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SHORT RESEARCH AND DISCUSSION ARTICLE

Nuclear energy consumption and energy-driven growth nexus: a system GMM analysis of 27 nuclear utilizing countries across the globe

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Abstract
While the general environmental quality level continues to decline in today's global economy, aggregate energy consumption levels are often linked to countries' economic growth and environmental performances, thereby overlooking the specific roles of individual energy types. Thus, this study focuses on examining nuclear energy consumption-growth nexus in 27 selected nuclear energy–consuming countries across the globe. The system GMM estimator was applied to available post-2008 global financial crisis data spanning from 2010 to 2020 while accounting for influential factor inputs (labor and capital) within the framework of the traditional growth model. The results posit that both capital and labor significantly induce economic growth levels among the countries, while nuclear energy consumption is not a significant driver of growth levels despite some evidence of its positive roles. Hence, more investments in nuclear energy production are recommended to trigger an overall consumption level that will not only yield significant desirable economic growth impacts among the countries but also enhance possible environmental benefits in contrast to the growing environmentally detrimental fossil energy consumption among the countries.

Keywords Energy consumption · Nuclear energy · Economic growth · System GMM · Environmental sustainability

JEL Classification Q43 · F43 · C50 · B40

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Introduction

Achieving sustainable economic growth and development is a factor directly related to the availability of energy resources in countries since the expansion in production activities in countries increases their energy needs. For this reason, it is inevitable for economies that want to achieve high growth rates and ensure the continuity of investments to not only increase energy generation but also increase the diversity of the energy resources used. Doing this has been noted to be a right step toward reducing the fragility of economies against the backlash of foreign energy dependency, energy poverty, and general lack of energy accessibility (González-Eguino 2015; Sovacool and Drupady 2016; Erdoğan et al. 2021).

Energy is important for the development of countries, and the need to increase energy production is often a natural phenomenon. As energy supply shortage occurs over time with price volatilities amidst rising environmental challenges, it is important to create an alternative energy sector and take steps to ensure diversity in energy portfolios, use new innovative technologies and alternative energy sources, and establish new energy production facilities (Shan et al. 2021; Alola and Onifade 2022; Fareed et al. 2022; Bekun et al. 2022; Onifade and Alola 2022). Thus, achieving a sufficient and steady increase in energy supply has become a major priority for both developed and developing countries. At this point, nuclear power plants appear as an effort to meet this goal. After the oil and gas energy crisis in the 1970s, countries that were dependent on foreign energy gradually started exploring possible nuclear energy alternatives (Ağbulut et al. 2021; Hultman 2011). Besides, there has been an increasingly growing demand to boost alternative energy sources given that the popular fossil energy consumption is often linked to rising CO_2 emissions among other environmentally detrimental greenhouse gas (GHG) emissions (Ozturk 2017; Gyamfi 2022; Adebayo et al. 2022a, b; Onifade et al. 2022; Apergis and Payne 2014; Gyamfi et al. 2022).

Economic growth in a generally accepted and simple definition can be seen as an increase in real gross national product. Theoretically, it is the formation of a development process to the right in the production possibilities curve (Savosnick, 1958). Growth can also be seen as the increase in the economic values of many production factors such as labor, capital, and natural resources, which allows for obtaining higher real income from one year to the next. Therefore, growth has a complex structure that cannot be explained by a single factor of production. As such, studies dealing with the factors affecting economic growth in various regions of the world have repleted the general macroeconomics literature (Ding and Knight 2009; Çevik et al. 2020; Hakan et al. 2022; Taiwo et al. 2020; Asongu et al. 2020).

The traditional growth literature has been dominated by several growth-inducing factors especially labor and capital in some of the earliest growth models (Solow 1956), and other factors like foreign direct investments (Çoban et al. 2020) and demographic issues like population and human capital among other factors (Brock and Taylor 2010; Pelinescu 2015). However, in recent times, many studies have identified the immense contribution of energy use to economic growth and this discussion keeps growing by the day (Erdoğan et al. 2022; Onifade et al. 2021; Gyamfi et al. 2021a; Onifade 2022).

In today's global economy, energy consumption is often linked to economic growth among nations. However, this link is mostly built on countries' aggregated energy consumption profiles, whereas it is important to also examine the disaggregated roles of various energy types on growth. Besides, most studies on the energy use growth nexus mainly focus on the role of fossil fuels energy consumption being the dominant energy source in the global economy (Apergis and Payne, 2017, 2014; Dogan and Inglesi-Lotz 2020; Adebayo 2022a, b; Gyamfi et al. 2021b; Akadiri et al. 2022) with just a handful of studies that have addressed the aspect of nuclear energy utilization (Ozturk 2017; Ozcan and Ari 2015; Gyamfi et al. 2021a, b, c; Piłatowska et al. 2020; Kirikkaleli et al. 2020). Meanwhile, examining the nuclear components provides more insights into the energy consumption discussion not only on the economic perspectives alone but also on some environmental implications as energy demand rises among countries. As such, in this study, we attempt to examine the specific role of nuclear energy in the energy-driven growth conjecture. To this end, this study focuses on examining the energy consumption-growth nexus in a panel of 27 selected nuclear energy–consuming countries across the globe some of which no prior similar study has been conducted on in the extant literature including England, America (the USA), Germany, Canada, France, India, Brazil, South Africa, Mexico, Japan, Russia, Argentina, South Korea, Austria, Belgium, Finland, Hungary, the Netherlands, Slovakia, Slovenia, Romania, Spain, Switzerland, Czech Republic, Ukraine, Sweden, and Pakistan. The empirical application follows the GMM estimator for available nuclear energy data between 2010 and 2020 while accounting for influential factors like labor and capital within the framework of the traditional growth model.

The first part of the study is the introductory part in which the conceptual framework of nuclear energy and its situation in the world is explained. In the second part, a large literature including studies in this field is given. In the third chapter, the definition of the model used to explain the relationship between the variables and the empirical application is included. The fourth and last part consists of the conclusion part, which includes a broad assessment.

Nuclear energy: a synopsis of history and recent trend

Nuclear energy is a type of energy obtained from the nucleus of the atom. Uranium-fueled nuclear power is a clean and efficient method of boiling water used to obtain the steam required to propel generator turbines (Lau et al. 2019). Nuclear energy is formed by one of three reactions. These reactions are fission, fusion, and radioactive decay (halving) (Zinkle and Busby, 2009). Studies on atomic energy could not go beyond some small-scale scientific studies until the development of various methods of accelerating charged particles and the discovery of nuclear reactions that produce large amounts of energy. With the discovery of the nuclear fission event in 1939, expectations that its large quantity can be converted into energy have gradually increased (Amaldi, 1984).

The earliest nuclear reactors began to emerge during the cold war periods between the USA and the USSR, which affected the whole world. The first nuclear reaction was carried out by Enrico Ferm on December 2, 1942, at the University of Chicago. The "Manhattan Project," the nuclear weapons project of the USA; and the “Little Boy,” the first atomic bomb; and the “Fat Man,” the second atomic bomb in 1945, showed the power of nuclear energy. On the other hand, on 20 December 1951, electricity production based on nuclear energy was realized with the experimental plant named “Experimental Breeder Reactor 1” in the USA, while civilian electricity generation was initially realized by the USSR on 27 June 1954 in Obninsk and Kaluga Oblast reactors (Romenkov, 2009).

The energy crisis in the world, especially with the oil shock that emerged in the 1970s, led the countries that met their energy resources through imported means to use nuclear energy to a large extent. For this reason, the construction of 157 power plants in 19 countries around the world was completed in 1975, and it was observed that the electricity generation power of nuclear power plants increased up to 700 MW in this way (Temurçin and Aliağaoğlu, 2003). On the other hand, according to IEA 2021 data, there are 453 nuclear reactors in operation in about thirty-one countries. The USA has the largest share in the world with 93 reactor operations; this country is followed by France, China, and Russia, respectively. In addition, these reactors installed in the world realize about 11% of the world’s electricity production.

It is thought that the capacity of nuclear energy will increase rapidly in the next 50 years, considering the damage caused by fossil fuels to the environment (Adebayo 2022a, b; Bekun et al. 2021; Alola et al. 2021) and given that the production of electrical energy from this source does not cause same environmental pollution level like the burning of fossil fuels (Saidi and Omri, 2020). The increase in the amount of population in the world with each passing year makes the countries in search of new energy sources. The fact that non-renewable energy sources face the risk of depletion also increases the need for renewable energy sources. In addition, this increase in energy demand caused by the rapidly increasing population causes both developed and developing countries to increase their investments in this field. Nuclear energy is one of the main energy sources for many countries and the number of nuclear energy facilities in the world is increasing day by day. In the 1970s, approximately 25% of the electricity in the world was produced from oil, and the share of nuclear energy in this electricity production was only 3%. In the early 2000s, while the global electricity supply met by oil decreased to 7.2%, the amount originating from nuclear energy increased to 16.6% (Toth and Rogner, 2006). While the share of nuclear energy in electricity production decreased to about 10% in 2020, it is predicted that it will reach 15% again in 2030. Also, the NEI (2010) the importance of nuclear energy will increase gradually mainly because of new technologies and increased security measures. According to the International Atomic Energy Agency, it is expected that the world nuclear energy capacity will double in the 2030s due to the developments and improvements in the field of nuclear energy in countries such as China, South Korea, and the USA, as well as the increase in investment in these countries (NEI 2010).

In a nutshell, looking at the rapid price increase in fossil fuels recently and the fact that these fuels will be depleted in the next century, it is also believed that the capacity of nuclear energy use will be increased rapidly over the next couple of decades (NEI 2010). According to the data of the World Nuclear Energy Institute for 2021, 19.7% of the electrical energy production is realized by nuclear energy from 93 nuclear power plants in the USA, while this rate is 70.6% in France, 5.1% in Japan, 4.9% in Turkey, and 20.6% in Russia, respectively. In addition, the top 5 countries with the highest share of nuclear fuel in electricity generation in the world are Slovakia (82.3%), Ukraine (51.2%), France (70.6%), Hungary (48.0%), and Bulgaria (40.8%) (NEI 2021).

Empirical literature review on nuclear energy consumption

Energy is one of the basic factors for a country’s economic growth and social development, and it is beyond doubt that achieving sustainable development requires an increase in energy consumption. On the other hand, increasing energy consumption may also be occurring indirectly due to the increase in economic growth coupled with an increase in production factors (Solow 1956; Ding and Knight 2009). This situation reveals a triple helix in which increased production amounts increase energy consumption and increase economic growth.

The literature investigating the relationship between energy and growth is quite extensive. However, in the studies conducted, the results of the analysis differ due to factors like sample size or analysis period, the country group, and the methods used. Based on the findings, the general opinion is that energy positively affects economic growth. Likewise, studies examining nuclear energy consumption may differ in relation to growth. In this section, a summary of the studies on nuclear energy and growth is given.

Yoo and Jung (2005) were among the first to address this relationship in the literature on the Korean economy. They found a one-way causality relationship from nuclear energy consumption to economic growth in the Korean economy. Moving on, 4 years later, Yoo and Ku (2009) consider 6 countries together (France, Pakistan, Germany, Argentina, Korea, and Switzerland) in another study. In the study, a causal relationship between the variables is determined in countries other than Germany and Argentina. Wolde-Rufael and Menyah (2010) investigated the relationship between series between 1971 and 2005. Their analysis showed a unidirectional causality relationship in Switzerland, Canada, the Netherlands, Japan, and Sweden, while the study shows a two-way causality relationship between nuclear energy use and growth in France, the UK, the USA, and Spain.

Nazlioglu et al. (2011) used Toda Yamamoto causality analysis for the period 1980–2007 in their studies aiming to determine the causal relationship between the series in 14 OECD countries. The results of the analysis show that there is no causal relationship between the series in eleven of fourteen countries. Chu and Chang (2012) determined the relationship between variables in Japan, England, and the USA between 1971 and 2010. Their study did not find any relationship in Canada, France, and Germany.

Akhmat and Zaman (2013) investigate the relationship between the variables in 8 South Asian countries, and the study reveals that nuclear energy consumption influenced economic growth in Nepal and Pakistan, while economic growth had an impact on nuclear energy consumption in Pakistan between 1975 and 2010. Naser (2015) explores the relationship between the variables for four emerging economies between 1965 and 2010. It is confirmed that there is a long-term relationship between the series. Omri et al. (2015) found a unidirectional causality relationship between the series in their studies between 1990 and 2011. Saidi and Mbarek (2016) investigate the relationship between nuclear energy consumption and economic growth in nine developed countries in their study covering the years 1990–2013. In the study, in which Granger causality analysis was performed with the panel DOLS and FMOLS estimator, no relationship was found between the series.

Ozcan and Ari (2015) examined the causal relationship that may exist between nuclear energy utilization and economic growth among 15 Organisation for Economic Co-operation and Development (OECD) countries. The exercise was carried out with a panel bootstrap causality approach, and they discovered that economic growth is neutral to nuclear energy consumption in 10 countries among the 15 OECD countries since there is no evidence of causality among these variables. However, Ozcan and Ari (2017) in a different study analyzed the same relationship using a different sample set of 13 OECD member countries between 1980 and 2012. There is a positive and statistically significant relationship between the series in both the short and long terms. Besides, Özdemir (2019) also determined that the series moved together in the long run in France between 1970 and 2015. In addition, the causality analysis test applied confirmed the existence of a one-way relationship from the nuclear energy consumption variable to economic growth. Kirikkaleli et al. (2020) investigate the relationship between the series using data from 1998 to 2017 in the UK. But the findings from their analyses show that the relationship between nuclear energy and growth at different frequencies, in the long run, differs in the case of the UK.

Data description

The sample group used in the study consists of 27 countries with nuclear energy data availability in the British Petroleum (BP) Statistical Review of World Energy 2021 report including England, America, Germany, Canada, France, India, Brazil, South Africa, Mexico, Japan, Russia, Argentina, South Korea, Austria, Belgium, Finland, Hungary, the Netherlands, Slovakia, Slovenia, Romania, Spain, Switzerland, Czech Republic, Ukraine, Sweden, and Pakistan. China was excluded from the analysis due to the non-availability of adequate data on other variables of interest. Considering the disruptions to the global economic growth level in the year 2008 following the US Mortgage Crisis that resulted in a deep worldwide financial crisis, the scope of this study covers the period between 2010 and 2020. The years after 2009 especially the year 2010 is often seen as a critical time in the global economic growth recovery moment. In the study, the dependent variable is GDP, nuclear energy is the independent variable while labor and capital are included in the model as control variables based on their acknowledged roles in the general traditional growth model. The natural logarithmic forms of the variables were used. The variables and source databases used in the model are shown in Table 1.

Model and econometric application

To model the impact of nuclear energy use on growth, the general baseline model to be used in the study follows Eq. (1) where the impact of nuclear energy is observed alongside the roles of labor and capital as prominent production factors in the popular traditional growth model as seen in the Cobb–Douglas production function in Eq. (2).

Table 1 Variable definition and source databases

Variables	Definition of variable	Measurement	Symbols	Database
GDP	Gross domestic product	Constant 2015 US$	*gdp*	WDI
Capital	Gross fixed capital formation	Constant 2015 US$	*cap*	WDI
Labor	Labor force	Total	*labor*	WDI
Nuclear Energy	Nuclear energy consumption	Input-equivalent	*ne*	BP Statics

WDI denotes World Development Indicator data available at (https://databank.worldbank.org/source/world-development-indicators) while BP represent British Petroleum data available at (https://www.bp.com)

$$Log\_gdp_{it} = \beta_0 + \beta_1 Log\_gdp_{i,t-1} + \beta_2 Log\_cap_{it} + \beta_3 Log\_cap_{i,t-1} + \beta_4 Log\_Labor_{it} + \beta_5 Log\_Labor_{i,t-1} + \beta_6 Log\_ne_{it} + \beta_7 Log\_Labor_{i,t-1} + u_{it} \quad (1)$$

where β in the equation stands for the slope coefficients while i and t denotes the horizontal section and time. On the other hand, u represents the error term. The model follows the property of dynamic models such that the variable with the β_1 coefficient expresses the situation in which the lagged value of the dependent variable is included in the model as an independent variable. In addition, the lagged values of the independent variables are added to the model and their effects on the dependent variable are consequently observed. According to the Cobb–Douglas production function, which considers only two inputs in the production function, the production model used by a firm can be expressed in Eq. (2) (Zellner et al., 1966).

$$X = AL^{\alpha_1}K^{\alpha_2} \quad (2)$$

In Eq. (2), X represents the amount of output. L and K represent labor and capital inputs, respectively. Models in which the lagged values of the dependent variable are placed on the other side of the equation as independent variables are called dynamic models. In these dynamic models, if there is a relationship between the lagged value of the dependent variable and the error term, ordinary least squares (OLS) estimators cause biased and inconsistent results (Baltagi 2005). To eliminate these emerging problems, it is recommended to use the generalized method of moments (GMM) in dynamic panel estimations. The GMM method is widely used in the estimation of dynamic models due to its ease of application and because it contains relatively simple assumptions about the instrumental variables to be used in the estimation (Asongu and Odhiambo, 2019).

This method is the Arellano and Bond (1991) estimator, and it can also be used with dynamic two-stage standard error correction. This method is also known as "*difference GMM*." The second phase of the method is a different version outlined by Arellano and Bover (1995) and fully developed by Blundell and Bond (1998). This second stage is called *"System GMM*." Later, Roodman (2009) developed a new approach to linear GMM estimators. Roodman developed estimators for fixed effects and, apart from these fixed effects, dynamic "small T, large N" panels that are heteroscedastic and can include idiosyncratic errors, which implies the existence of a correlation between cross sections. The model generally used for dynamic modeling follows the expression in Eq. (3).

$$y_{it} = x_{it} * b_1 + w_{it} * b_2 + u_{it} \quad (3)$$

where $i = 1, \ldots, N.andt = 1, \ldots, T$

$$u_{it} = v_i + e_{it} \quad (4)$$

In the equation x_{it} x is a vector of exogenous variables. v_i are individual-level effects that are not observed. As seen in Eq. (4), e_{it} defines the error term. w_{it} denotes a vector of predetermined covariates (which may also include y lagged values) and endogenous covariates, all associated with v_i. Finally, b_1 and b_2 represent the vectors of the parameters to be estimated.

Empirical procedure and preliminary results discussion

In empirical practice, since the time interval is 2010–2020 and T < 15, the necessity of applying the unit root test is eliminated. However, since we are dealing with the case of a very small sample framework, there is the possibility of encountering the undesirable effects of cross-sectional dependency (CD) pitfalls (Pesaran 2007; Jönsson 2005). Hence, the system GMM test was applied instead. The GMM approach has been noted to be very effective and consistent in handling CD issues in panel observations and much beneficial in very small samples (De Hoyos & Sarafidis 2006; Boukhelkhal 2021).

As shown in Table 2, a test for the consistency of system GMM estimators was conducted. Three basic tests were used for this. The first was the Wald test, which tests whether the variables included in the model are significant together. The second is the Sargan test, which expresses the validity of the instrumental variables in the model, while the third was the Arellano-Bond (AB) test, which detect the presence of any autocorrelation problem in the model. In the present study, the Wald Chi2 test indicates that the model is significant altogether.

Moving on, to know the validity of the instrumental variables used in the system GMM, in other words, to examine whether there are excessive determination

Table 2 System GMM (generalized moments method) test results

Dependent variable (Log_gdp)	Coefficient	p value
$\boldsymbol{Log\_gdp_{t-1}}$	0.632	0.000***
Log_cap	0.259	0.000***
$\boldsymbol{Log\_cap_{t-1}}$	−0.105	0.040**
Log_lab	0.685	0.000***
$\boldsymbol{Log\_lab_{t-1}}$	−0.368	0.003**
Log_ne	0.004	0.476
$\boldsymbol{Log\_ne_{t-1}}$	−0.005	0.238
Wald Chi2 (prob)	1518.02	(0.000***)
Sargan Chi2	212.46	0.000***
Arellano-Bond Test for AR (1) (P-value)	−2.39	(0.017**)
Arellano-Bond Test for AR (2) (P-value)	1.19	(0.234)

Note: ***, **, and * indicators express statistical significance levels at the level of 1%, 5%, and 10%, respectively constraints for the panel estimations, the study utilizes the Sargan test. The null hypothesis is used to test the validity of the instrumental variables. This hypothesis shows the relationship between instrumental variables and error terms. According to the null hypothesis, the validity of the instrumental variables was accepted. In addition, by applying the AB test, it is concluded that there is no AR (2) type autocorrelation problem.

Further results discussion

Looking at the system GMM panel results in Table 2, most of the findings are in line with apriori expectations. To begin with, the coefficient interpretation of the lagged value of the dependent variable is statistically significant with regard to the obtained *p* value and has a positive impact on growth. Accordingly, when there is a 1% increase in the lagged value of the dependent variable, there is an increase of 0.63% in GDP. This is a strong indication that the previous trends in growth dynamics play a significant role in improving the economic growth trajectory of the understudied 27 nuclear energy–consuming countries.

Moving on, the findings from the system GMM estimations show that the probability values of the obtained estimates on the roles of nuclear energy consumption on economic growth are not statistically significant. There is evidence of positive impacts of nuclear energy use on GDP growth, especially when looking at the current period estimate unlike the observed impacts on growth in the previous period. Nevertheless, both outcomes are insignificant. Thus, it is concluded that the economic growth levels among the understudied 27 countries are not particularly significantly attributed to nuclear energy consumption. This is an indication that more investments in nuclear energy production are needed to trigger an overall consumption level that will not only yield significant desirable economic growth impacts among the countries but also enhance possible environmental benefits in contrast to fossil energy consumption. Although there are studies in the literature that tried to deal with the nuclear energy-growth nexus, however, most of them only establish a causal relationship between nuclear energy consumption and economic growth (Lee and Chiu 2011; Akhmat and Zaman 2013; Naser 2015; Kirikkaleli et al. 2020). On the other hand, the present findings provide more evidence to support studies in which no significant impacts could be obtained between nuclear consumption and economic growth (Nazlioglu et al., 2011; Saidi and Mbarek 2016). In addition, Ozcan and Ari (2015) have also observed that there may be no impacts on economic growth if nuclear energy is relatively small as a component of the overall energy use.

As for the control variables capital and labor, we begin the analysis with the capital variable, both capital component and its lagged value are statistically significant in influencing economic growth levels in the combined 27 nuclear energy–consuming countries. However, their coefficients have different signs meaning that they influence growth levels in different dimensions. According to the results, a 1% increase in current capital formation tends to stimulate economic growth by 0.25%. This supports the general stand in the traditional growth literature that capital accumulation stimulates economic growth (Uneze 2013; Bond et al. 2010; Çevik et al. 2020). On the other hand, the observed impacts of capital formation in the previous period negates the apriori expectation of a positive nexus between capital and growth as a 1% increase in the value of capital in the previous period relates with a 0.1% decrease in economic growth. One major explanation for this may be that total factor productivity account for more growth trends in the previous period. The findings regarding the previous period scenario thus partly corroborate the stands of Easterly and Levine, (2001) that economic growth may not be promoted by capital accumulation.

The impacts of the labor component on economic growth in the 27 nuclear energy–consuming countries were similar to those of the capital variable. It is seen that both the labor variable and its lagged value are statistically significant. The findings show that a 1% increase in the labor input induces growth by 0.68%, thus supporting studies like McDonald and Kippen (2001) that emphasized the significance of labor supply in 16 advanced economies, and Cao et al. (2020) that argued that increased effective labor input can stimulate economic growth following their empirical results from the case of the Chinese economy. But the labor-growth nexus was unfavorable in the lag period as a 1% increase in the variable relates to about a 0.36% decrease in growth. This situation may be linked to the possible influence of labor productivity level rather than just the roles of labor supply among the countries (McDonald and Kippen 2001).

Summary, conclusion, and recommendations

This study covers 27 countries for which nuclear energy data is available using the BP Statistical Review of World Energy 2021 report. The study focuses on examining nuclear energy consumption-economic growth nexus in a panel of 27 selected nuclear energy–consuming countries across the globe. In addition to the nuclear energy variable, following the traditional growth model on the roles of factor inputs, labor and capital were also included in the model and their effects on growth are investigated for the period after the global financial crisis of 2008 covering 2010 to 2020. GMM estimator was used to investigate these relationships. It was observed that both factor inputs (labor and capital) have statistically significant relations with economic growth. The nuclear energy consumption level, on the other hand, was not a significant driver of economic growth level among the countries. Thus, it is concluded that the economic growth levels among the understudied 27 countries are not significantly linked to nuclear energy consumption.

This is an indication that more investments in nuclear energy production are needed to trigger an overall consumption level that will not only yield significant desirable economic growth impacts among the countries but also enhance possible environmental benefits in contrast to fossil energy consumption. In today's world, where the role of energy consumption on economic growth is increasing intensively, understanding the effects of individual energy types is also important to design and implement energy policies more healthily and to increase overall efficiency. Governments in the 27 countries are encouraged to boost their commitments toward supporting nuclear energy projects as an alternative to fossil fuels to stimulate its relevance in terms of overall economic contributions aside from the inherent environmental benefits. The authority can take advantage of various approaches including public–private partnership schemes and the governments should also encourage private investors in nuclear energy projects by providing the right incentives including but not limited to taxes and subsidies.

As noted earlier, the importance of nuclear energy in the world is increasing day by day due to its environmental benefits from factors such as lower carbon emissions. However, there are various skepticisms around nuclear energy power plants construction and utilization which have limited its potential among countries considering the possibility of security threats from nuclear proliferation, the challenges of nuclear waste (radioactive) disposals, and other matters of the required safety and operational technicality. Hence, the understudied countries need to take more strategic steps to address these concerns by leveraging new technology and providing better and regular training activities for operators at facilities while ensuring that paramount safety measures are prioritized to keep nuclear resources from the reach of terror organizations.

Lastly, considering the desirable roles of the factor inputs (labor and capital) as they were significant drivers of growth, the authorities of the 27 countries need to take advantage of these factors for greater economic benefits. For instance, more investments can be channeled towards critical issues that influence labor productivity levels such as education and health care measures.

Limitations and direction for future studies

Due to the complicated nature of the economic growth composition, there may have been the exclusion of some other variables that are affecting the growth-nuclear energy consumption nexus. Thus, future studies can be augmented to incorporate more variables that may be influencing growth specifically from the factor input (labor and capital) perspective in the model. For instance, education and healthcare measures can be considered in the case of labor. Further studies can also strategically explore the roles of labor productivity rather than focusing on the labor supply. In a nutshell, future studies that explore the effects of nuclear energy consumption on economic growth may be able to keep the analysis period wider and, at the same time, add different instrumental variables that affect nuclear energy and growth.

Author contribution The first author (Mahmut Sami DURAN) was responsible for the conceptual construction of the study's idea. The second author (Şeyma BOZKAYA) alongside the third author (Stephen Taiwo ONIFADE) handled the introduction and literature sections. The data gathering, preliminary analysis, simulation, and interpretation of the simulated results were carried out by the first and second authors while the proofreading and general manuscript editing were joint efforts of the third author and the fourth author (Mustafa Göktuğ KAYA). The third author (Stephen Taiwo ONIFADE) handled all the correspondence.

Availability of data and materials The data for this present study are sourced from the database of the World Development Indicators (WDI) (http://info.worldbank.org) and British Petroleum (BP) database (https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html).

Declarations

Ethics approval and consent to participate NA.

Consent to participate NA.

Consent for publication NA.

Competing interests The authors declare no competing interests.

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