, we use the Pooled Ordinary Least Squares (POLS), the Panel Fully Modified Ordinary Least Squares (PFMOLS), and the Panel Dynamic Ordinary Least Squares (PDOLS) approaches. The PFMOLS and the PDOLS methods are more robust than the POLS since the findings of the POLS can be biased due to its endogenous estimation procedure (Liddle, 2012).

The PFMOLS estimator, proposed by Pedroni (2001a) and Phillips and Moon (1999), provides unbiased evidence since there are normally distributed asymptotic standard errors. This issue provides elastic and efficient long-run parameters. Phillips and Hansen (1990) also show that the semi-parametric correction of the FMOLS can solve the potential problems of endogeneity and residual autocorrelation. However, we should consider the PFMOLS method when all indictors are cointegrated in the model (Pedroni, 2001b). The PFMOLS technique is based on the group mean or the between-group estimator. It allows for high heterogeneity in the panel datasets (Gozgor et al., 2020).

Similarly, the PDOLS estimator, proposed by Mark and Sul (2003) and Pedroni (2001b), is also a fully parametric method. It is an alternative technique to the PFMOLS estimator. According to Kao and Chiang (2001), the small-sample performance of the PDOLS is significantly better than the PFMOLS. Therefore, we also consider the PDOLS for removing possible finite sample bias in the estimations.

Second, we utilize the Augmented Mean Group (AMG) estimator

[3] We use overall globalization index to capture economic openness, which helps to mobilize technology from one country to the other.

proposed by Eberhardt and Teal (2010) and Eberhardt (2012) as an alternative to Pesaran's (2006) Common Correlated Effects Mean Group (CCEMG) estimator. Eberhardt and Bond (2009) show that the AMG is flexible with nonstationary variables (cointegrated or not). It can be used in the case of cross-sectional dependence. Therefore, it is a useful estimator and considered in the empirical energy economics literature (see, e.g., Sadorsky, 2013, 2014).

Third, we consider the NPARDL estimation technique proposed by Shin et al. (2014) to model the potential asymmetric impact of energy diversification on economic development in the short-run and long-run. The asymmetric effects and other nonlinear effects are common in the energy economics literature. For instance, Hamilton (2009) shows that a rise (positive impact) in oil prices has stronger effects on economic growth than a decrease (negative impact). At this stage, asymmetry is the key issue in analyzing the short-run and the long-run effects of energy indicators on economic performance. We adapt these issues on the effects of energy diversification on economic development.

4. Empirical analyzes and discussion

4.1. Preliminary investigation

Our analysis starts with unconditional correlations among the variables.[4] Table 1 reports that the economic growth (GDP) is positively correlated with gross capital formation (GFC), the labor force (LF), and globalization (GLB) indicators. These relationships remain consistent across the panels of the full sample, low-income, high-income, EU, OECD, and G20 groups. Economic growth is highly positively correlated with gross capital formation and labor force among these indicators. Further, among these nations, economic growth had a higher positive correlation with globalization in the EU, the high-income, and the G20 nations. Our preliminary statistics also show that economic growth is negatively correlated with the energy diversification (ED) indicator across all groups of nations. Their negative nexus is more in the G20 and the high-income nations. In contrast, their lowest negative relationship is found in the low-income economies. Overall, these preliminary statistics suggest that higher energy diversification is negatively associated with economic growth. In contrast, the rest of the indicators play an important role in the growth story of those economies.

4.2. Baseline results

Our main objective in this paper is to empirically explore the impact of energy diversification on economic growth by controlling various factors, including traditional and modern factors that have a considerable role in the growth story of the nations around the world. In doing so, we start our empirical investigation by applying the POLS, PDOLS, PFMOLS, and AMG estimators. The results of all these techniques are presented in Table 2.

The findings from the POLS show that energy diversification has a significant negative impact on the economic growth of full sample, low-income, and G20 nations. However, energy diversification from fossil fuels to renewable energy sources has no negative impact in the panels of high-income, EU, and OECD economies. It suggests that the energy transition towards a greener economy favors sustainable economic development in these economies. As expected, both capital and labor forces play an important role in driving economic growth across these panels. It is important to note that the major developed economies (the EU, the OECD, and the high-income countries) have enjoyed the fruits of globalization much more than those of the low-income economies.[5]

The above results provide an overview of the relationship among the dependent and independent variables without addressing several issues that need to be handled to obtain reliable inferences. We again estimate this model for all countries' panels using the PDOLS and the PFMOLS methods. The main advantage of these techniques is that the PDOLS method uses both leads and lags to address endogeneity and serial correlation issues in the model. In contrast, the PFMOLS method uses a non-parametric approach to address the same issues.[6] Therefore, these two methods provide more reliable results by addressing endogeneity and serial correlation issues in the model. The results of the PDOLS (see Table 2) suggest that the impact of energy diversification is against the economic development in the full sample, high-income, OECD, and G20 nations. In contrast, the results do not cross the statistical barriers in two other groups (low-income and EU).

The results from the PFMOLS also suggest that energy diversification has a substantial negative impact on economic growth of high-income, EU, and OECD economies. In contrast, it has a substantial positive impact on growth in low-income economies. As expected, rest of the control variables are found mostly significant and have a substantial positive impact on growth. As noted previously, the impact of globalization on economic growth is more in high-income and developed countries (e.g., EU and OECD).

We also use another alternative technique, namely the AMG, to account for cross-sectional dependence in the model. The recent literature has also paid serious attention to this issue (see, e.g., Sadorsky, 2013, 2014; Paramati and Roca, 2019). Therefore, we utilize the AMG method to investigate the research objective of our study. The results show that only one coefficient of energy diversification is statistically significant, confirming that the energy diversification has no negative effect on growth in the full sample. Other variables are mostly consistent with the expected signs, except globalization in the low-income economies.

4.3. Main results

Since above results overall offer mixed evidence in terms of the impact of energy diversification on economic growth across the methods. These contradicting results might have arrived because there may be a nonlinear relationship between energy diversification and economic growth. This argument is supported by the fact that countries around the globe have made considerable efforts to transit from fossil fuel energy-based to more renewable energy sources in the last two decades. Due to internal and external factors, both economic growth and energy diversification have experienced considerable nonlinearity in this transition journey. Given that, to address the nonlinearity in the model, we use the NPARDL method. The results are displayed in Table 3.

The long-run results confirm that an increase in energy diversification has a significant positive impact on economic growth of full sample, high-income, EU, OECD, and G20 nations. Specifically, the degree of impact from energy diversification to economic growth varies from 0.115% to 0.376%. However, the decreasing trend of energy diversification seems to hurt economic progress, by −0.193%, of the full sample countries; but it has no negative impact on high-income economies. As documented previously, the impact of globalization on economic growth is more in developed (including the G20 group) economies than those of low-income economies. This evidence again confirms that globalization

[4] We provided summary statistics in Appendix II.

[5] We also present the results using fixed effect method by clustering standard errors at the country level in Appendix III. The results display that energy diversification is not in favor of economic development. However, capital formation, labor force and globalization continue to drive economic performance across all the sub-sample analyses.

[6] See Sadorsky (2009b, 2011) for more details.

Table 1
Unconditional correlations among the variables across the country groups.

	GDP	GCF	LF	GLB	ED	GDP	GCF	LF	GLB	ED	GDP	GCF	LF	GLB	ED
	Full Sample					Low-income Economies					High-income Economies				
GDP	1.000					1.000					1.000				
GCF	0.985	1.000				0.965	1.000				0.993	1.000			
LF	0.724	0.723	1.000			0.809	0.797	1.000			0.930	0.926	1.000		
GLB	0.253	0.243	−0.351	1.000		0.196	0.199	−0.128	1.000		0.346	0.337	0.110	1.000	
ED	−0.259	−0.237	−0.060	−0.385	1.000	−0.066	−0.006	0.016	−0.405	1.000	−0.316	−0.320	−0.356	−0.184	1.000
	EU					OECD					G20				
GDP	1.000					1.000					1.000				
GCF	0.985	1.000				0.993	1.000				0.973	1.000			
LF	0.883	0.864	1.000			0.921	0.917	1.000			0.518	0.585	1.000		
GLB	0.560	0.576	0.252	1.000		0.253	0.245	−0.018	1.000		0.376	0.297	−0.465	1.000	
ED	−0.218	−0.231	−0.312	−0.168	1.000	−0.209	−0.219	−0.225	−0.234	1.000	−0.403	−0.330	0.267	−0.666	1.000

Notes: GDP = gross domestic product, GCF = gross capital formation, LF = labor force, T = globalization, ED = energy diversification index.

Table 2
Results of the POLS, the PDOLS, the PFMOLS, and the AMG estimations.

Variable	Full Sample		Low-income		High-income		EU		OECD		G20	
	Coef.	Prob.	Coef.	Prob.	Coef.	Prob.	Coef.	Prob.	Coef.	Prob.	Coef.	Prob.
POLS												
GCF	0.868***	0.000	0.785***	0.000	0.839***	0.000	0.766***	0.000	0.843***	0.000	0.809***	0.000
LF	0.092***	0.000	0.130***	0.000	0.162***	0.000	0.246***	0.000	0.160***	0.000	0.053***	0.007
GLB	0.482***	0.000	0.149*	0.099	0.743***	0.000	0.953***	0.000	0.804***	0.000	0.593***	0.000
ED	−0.045***	0.000	−0.133***	0.000	0.042***	0.000	0.095***	0.000	0.077***	0.000	−0.129***	0.000
Constant	0.823***	0.000	3.213***	0.000	−0.354	0.197	−0.760	0.113	−0.748***	0.007	1.585***	0.001
R-squared	0.972		0.940		0.989		0.977		0.989		0.956	
PDOLS												
GCF	0.351***	0.000	0.441***	0.000	0.290***	0.000	0.293***	0.000	0.271***	0.000	0.376***	0.000
LF	0.182	0.147	−0.156	0.433	0.413**	0.011	0.271	0.225	0.372**	0.026	−0.115	0.484
GLB	1.033***	0.000	0.481***	0.000	1.410***	0.000	1.866***	0.000	1.546***	0.000	0.774***	0.000
ED	−0.081*	0.084	0.054	0.395	−0.173***	0.009	−0.120	0.158	−0.117**	0.013	−0.187**	0.014
PFMOLS												
GCF	0.297***	0.000	0.381***	0.000	0.240***	0.000	0.255***	0.000	0.243***	0.000	0.335***	0.000
LF	0.830***	0.000	0.787***	0.000	0.859***	0.000	0.702***	0.000	0.827***	0.000	0.858***	0.000
GLB	0.752***	0.000	0.452***	0.000	0.957***	0.000	1.154***	0.000	1.052***	0.000	0.402***	0.000
ED	−0.022	0.163	0.075**	0.021	−0.089***	0.000	−0.048***	0.007	−0.077***	0.000	−0.022	0.483
AMG												
GCF	0.219***	0.000	0.192***	0.000	0.178***	0.000	0.122***	0.000	0.186***	0.000	0.282***	0.000
LF	0.149	0.237	0.539**	0.035	0.218*	0.058	0.070	0.690	0.191	0.105	0.086	0.687
GLB	−0.111	0.270	−0.220**	0.045	−0.124	0.200	0.038	0.829	−0.027	0.791	−0.040	0.808
ED	0.068**	0.018	0.037	0.375	0.008	0.784	−0.001	0.989	−0.004	0.864	0.074	0.224
Constant	9.454***	0.000	8.684***	0.000	10.642***	0.000	10.596***	0.000	10.328***	0.000	9.655***	0.000
Wald Chi^2	180.000***	0.000	54.480***	0.000	118.880***	0.000	27.470***	0.000	134.140***	0.000	97.200***	0.000

Note: The dependent variable is the log GDP. *** $p < 0.01$, ** $p < 0.05$ & * $p < 0.10$.

has benefited the developed economies more than the underdeveloped nations.

Our short-run estimates provide very interesting results. Specifically, our results show that the increasing trend of energy diversification has a substantial negative impact on economic growth in the panels of OECD (−0.037%) and G20 nations (−0.087%). At the same time, the negative trend of energy diversification seems to work in favor of economic growth in the samples of low-income (0.069%), OECD (0.034%), and G20 nations (0.049%). As expected, the short-run error correction (EC) term is negative and statistically significant for all the models. This evidence establishes that if the long-run equilibrium deviates in the short-run, then the disequilibrium could be corrected by 6% to 11% each year. The main takeaway knowledge from the analysis of the NPARDL method is that the countries (e.g., OECD and G20) usually experience negative economic growth when they begin to transit from fossil fuel to renewable energy in the short run. At the same time, if countries experience a slow down or a negative trend in energy diversification in the short run due to internal and external factors, it will again boost economic growth in countries, such as the low-income, OECD, and G20 groups. The results also confirm significant long-run and short-run asymmetric impacts across the panels, which establishes that the positive and the negative trends of energy diversification have varying roles on economic growth of the selected panels of the study.

Further, we replace the GDP with the GDP per capita as a dependent variable for the robustness check. We then re-estimate the models using the NPARDL method. The results are presented in Table 4.

The findings reveal that the increasing energy diversification, in the long run, has a significant positive impact on promoting economic development of major economies. However, energy diversification adversely affects economic growth in low-income countries. Interestingly, the negative trend of energy diversification has a substantial negative impact on economic growth in the long run. This evidence

Table 3
Main investigation: results of the NPARDL method.

	Full sample		Low-income		High-income		EU		OECD		G20	
	Coef.	P > z	Coef.	P > z	Coef.	P > z	Coef.	P > z	Coef.	P > z	Coef.	P > z
Long-run Estimates												
CAP	0.459***	0.000	0.664***	0.000	0.494***	0.000	0.536***	0.000	0.553***	0.000	0.607***	0.000
LF	−0.079*	0.095	−0.098	0.268	0.484***	0.000	0.050	0.521	0.033	0.676	−0.659***	0.000
GLB	0.040	0.485	0.511***	0.000	0.999***	0.000	0.766***	0.000	0.749***	0.000	1.015***	0.000
ED_pos	0.376***	0.000	−0.051	0.604	0.115***	0.000	0.177***	0.000	0.176***	0.000	0.286***	0.000
ED_neg	−0.193***	0.000	0.003	0.962	0.070***	0.001	−0.017	0.563	−0.026	0.355	−0.046	0.270
Short-run Estimates												
ect	−0.098***	0.000	−0.063***	0.000	−0.111***	0.000	−0.112***	0.000	−0.096***	0.000	−0.065***	0.003
ΔCAP	0.155***	0.000	0.146***	0.000	0.164***	0.000	0.167***	0.000	0.173***	0.000	0.197***	0.000
ΔLF	0.105	0.325	0.122	0.207	0.064	0.432	0.113	0.310	0.080	0.365	0.140	0.190
ΔGLB	0.030	0.466	−0.057	0.249	0.086*	0.082	0.107	0.107	0.091	0.121	−0.031	0.745
ΔED_pos	−0.012	0.710	−0.029	0.256	0.046	0.394	0.019	0.652	−0.037**	0.024	−0.087***	0.000
ΔED_neg	0.040	0.140	0.069***	0.008	−0.008	0.829	−0.027	0.633	0.034*	0.077	0.049*	0.067
Constant	0.716***	0.000	0.242***	0.000	0.231***	0.000	0.348***	0.000	0.310***	0.000	0.339***	0.003
Long-run and Short-run Asymmetric Impacts												
Long-run Asymmetric Impact	383.670***	0.000	0.410	0.524	6.600***	0.010	40.190***	0.000	42.170***	0.000	41.690***	0.000
Short-run Asymmetric Impact	1.070	0.300	7.020***	0.008	0.460	0.498	0.240	0.626	8.240***	0.004	12.770***	0.000
Number of Observations	1472		598		874		621		828		391	
Number of Groups (Countries)	64		26		38		27		36		17	

Note: The dependent variable is the log GDP. *** $p < 0.01$, **$p < 0.05$ & * $p < 0.10$.

Table 4
Robustness checks: NPARDL method (GDP per Capita).

	Full sample		Low-income		High-income		EU		OECD		G20	
	Coef.	P > z	Coef.	P > z	Coef.	P > z	Coef.	P > z	Coef.	P > z	Coef.	P > z
Long-run Estimates												
CAP	0.465***	0.000	0.634***	0.000	0.562***	0.000	0.516***	0.000	0.559***	0.000	0.583***	0.000
LF	−0.866***	0.000	−0.592***	0.000	−1.549***	0.000	−1.547***	0.000	−1.488***	0.000	−1.388***	0.000
GLB	0.129**	0.037	0.637***	0.000	0.190	0.249	0.266	0.116	0.220	0.178	1.006***	0.000
ED_pos	0.264***	0.000	−0.176*	0.063	0.230***	0.000	0.200***	0.000	0.230***	0.000	0.304***	0.000
ED_neg	−0.242***	0.000	−0.002	0.966	−0.179***	0.000	−0.173***	0.000	−0.167***	0.000	−0.017	0.663
Short-run Estimates												
ect	−0.087***	0.000	−0.069***	0.000	−0.072***	0.000	−0.097***	0.000	−0.076***	0.000	−0.077***	0.001
ΔCAP	0.161***	0.000	0.146***	0.000	0.174***	0.000	0.171***	0.000	0.180***	0.000	0.197***	0.000
ΔLF	0.049	0.584	0.221	0.246	0.108	0.245	0.170	0.147	0.131	0.149	0.080	0.554
ΔGLB	0.049	0.247	−0.081	0.116	0.134**	0.021	0.137**	0.031	0.126**	0.040	−0.038	0.694
ΔED_pos	0.000	0.993	−0.037	0.201	0.051	0.372	0.041	0.341	−0.030*	0.099	−0.087***	0.001
ΔED_neg	0.046*	0.099	0.090***	0.005	−0.006	0.884	−0.017	0.744	0.035*	0.056	0.054*	0.089
Constant	0.498***	0.000	0.069***	0.000	0.404***	0.000	0.548***	0.000	0.411***	0.000	0.279***	0.001
Long-run and Short-run Asymmetric Impacts												
Long-run Asymmetric Impact	375.520***	0.000	4.560**	0.033	75.920***	0.000	78.980***	0.000	75.330***	0.000	31.140***	0.000
Short-run Asymmetric Impact	0.700	0.404	6.750***	0.009	0.460	0.498	0.400	0.525	5.790**	0.016	7.540***	0.006
Number of Observations	1472		598		874		621		828		391	
Number of Groups (Countries)	64		26		38		27		36		17	

Note: The dependent variable is the log GDP per capita. *** $p < 0.01$, **$p < 0.05$ & * $p < 0.10$.

suggests that once countries transform from fossil fuels to renewable energy, they will not return to fossil fuels. As reported previously, energy diversification works against economic development in the short term, but reducing energy diversification boosts economic growth. The other results remain mostly consistent with the previous estimates.

4.4. Policy implications

Our analysis provides very interesting results and offers important policy implications. Specifically, our results suggested that energy diversification promotes economic growth of major economies in the long run. At the same time, energy diversification is not in favor of economic development, particularly in low-income countries, where over 90% of energy is sourced from fossil fuels. Our estimates also revealed that energy diversification in the short-run works against economic development even in major developed economies of the world. It is also discovered that any reduction in energy diversification in the short run boosts economic development across most groups of countries. These findings have very important practical and policy implications.

The above results can be argued as follows: For instance, in the short-run, when countries begin to transit from fossil fuel energy to renewable energy, then their economies may realize the economic slowdown; however, if the energy diversification continues from short-run to the long-run then the major economies likely to realize positive economic performance. Given that, we argue that most developed and major economies of the world have already crossed the transition period in energy and have begun to realize the potential benefits of energy diversification. On the other hand, the story is completely different in low-income countries. These countries are still trapped with conventional energy sources. They lack the support and enthusiasm to devote significant financial resources to diversify their energy sources. Consequently, the energy diversification in this group of nations is yet seen as a positive driver of economic growth.

Given that discussion, we suggest that the policymakers of developing economies, particularly low-income ones, need to improve their efforts to diversify their energy sources from fossil fuel to renewable energy sources to realize sustainable economic development. At the same time, global organizations, such as the United Nations (UN) and the World Bank, should provide required financial support and technical skills to these nations to improve the alternative energy sources. Furthermore, the developed nations should also assist the low-income economies financially and technically to improve renewable energy share in their total energy-mix. In such a way, not only does one part of the globe (mostly the Western part) improves their quality of life by moving from conventional energy sources to renewable energy, but other regions will catch up shortly if these Western countries support the low-income countries. However, it is critical to understand that climate change and greenhouse gases are not region-specific. They are rather global issues (Tawiah et al., 2021). Therefore, the combined efforts and cooperation among all the nations are the only ways to tackle such global issues.

5. Conclusion

This paper examined the effect of energy diversification on economic performance across the panel datasets of low-income, high-income, EU, OECD, and G20 countries from 1995 to 2018. For this purpose, we use the annual energy consumption data to introduce a new measure of energy source diversification. The NPARDL estimation results show that energy diversification does not promote economic performance in the short-run, particularly in the OECD and the G20 countries. Nevertheless, the short-run reduction in energy diversification boosts the economic activities in low-income, OECD, and G20 countries. However, in the long-term, energy diversification has no negative impact on economic performance across the country groups, except in the low-income economies.

Given this evidence, we argue that energy diversification works against economic development only in the short term. Still, once the countries cross a threshold point in their energy transition period, they begin to realize the positive impact of energy diversification on their economic output. However, the transition is tricky in developing, or low-income countries as these countries are trapped with mostly conventional energy sources, which roughly contribute 90% of their total energy. Consequently, the energy transition is very slow, harming economic prosperity and development. However, the transition can be quicker in these countries if the world-leading organizations (such as the UN and the World Bank) and developed economies (e.g., the US and EU) provide technical and financial support to improve their renewable energy accessibility. We suggest that technological innovation and financing renewable energy may help diversify energy. Hence, the increasing energy diversification, from conventional to renewable energy, improves economic development and alleviates overall environmental and public health, which is crucial in achieving the UN's sustainable development goals.

This study contributes to the related literature by providing a new measure of the energy diversification index, which helps to investigate its role in economic development across regions and countries. However, our findings are limited to the panel datasets. Given that our energy diversification measure data started in 1965, future studies can use our new measurement and focus on the individual economies (e.g., BRICS economies) using time-series techniques or regional studies. Further research can also be carried out by investigating the determinants of energy diversification. Energy diversification can be an irreversible process, and which might be influenced by several factors such as economic structure, energy prices, exchange rates, financial development, foreign direct investments, human capital, infrastructure (physical capital), institutional quality, international trade (especially quality of exporting products), macroeconomic stability, market regulations, and technological innovations. Therefore, our study opens a new discussion in the energy-growth literature that requires future studies to explore and provide detailed implications for the policy and practice.

CRediT authorship contribution statement

Giray Gozgor: Writing - original draft; Writing - review & editing; Data curation; Methodology. **Sudharshan Reddy Paramati**: Conceptualization; Data curation; Formal analysis; Investigation; Writing - original draft.

Appendix I. Countries in the sample

Algeria, Argentina, Australia, Austria, Bangladesh, Belarus, Belgium, Brazil, Bulgaria, Canada, Chile, China, Colombia, Croatia, Cyprus, the Czech Republic, Denmark, Ecuador, Egypt, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, India, Iran, Ireland, Israel, Italy, Japan, Kazakhstan, Korea Republic, Latvia, Lithuania, Luxembourg, Malaysia, Mexico, Morocco, Netherlands, New Zealand, Norway, Pakistan, Peru, Philippines, Poland, Portugal, Romania, Russia, Singapore, Slovakia, Slovenia, South Africa, Spain, Sri Lanka, Sweden, Switzerland, Thailand, Turkey, Ukraine, the United Kingdom, the United States, and Vietnam.

Appendix II. Summary statistics of the full panel data set

Variable	Mean	Std. Dev.	Min	Max	Observations
GDP	878,264.00	2,056,881.00	8150.52	17,913,249.00	1536
GCF	213,428.90	518,823.60	269.49	4,883,806.00	1536
LF	37.29	107.71	0.15	784.95	1536
GLB	71.21	12.74	32.40	90.98	1536
ED	27.14	16.77	4.98	98.58	1536

Note: GDP, GCF and LF are in millions.

Appendix III. Results of Fixed Effect method by clustering standard errors at the country level

Variable	Full Sample		Low-income		High-income		EU		OECD		G20	
	Coef.	Prob.	Coef.	Prob.	Coef.	Prob.	Coef.	Prob.	Coef.	Prob.	Coef.	Prob.
Fixed effect method												
GCF	0.316***	0.000	0.298***	0.008	0.348***	0.000	0.207**	0.047	0.347***	0.000	0.590***	0.000
LF	0.556***	0.000	0.452**	0.011	0.657***	0.000	0.647***	0.001	0.539***	0.000	0.044	0.818
GLB	0.898***	0.000	0.900***	0.002	1.038***	0.000	1.370***	0.000	1.201***	0.000	0.492*	0.052
ED	−0.157***	0.000	−0.213***	0.003	−0.095**	0.043	−0.082	0.200	−0.078*	0.063	−0.218**	0.018
Constant	4.432***	0.000	4.649***	0.000	3.436***	0.000	3.352***	0.005	2.887***	0.000	5.140***	0.000

Note: The dependent variable is the log GDP. *** $p < 0.01$, **$p < 0.05$ & * $p < 0.10$.

Appendix I. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eneco.2022.105970.

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