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Original Article

Nuclear energy consumption, nuclear fusion reactors and environmental quality: The case of G7 countries

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ABSTRACT

Global climate change brings environmental quality sensitivity, especially in developed countries. Developed countries use non-renewable energy sources intensively both in their own countries and in other countries, they make productions that cause an enormous rate of increase in CO_2 emissions and unsustainable environmental costs. This has increased the interest in environmentally friendly alternative energy sources. The aim of this study is to investigate the impact of nuclear energy consumption and technological innovation on environmental quality in G7 countries using annual data over the period 1970–2015. The Panel Threshold Regression Model was used for the analysis. Empirical findings have indicated that the relationship between nuclear energy consumption and carbon emissions differs according to innovation for nuclear power plants. It was also concluded that nuclear energy consumption reduces carbon emissions more after a certain level of innovation. This result shows that the increase in innovative technologies for nuclear power plants not only increases energy efficiency but also contributes positively to environmental quality.

1. Introduction

There is a trade-off between more production and energy consumption which causes more CO_2 emissions, leading to the greenhouse effect and global climate change. The most effective solution in combating global warming is the use of environmental-friendly energy sources that will cause the least environmental degradation. In this context, nuclear energy, whose contribution to protecting the environmental quality has not been confirmed, is one of the energy sources that come to the fore. There has been debate on the pros and cons of benefiting from nuclear energy.

Proponents of nuclear energy point out that nuclear energy can be used in reducing the dependence on external energy sources and oil-price volatility. Since nuclear power plants are capital-intensive, nuclear energy costs are relatively less affected by fluctuations in fuel prices [1]. Besides, fluctuations in fuel prices affect nuclear energy demand positively, particularly as fuel prices rise. The preference for nuclear energy as an alternative energy source as fuel prices increase shows the substitution of nuclear energy as an alternative to the other energy sources. By testing the data of six developed countries for the period 1971–2006, Lee and Chiu (2011) [2] indicated that there is a substitutive relationship between nuclear energy since oil prices have a positive effect on nuclear energy consumption in the long run. Supporters of nuclear energy also underline that the safety of this energy source is high. They stated that the number of large-scale nuclear accidents was few, and the major accidents were caused by inadequate safety standards. It was also underlined that strong measures for the protection of nuclear power plants reduce the risk of danger [3]. Nuclear energy has a positive effect on employment as well. According to nuclear energy supporters, nuclear power plant makes a positive contribution to the volume of employment. The demand for labor increases during the construction and operation phases of nuclear facilities [4].

On the other side of the coin there are operational safety risks, problems related to the location of facilities, disposal of radioactive waste, installation and operating costs, errors in reactor design, risk of explosion during installation, risk of proliferation of nuclear materials, negative perception of nuclear energy and tragic past experiences that constitute the reasons of the negative perception

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of nuclear energy [1,5]. The greatest criticism on nuclear power is that it is not safe. After the tragic Chernobyl accident in 1986, a large number of radionuclides were released into the atmosphere. In the following years after the accident, there was a tremendous increase in thyroid cancer, malformations in newborns as well as an increase in environmental degradation in the region. The second greatest nuclear reactor accident was recorded in 2011 in Japan due to natural disasters and human error [5,6]. Especially after Fukushima, public opinion and awareness of nuclear energy increased. Those two dramatic events played a key role in the negative perception of nuclear power programs [7,8].

Actually, apart from those two incidents, there is a great safety record as a result of governmental and regulatory oversight of nuclear generation operations. After approximately 60 years of development, the operational safety of nuclear power plants has been improved. In many applications, hundreds of thousands of hours of safe operations brought a great experience in this field. Another criticism of nuclear power expansion is that existing and potential new facilities can be vulnerable to terrorist attacks. If there is a terrorist attack, there may be a great environmental disaster. Therefore, supporters strongly suggest additional measures to protect the assets from terrorist attacks [9]. Opponents also argue that investments in nuclear facilities are too expensive. With limited sources, it is difficult for developing countries to initiate the construction of these expensive facilities. Supporters oppose this criticism. They state that although the construction cost of nuclear units is high in the beginning, their operating costs are less than those of fossil fuels once the operation is started.

For a successful expansion and introduction of nuclear power, innovative and new technology infrastructure is critical. Innovative technologies will bring more safety and reliability, economic competitiveness, as well as public acceptance and waste management [10]. Opponents also point that while calculating nuclear energy costs, it is necessary to take into account the burden of waste disposal. They also state that compared to nuclear energy production costs, it is possible to produce energy with solar energy or wind energy at more reasonable prices [4]. However, since nuclear power does not burn fossil fuels, it could contribute to the decreasing of greenhouse gases. Furthermore, contrary to popular myth, the amount of waste generated from the production of nuclear power is less than the waste produced from coal and oil-fired generation facilities [9,11]. Therefore, while examining the positive and negative aspects of nuclear energy consumption, the main issue that needs to be emphasized is not only the relationship between nuclear energy and economic growth but also its limited impacts on environmental quality. While analyzing its contribution to sustainable development, it is necessary to investigate the environmental costs of nuclear energy. Findings of the researches on the effects of nuclear energy on environmental quality can be considered as a data source in determining energy policies. The development of a technological innovation that will reduce the environmental costs of energy consumption is as important as the choice of clean energy resources for the protection of the environment. Although studies investigating the relationship between nuclear energy consumption and CO_2 emissions are not few, in order to demonstrate the environmental effects of technological innovation, studies on the CO_2 emission of technological innovation related to nuclear energy should also increase. Whether nuclear energy is considered a clean energy source is as important as the extent to which the negative effects of this energy source on environmental quality can be controlled by technological innovations.

Findings of the studies on the effect of nuclear energy on CO_2 emissions are necessary to determine the real impacts of this energy source on the environment compared with the other environmentally friendly energy sources.

The aim of this study is to examine the impact of nuclear energy consumption and nuclear energy-related technological innovations on environmental quality in the G7 countries for the period 1970–2015. The relationship between nuclear energy consumption and carbon emissions is investigated with the Panel Threshold Regression Model. Accordingly, this study seeks to answer the following questions. First, what is the role of nuclear energy consumption in reducing environmental degradation? Second, do technological innovations in nuclear energy change the impact of this energy source on environmental quality? The answers to these questions will be given within the scope of the G7 countries. The reasons for choosing the G7 countries as the sample countries are as follows: Since the G7 countries are the most advanced economies in the world, they are also the countries that consume the most energy due to their highly developed industries and high production levels. Fig. 1 illustrates the year-on-year (YOY) energy consumption of the G7 countries.

Based on the data from BP [12], it can be concluded that while G7 countries decreased coal consumption, the energy mix changed in favor of renewable energy in all G7 countries in 2019. Japan increased its energy consumption in favor of nuclear energy despite the Fukushima incident in 2011. The country has made remarkable progress in energy efficiency, safety, and environmentally sustainable energy systems. Japan has diversified its energy mix and reduced its energy demand. After the Fukushima accident, the country's greenhouse emissions reached the highest level with the replacement of nuclear plants with fossil fuels. As of 2018, the level of carbon emissions has dropped to 2009 levels. Although recently Japan remains heavily dependent on fossil fuels, the country has declared its goal of achieving carbon neutrality by 2050 by increasing the share of renewable energy and nuclear energy in electricity generation. Japan also announced that the government would initiate advanced regulatory reforms, digitize and apply innovative technologies for low-carbon hydrogen and carbon recycling to achieve energy efficiency and carbon neutrality [13]. In Italy, the government has been working on incentives and subsidies to have greater efficiency in energy production with lower carbon emissions but has no plan to invest in nuclear energy facilities. Canada tries to strike a balance between resource development and environmental quality including reducing carbon emissions 30% below 2005 levels and finalize the coal power by 2030 and achieving net-zero emissions by 2050. The country is one of the most successful countries in clean electricity production with a large share of renewables and nuclear power. It has also initiated a maintenance and refurbishment program to improve the safety and extend the life of existing nuclear reactors which will lead low-carbon electricity mix in the near future. The USA is the country which has the highest number of nuclear power plants. In recent years, the country has invested in reliable, affordable, and environmentally friendly energy systems. The fuel mix of the US power generation has driven the transition from coal power to natural gas-powered generators. France has the second-largest number of nuclear facilities after the US. The country owes its low-carbon electricity mix to nuclear reactors. France also targeted to reach net-zero emissions by 2050. The country will reduce the share of nuclear power from 70% to 50% in its electricity mix and close its last coal plants by 2022. Also, many reactors in the country are old and reaching the end of their operating time. In 2010, Germany introduced the major plan for having more energy efficiency mainly provided by renewable energy sources and phasing out nuclear power by 2022. Besides, all electricity supply will come from renewable energy sources and cease coal-fired generation by 2038 [14].

Due to the 2050 targets of achieving net-zero emissions, the G7 countries initiated to phase out their carbon-intensive fossil fuels policy and plan to limit the rise in global temperature to 1,5°

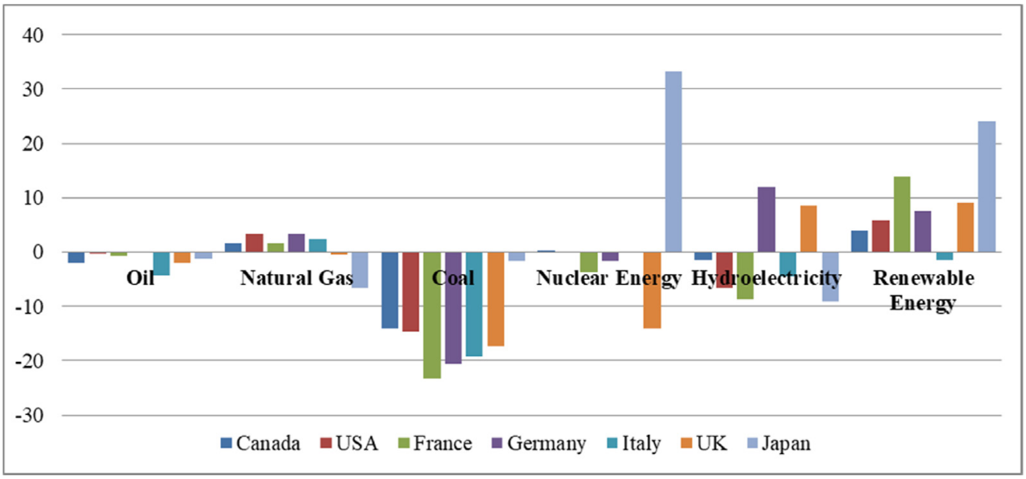

Fig. 1. YoY change of energy consumption in G7 Countries by sources (2019) [12] (authors' calculations).

Celsius. In this context, the G7 governments will end direct support to international thermal coal power generation by the end of 2021. The G7 countries also agreed that natural gas will still play an important role in the energy transition in the 2030s. Besides, the countries plan to increase the investments in secure, safe, and sustainable clean energy chains, including critical minerals and renewable components. Accordingly, the UK revealed £16.5 million in funding to enable the development of green technologies to reduce carbon emissions. All G7 countries also planned to allocate to innovative technologies to reduce the cost of industrial decarbonization technologies such as electrification and the use of hydrogen and nuclear power [15]. The number of nuclear reactors is 93 in the USA, 56 in France, 33 in Japan, 19 in Canada, and 6 in Germany in May 2021. Between 2004 and 2019, nuclear consumption rose by 3,2% globally [16]. The fastest growth was recorded in China (0,5 Ej) and Japan (0,1 Ej) [17]. Fig. 2 represents the nuclear consumption levels of G7 countries. As expressed in Fig. 2, the US has the highest nuclear energy consumption during the period. France follows the US. Although Japan ranks third in nuclear energy consumption, the Fukushima accident affected the use of nuclear reactors in this country. Japan shut down all nuclear reactors between 2013 and 2015. Some of the reactors in G7 countries were retired (some of them were more than 40 years) for national policy measures including post-Fukushima measures in Japan as well as negative market conditions. While Japan shut down 5 units, the USA 2 units, and Germany 1 unit [18]. During this period, Japan applied fossil fuels as an alternative energy source. However, as the country recorded very high carbon emissions rates, the government changed the energy policies and started to invest in nuclear reactors again.

The pandemic period has affected energy production at the global level. Indeed, due to sectorial shutdowns during the pandemic, nuclear power was generated about 3% less in 2020Q1 than in 2019Q1. In 2020, nuclear power generation in the US is expected to drop by −2.1% due to lower electricity demand. Similarly, nuclear energy generation in France decreased by 11 TWh (10%) in 2020Q1. In Germany, production fell by 3 TWh (17%) since the government plans to end production by 2022. On the contrary, nuclear power grew in China with a 1% increase in output between 2019Q1 and 2020Q1. While Germany took steps to shut down nuclear power completely, China initiated a pair of large nuclear reactors in June 2019 [19].

Fig. 3 illustrates the CO_2 emissions growth of the G7 countries for the 2009–2018 period. The CO_2 emissions of the US are almost five times more than the CO_2 emissions of other G7 countries.

Because of the pandemic containment, CO_2 emissions contracted in 2020 particularly CO2 emissions from fossil fuels combustion decreased by 9% in Germany, 11% in Italy, 11% in France [20]. The US had 14,5%, Japan 3,3%, Germany 2%, Canada 1,6%, Italy and the UK 1%, and France 0,9% CO_2 emissions growth in 2019 [12]. Due to the fact

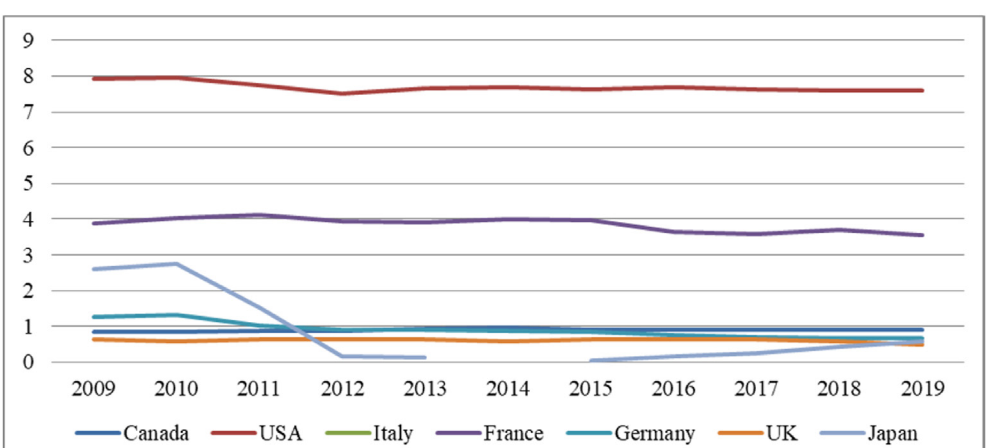

Fig. 2. Nuclear energy consumption of G7 Countries (2009–2019) (Exajoules) [12].

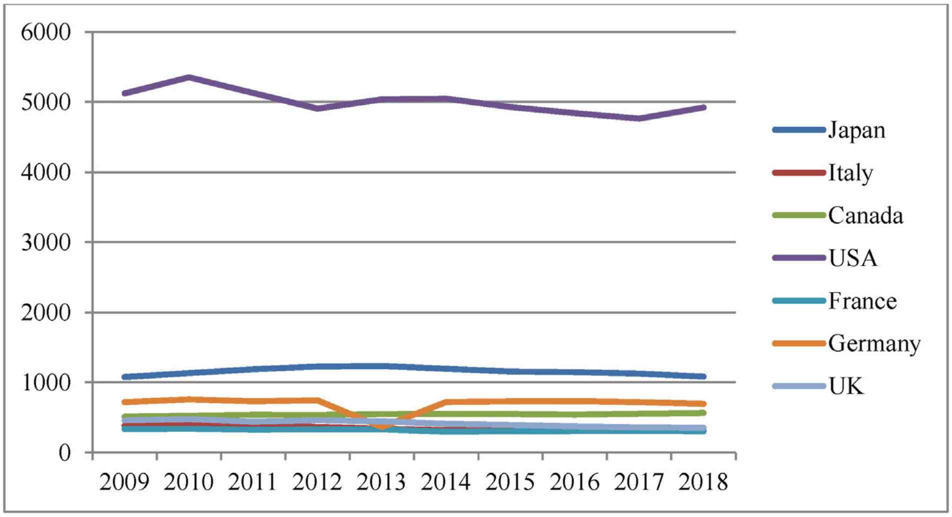

Fig. 3. Total CO_2 emissions of G7 Countries (2009–2018) [14] (authors' calculations).

that these countries contribute more to CO_2 emissions at the global level, the use of energy sources that can reduce CO_2 emissions in these countries is even more important. In addition to the use of energy sources that are less harmful to the environment in G7 countries, the reduction of the contribution of these energy sources to CO_2 emissions through technological innovations makes the fight against global climate change more effective. Besides, the G7 countries are the countries with the highest per capita income in the world. Due to the high per capita income in these countries, relatively more funds can be allocated to R&D expenditures. Also, since technological investments are encouraged more in developed countries than in their less developed counterparts, most of the technological innovations are made in these countries. Advanced countries invest in technological innovations for energy efficiency to produce more energy with less fuel and less environmental costs of energy consumption. Nuclear fusion reactors make a great contribution to energy savings and the reduction of environmental damage. In these countries, technological innovations are encouraged by granting trademarks and patents to the new innovative products. In other technological products, patents are granted for nuclear fusion reactors.

This study differs from prior studies in certain points. Although there are studies investigating the relationship between nuclear energy consumption and CO_2 emissions, evaluating the contribution of technological innovation to this relationship is ignored. Since technological innovation may bring cleaner energy production as environmental pollution risk is reduced, technological innovation parameter deserves to be investigated in nuclear energy consumption-CO_2 emissions nexus. In addition, by choosing the G7 countries for the analysis, it will be more realistic to analyze the relationship between the variables as these countries are the most advanced ones which has the highest GDP, the greatest number of nuclear energy investments, and the highest amount of R&D expenditures on technological innovation. Thus, we tried to fill this gap and in this study, not only through investigating the relationship between nuclear energy consumption and CO_2 emissions but also by analyzing effect of technological innovation in nuclear energy on CO_2 emissions. To the best of our knowledge, there is no other study investigating the impact of technological innovation in nuclear energy on CO_2 emissions.

The remainder of the paper is organized as follows: The next part is the literature review. Then we explained the econometric framework and empirical findings. In the last part, we have the conclusion and policy implication.

2. Literature review

The findings of the studies within the scope of the relevant literature are gathered under the headlines of nuclear energy consumption-economic growth relationship, nuclear energy consumption-environmental quality relationship, and technological innovation-environmental quality relationship.

2.1. Nuclear energy consumption-Economic growth relationship

A significant number of studies in the literature indicated a relationship between the two variables. Yoo and Ku [21] investigated the relationship between nuclear energy consumption and economic growth in six countries for more than 20 years until 2005. The same results were not obtained for all countries within the scope of the analysis. The authors stated that there was a bidirectional relationship between the variables in Switzerland. They also found that there was unidirectional causality running from economic growth to nuclear energy consumption in France and Pakistan. They also concluded a unidirectional causality from nuclear energy consumption to economic growth in Korea. They could not find a relationship between the variables in Argentina and Germany. Apergis and Payne [22] investigated the relationship between nuclear energy consumption and economic growth in sixteen countries for the period 1980–2005. According to the results obtained, while there was bidirectional causality between the variables in the short run, there was unidirectional causality running from nuclear energy consumption to economic growth in the long run. Yoo and Jung [23] conducted similar research for the 1977–2002 period in Korea. A unidirectional causality running from nuclear energy consumption to economic growth had been determined. Wolde-Rufael and Menyah [24] investigated the relationship between the two variables in nine developed countries for the period 1971–2005. The empirical results indicated that although there was unidirectional causality from nuclear energy consumption to economic growth in Japan, Netherlands and Switzerland, in Canada and Sweden there was the opposite unidirectional causality running from economic growth to nuclear energy consumption. The authors stated bidirectional causality between the variables in France, Spain, the United Kingdom, and the United States. In their study of 17 developed and developing countries during the period 1990–2011, Omri, Mabrouk, and Sassi-Tmar [25], showed that while there was a unidirectional relationship from nuclear energy consumption to economic growth in Belgium and Spain, there was causality from economic growth to nuclear energy consumption in Bulgaria, Canada, Netherlands, and Sweden. There was bidirectional causality between the variables in Argentina, Brazil, France, Pakistan, and the USA. There was no causal relationship determined between the variables in Finland, Hungary, India, Japan, Switzerland, and the U.K. For the whole panel, it was found that there was a bidirectional relationship between the variables. Luqman, Ahmad and Bakhsh [26] investigated asymmetric effects of nuclear and renewable energy on economic growth for Pakistan over the period 1990–2016. The authors indicated that nuclear energy had a positive effect on economic growth. Kirikkaleli, Adedoyin and Bekun [27] conducted similar research for the United Kingdom for the period 1997–2017. Based on the test results, the authors obtained that changes in economic growth caused changes in nuclear energy consumption in different periods. The authors also indicated that there was a positive relationship between nuclear energy consumption and economic growth in the short term in the 2002–2002 period.

In the relevant literature, there are studies that could not find any relationship between nuclear energy consumption and economic growth. In their study, Payne and Taylor [28] could not find causality between the variables for the USA during the 1957–2006 period. Ozcan and Ari [29] conducted a similar empirical analysis for 15 OECD countries during the 1980–2012 period. While they could not indicate a causality relationship between the two variables in 10 countries, they found a significant relationship between economic growth and nuclear energy consumption in 5 countries. Saidi and Mbarek [1] could not find a relationship between the variables either while investigating the relationship between nuclear energy consumption and real GDP per capita by testing the data of nine developed countries for the period 1990–2013.

2.2. Nuclear energy consumption-Environmental quality relationship

The findings of the studies revealing the existence of the relationship between nuclear energy consumption and environmental quality are as follows: Menyah and Wolde-Rufael [30] investigated the relationship between CO_2 emissions and nuclear energy consumption in the USA in the period 1960–2007. Nuclear energy consumption has been found to reduce CO_2 emissions. Apergis et al. [31] examined the relationship between CO_2 emissions and nuclear energy consumption using data from 19 developed and developing countries for the period 1984–2007. Empirical results indicated that a 1% increase in nuclear energy consumption reduces carbon emissions by 0.477%. Baek and Pride [32] investigated the nuclear energy- CO_2 emissions nexus for 6 nuclear-producing countries. The starting year of the analysis period differed depending on the start of electricity generation from nuclear energy. Nuclear energy has been found to reduce carbon emissions. In a similar study, Rani and Kumar [33] investigated the relationship in India using data from 1969 to 2014. The authors determined that nuclear energy consumption reduces CO_2 emissions both in the short and long term. There are other studies with similar results for India. Danish, Ozcan and Ulucak [34] tested the data for the period 1971–2018, determined that a sudden increase in the consumption of nuclear energy reduces CO_2 emissions. Sahoo and Sahoo [35] tested the data for the period 1965–2018 and obtained findings that nuclear energy consumption negatively affects CO_2 emissions. Lee, Kim and Lee [36] investigated the effect of nuclear power generation on CO_2 for the period 1970–2015 in 18 countries. According to the empirical results, a 1% long-term increase in nuclear power reduces CO_2 emissions per capita by 0.26–0.32%. Dong et al. [37] investigated the relationship between per capita CO_2 emissions and per capita nuclear energy consumption for the 1993–2017 period in China. The researchers found that nuclear energy had a significant effect on reducing CO_2 emissions in both the short and long term. Saidi and Omri [38] reached the same results for 150 OECD countries over the period 1990–2018. Danish, Khan and Ahmad [39] investigated the environmental consequences of nuclear energy consumption in China during the period 1994–2018 in the context of the pollution haven hypothesis. The results showed that this hypothesis was not valid. On the other hand, it was determined that nuclear energy was effective in reducing carbon emissions. Hassan et al. [40] investigated the role of nuclear energy in reducing environmental pollution for the BRICS countries between 1993 and 2017. The results showed that nuclear energy consumption reduced CO_2 emissions. Azam et al. [41] investigated the effects of natural gas, renewable energy, and nuclear energy consumption on CO_2 emissions for the period 1990–2014 for the 10 countries that contributed the most to CO_2 emissions. According to the results obtained, renewable energy and nuclear energy, excluding natural gas, have a significant effect on reducing carbon emissions.

There are also some studies in the literature that could not determine any relationship between nuclear energy consumption and CO_2 emissions. Below are the findings of the studies that found no relationship between the variables or that nuclear energy contributed to environmental degradation. Al-Mulali [42] investigated the effect of nuclear energy consumption on economic growth CO_2 emissions for the period 1990–2010 in the 30 top nuclear energy-consuming countries. It was observed that nuclear energy consumption had a positive effect on economic growth in the long run, but had no effect on CO_2 emissions. Jin and Kim [43] investigated which renewable and nuclear energy forms could reduce carbon emissions for 30 countries in the period 1990–2014. According to the test results, nuclear energy did not contribute to the reduction of carbon emissions. Renewable energy was essential for environmental quality. Mahmood et al. [44] investigated the relationship between nuclear energy and CO_2 emissions for Pakistan during the 1973–2017 period. The authors concluded that nuclear energy contributed to environmental pollution. They also indicated that there was bidirectional causality between the variables.

2.3. Technological innovation-Environmental quality relationship

Despite the fact that there are many studies investigating the effect of technological innovation on environmental quality in the literature, to the best of our knowledge, there is no study investigating the effect of technological innovation on the relationship between nuclear energy and environmental quality. Therefore, in this section, the findings of studies investigating the effects of technological innovation on environmental quality will be analyzed. Fei, Rasiah and Shen [45] investigated the relationship between clean energy, CO_2 emissions, economic growth, and technological innovation for Norway and New Zealand during the period 1971–2010. Based on the empirical results, the authors indicated that the use of clean energy reduces CO_2 emissions at the expense of economic growth. Based on these findings, policymakers are faced with a trade-off regarding economic growth and environmental quality preferences. Thus, the authors suggested that more attention should be paid to research and development processes in these countries to make more use of clean energy. In their study of investigating the relationship between economic growth and CO_2 emissions for 24 European countries spanning the 1980–2010 period, Ahmed, Uddin and Sohag [46] indicated that technological innovation contributed to the reduction of carbon emissions. Murad et al. [47] investigated the relationship between technological innovation and energy consumption for Denmark in the period 1970–2012 and showed that technological innovation negatively affects energy consumption. Erdogan et al. [48] investigated the effect of innovation on sectoral carbon emissions for the period 1991–2017 in 14 countries. The empirical findings were diverse in different sectors. Innovation has reduced carbon emissions in the industrial sector but increased in the construction sector. Mongo Belaïd and Ramdani [49] analyzed the impact of environmental innovations on CO_2 emissions during the period 1991–2014 for 15 European countries and determined that environmental innovations contribute to the reduction of CO_2 emissions in the long run. Erdogan [50] reached similar results in the BRICS countries for the period 1992–2018 and showed that the increase in technological innovation reduces carbon emissions. Alam et al. [51] examined the effect of R&D expenditures on clean energy consumption and CO_2 emissions in 30 OECD countries during the period 1996–2013 and determined that R&D positively affects clean energy consumption and reduced CO_2 emissions. In the study, the share of the alternative and nuclear energy in total energy consumption was chosen as a clean energy indicator. Godil et al. [52] investigated the impact of technological innovation on transport sector carbon emissions in China over the period 1990–2018 and indicated that the increase in innovation reduces CO_2 emissions from the transport sector. Altuntas and Kassouri [53] explored the impact of energy technology innovation on cleaner energy production and carbon footprint in Europe for the 1985–2016 period. The researchers stated that decline in carbon footprints is related to energy technology R&D. Alvarez-Herranz et al. [54] confirmed that energy R&D expenditures and promotion of renewable energy sources positively influence the air quality in 17 OECD coutnries over the period of 1990-2012. Ang [55] reached the similar results for China and Mensah et al. [56] for 28 OECD counties.

3. Material and methods

This study aims to examine the relationship between carbon emissions and nuclear energy usage by using linear and nonlinear models. Hence, we first consider the following linear regression model:

$$CO2_{it} = \beta_0 + \beta_1 NEC_{it} + \beta_2 Y_{it} + \beta_3 TRD_{it} + \beta_4 FDI_{it} + \varepsilon_{it} \tag{1}$$

where *CO2* is the per capita carbon emissions, *NEC* is the nuclear energy consumption, *Y* is the real per capita Gross Domestic Product, *TRD* is the trade openness (the sum of exports and imports of goods and services measured as a share of GDP) and *FDI* (net inflows to GDP ratio) is the foreign direct investment. β_1, β_2, β_3, and β_4 are the slope coefficients and indicate the effect of the variables in question on the carbon emissions. Both theoretical and empirical literature shows that nuclear energy produces fewer carbon emissions than conventional energy sources and therefore a negative relation between carbon emissions and the nuclear energy consumption is expected. For instance, Menyah and Wolde-Rufael [30] found a unidirectional causality relationship from nuclear energy consumption to carbon emissions in the US where nuclear energy consumption helps to mitigate carbon emissions. Similarly, Baek [57] determined that there is an inverse relationship between nuclear energy and carbon emissions in 12 major nuclear-generating countries. Dong et al. [37] found that nuclear and renewable energy consumption significantly reduce carbon emissions in China.

It should be noted that per capita, trade openness, and foreign direct investment are considered as control variables in Equation (1). Since economic growth increases the energy demand, it is expected that there is a positive relationship between per capita and carbon emissions [58,59]. Empirical studies show that although exports lead to decrease carbon emissions due to technology transfer, there is a positive relation between imports and carbon emissions. Hence, it can be said that the relationship between trade openness and carbon emissions is vary depending on whether the country is a net importer or exporter. In this context, Shahbaz et al. [60] found that trade openness provides a positive contribution to carbon emissions in the high-, middle- and low-income countries. On the other hand, Wang and Zhang [62] stated that the relationship between trade openness and carbon emissions also varies according to the income levels of countries. In this vein, their empirical results showed that while there is a reverse relationship between trade openness and carbon emissions in high-income and upper-middle-income countries, an increase in trade openness leads to raising carbon emissions in low-income countries. There are two opposite hypotheses namely the pollution-haven and the pollution-halo about the relationship between foreign direct investment and carbon emissions in the literature and hence positive or negative coefficients for foreign direct investments are welcome. For instance, Essandoh et al. [63] documented the presence of a long-run positive relationship between carbon emissions and foreign direct investments.

There has been a growing body of literature that focuses on examining the relationship between nuclear energy and carbon emissions but these studies generally focus on the linear relationship between the variables in question [30,37,38,57]. The common finding of these studies is that there is a negative relationship between nuclear energy and carbon emissions. On the other hand, there has been well-documented literature that shows innovations specifically on energy production significantly reduce carbon emissions [59,64–66].

On the other hand, it is noteworthy to investigate the presence of nonlinear relation between nuclear energy and carbon emissions in terms of innovation because it is well known that process improvements for nuclear energy power plants contribute positively to both energy efficiency and environmental quality. Therefore, after a certain level of innovation, the positive effect of nuclear energy on environmental pollution may be higher. At this point, the threshold regression model comes to the fore in investigating whether there is a significant difference in the relationship between nuclear energy and carbon emissions depending on a certain innovation level. In this vein, Hansen [67] indicated that the threshold regression model allows dividing observations into regimes according to the certain value of an observed variable. Therefore, we examine the regime-dependent relationship between nuclear energy and carbon emissions by using the panel fixed effect threshold regression model suggested by Hansen [67] where the regimes are identified according to the number of patents for nuclear fusion reactors. Mensi et al. [68] indicated that panel threshold model has several advantages over the linear model. The threshold model allows to examine nonlinear relationship between endogenous and exogeneous variables by considering asymmetry in the variables in question. Therefore, panel threshold model is able to take switching economic dynamics into account and hence non-uniform relationship between endogenous and exogenous variables can be examined. In this vein, regime-dependent coefficients can be obtained by using the panel threshold model when we examine the relationship between carbon emissions and energy consumption. Also, In the panel threshold model, both coefficients and regimes are estimated endogenously and simultaneously.

Hansen [67] defined the panel threshold regression model for balanced panel data as follows:

$$y_{it} = \mu_i + \beta_1' x_{it} I(q_{it} \le \gamma) + \beta_2' x_{it} I(q_{it} > \gamma) + e_{it}. \tag{2}$$

where dependent variables y_{it} (carbon emissions) is a scalar the threshold variable q_{it} (the numbers of patent for nuclear fusion reactors) is scalar and the regressor x_{it} (GDP, trade openness and foreign direct investment) is a k vector. $I(.)$ is the indicator function and γ is the threshold value. Equation (2) can be also written as follows:

$$y_{it} = \begin{cases} \mu_i + \beta_1' x_{it} + e_{it} \; q_{it} \le \gamma, \\ \mu_i + \beta_2' x_{it} + e_{it} \; q_{it} > \gamma. \end{cases} \tag{3}$$

Equation (2) also can be defined as follows:

$$y_{it} = \mu_i + \beta' x_{it}(\gamma) + e_{it} \tag{4}$$

where $\beta = (\beta_1' \; \beta_2')$ and $x_{it}'(\gamma) = [x_{it} I(q_{it} \le \gamma) \; \beta_2' x_{it} I(q_{it} > \gamma)]$. The observations are divided into two regimes according to the threshold value γ. When the threshold variable q_{it} is less (higher) than the threshold value, the regime is called as the first (second) regime. Hence, we can obtain the regime-dependent regression coefficients. Hansen [67] indicated that the regression coefficients can be estimated by using ordinary least squares and the threshold value is obtained by using the grid search. To examine the presence of the threshold effect, Hansen [67] suggested a LR test where the null hypothesis is no threshold effect (H_0: $\beta_1 = \beta_2$). Nevertheless, a problem is arising because since the threshold γ is not identified under the null hypothesis, the distribution of test statistics is not standard. As in Hansen (1999), we employ the bootstrap procedure to obtain critical value for the test statistic.

4. Data, empirical results, and discussion

The relationship between nuclear energy and carbon emissions is examined by using a fixed effect panel threshold regression model for the periods of 1970–2015 in the G7 countries namely Canada, France, Germany, Italy, Japan, the UK, and the US. The sample of the study is limited to G7 countries because the patent data for nuclear fusion reactors are not available for the other countries. The name, definition, and sources of the variables are presented in Table 1.

We consider per capita carbon dioxide emissions as a proxy for environmental quality. As in Baek [57], electricity production from nuclear power plants is used as a proxy for nuclear energy generation. The numbers of the patent for nuclear fusion reactors are used as a proxy for innovation in nuclear power plants. The GDP per capita, trade openness, and foreign direct investment are considered as control variables in the empirical analysis. We use the log of the GDP per capita in the empirical analysis.

The descriptive statistics for the variables are presented in Table 2. The results in Table 2 show that the panel mean of per capita carbon emissions is 11.476 metric tons and it is found that the US produces the highest carbon emissions whereas France has the lowest carbon emissions in the sample. The panel mean of nuclear energy generation is 20.64% that indicates nearly 20% of the total electricity production is obtained from nuclear power plants. Note that France is the first in terms of electricity generation from nuclear power plants among the countries in the sample. In 2015, 77% of the total electricity was produced by nuclear power plants in France. After 1987, electricity generation from nuclear power plants in Italy dropped dramatically to zero. Similarly, after the Tohoku earthquake in 2011, electricity generation from nuclear power plants decreased significantly in Japan. The panel mean of patent applications for nuclear fusion reactors is 45 and it varies between 0 and 253 in the sample periods. The US has filed the most patent applications for nuclear fusion reactors, while Italy has the fewest in the sample. The panel mean of log of per capita GDP is 10.398 that is equal to $32793. The panel mean of trade openness for the countries in the sample is 42%, and it varies between 10% and 86% over the sample periods.

The Pearson correlation coefficients that are presented in Table 3 show that there is a negative and statistically significant correlation between nuclear energy and carbon emissions. However, nuclear energy is positively correlated with patent, GDP, trade openness, and FDI. We also determine that there is a positive and significant correlation between carbon emissions and patent and GDP.

We also examined the presence of cross-sectional dependence by using the CD test suggested by Pesaran [69] and present the results in Table 3. The CD test results in Table 3 show that the null hypothesis of weak cross-sectional dependence can be rejected for all variables at a 1% significance level.

We start our analysis by first employing the unit root test. Therefore, we first employ the first-generation panel unit root test proposed by Im et al. [70]. Nevertheless, the CD test results in Table 3 show the presence of cross-sectional dependence and well-documenting literature shows that first-generation unit root tests provide biased results when there is cross-sectional dependence. Therefore, we employ the second-generation panel unit root test (CIPS) suggested by Pesaran [71] to examine the robustness of the results and test results are presented in Table 4. It should be noted that we conduct the CIPS panel unit root test with constant and trend in model specification.

The results in Table 4 show that the null hypothesis of non-stationarity cannot be rejected at a 1% significance level for all variables except for patent and foreign direct investment and these

Table 2
Descriptive statistics.

Variables	Obs	Mean	Std Dev.	Min	Max
CO2	322	11.476	4.688	4.543	22.484
NEC	322	20.640	20.494	0	79.511
PAT	322	45.131	52.042	0	253
Y	322	10.398	0.260	9.779	10.862
TRD	322	42.742	16.711	10.757	86.514
FDI	322	1.342	1.738	−0.726	12.763

Table 1
Variables definition.

Variable	Definition	Sources
CO2	Carbon dioxide emissions (metric tons per capita)	BP Statistical Review
NEC	Electricity production from nuclear power plants (% total)	WDI
PAT	The number of patents for nuclear fusion reactors	OECD
Y	GDP per capita (constant 2010 US$)	WDI
TRD	Sum of exports and imports of goods and services (% of GDP)	WDI
FDI	Foreign direct investment, net inflows (% of GDP)	WDI

Not: WDI is the World Development Indicators.

Table 3
Correlations and CD test results.

	NEC	CO2	PAT	Y	TRD	FDI	CD test
NEC	1.000						24.517 [0.000]
CO2	−0.307***	1.000					30.738 [0.000]
PAT	0.099*	0.523***	1.000				24.457 [0.000]
Y	0.297***	0.127**	0.246***	1.000			31.080 [0.000]
TRD	0.150***	−0.231***	−0.527***	0.236***	1.000		30.573 [0.000]
FDI	0.146***	0.074	−0.182***	0.327***	0.448***	1.000	23.256 [0.000]

Note: *** and ** indicate statistically significant correlation at 1% and 5% level. [.] is p-value.

Table 4
Panel unit root test results.

	Level		First Differences	
	Constant	Constant and Trend	Constant	Constant and Trend
CO2	−1.746	−2.274	−5.977***	−6.100***
NEC	−2.010	−2.544	−5.980***	−6.178***
Y	−1.186	−2.283	−4.903***	−4.990***
TRD	−1.779	−2.322	–	–
PAT	−3.690***	−4.279***	–	–
FDI	−4.111***	−4.407***	−4.935***	−4.992***

Note: *** and ** indicate stationarity at 1% and 5% significance level respectively.

findings indicate that patent and foreign direct investment are stationary at level. When we consider the first difference of the variables, the null hypothesis is rejected at a 1% significance level for all variables. These results indicate that it is appropriate to consider the first differences of all variables except for patent and foreign direct investment in the econometric analyses.

We employed fixed effect and random effect panel regression models and present the results in Table 5. We also conduct the Hausman test to determine which models perform well in modeling the relationship between the variables. According to the test results, we cannot reject the null hypothesis of the random effect model, and hence it can be said that the random effect model is more proper.

The random effect model results in Table 5 show that an increase in nuclear energy significantly reduces carbon emissions in G7 countries and this result is consistent with empirical findings of Menyah and Wolde-Rufael [30], Baek [57], and Dong et al. [37]. On the other hand, as in the earlier studies, we find that growth in per capita GDP significantly increases carbon emissions. It should be noted that we also consider the square of per capita GDP in the panel regression model to examine the relationship between carbon emissions and GDP in terms of the environmental Kuznets model but the estimate of the square of per capita GDP is not found to be statistically significant. The estimated coefficient of trade openness is positive and statistically significant at a 10% level and this result indicates that an increase in international trade deteriorates the environmental quality in G7 countries. This finding is consistent with the empirical findings of Shahbaz et al. [60]. Although the effect of foreign direct investment on carbon emissions is negative, it is not found to be statistically significant at the conventional level.

The results in Table 5 show that nuclear energy significantly reduces carbon emissions in G7 countries. We now focus on investigating whether the relationship between nuclear energy and carbon emissions is asymmetric due to process improvements in nuclear power plants. In other words, we examine whether the impact of nuclear energy on carbon emissions is asymmetric for a certain innovation threshold. In this context, we investigate the presence of threshold effect for the relationship between nuclear energy and carbon emissions when the number of patents for nuclear fusion reactors is considered as a threshold variable. Hence, we employ an LR test where the bootstrap resampling procedure with 1000 repetitions is used to calculate the critical values. Note that the threshold value is obtained by using grid search to minimize the sum squared of residuals (SSR).

The test results that are presented in Table 6 show that the null hypothesis of no threshold effect can be rejected at a 5% significance level. We also examine the presence double threshold effect and we cannot reject the null hypothesis of a single threshold. These results show that the number of patents for nuclear fusion reactors acts as a threshold effect for the relationship between nuclear energy and carbon emissions and hence linear model for the relationship in question is not suitable. Note that the threshold value is determined as 85.5 and this finding indicates that the relationship between nuclear energy and carbon emissions can be examined into two regimes depending on whether the number of patents for nuclear fusion is smaller or larger than 85.5.

Table 5
Fixed and random effect model results.

	Fixed Effects			Random Effects		
	Coefficient	Std. Error	p-value	Coefficient	Std. Error	p-value
Constant	−0.238	0.044	0.000	−0.230	0.057	0.000
ΔNEC_{it}	−0.035	0.006	0.000	−0.036	0.006	0.000
ΔY_{it}	10.235	1.440	0.000	10.177	1.511	0.000
ΔTRD_{it}	0.015	0.007	0.053	0.015	0.007	0.054
FDI_{it}	0.004	0.010	0.689	−0.001	0.009	0.902
Obs	315			317		
N of Country	7			7		
Time Effects	No			No		
R^2	0.366			0.357		
F-stat	41.56 [0.000]			175.93 [0.000]		
Hausman Test	0.23 [0.993]					

Note: We use robust standard errors suggested by Driscoll and Kraay [61] when there is cross sectional dependence. F-stat indicates the F statistics for testing whether the all-regression coefficients are significant. [.] is p-value.

Table 6
Threshold effect test.

H_0	H_1	Threshold	SSR	LM Statistics	Decision
None	Single	85.50	31.743	22.71 [0.012]	Reject
Single	Double	49.00	31.073	5.820 [0.884]	Accept

Note: SSR is the sum of squared residuals.

Table 7
Threshold model results.

	First regime ($\gamma \le 85.5$)			Second regime ($\gamma > 85.5$)		
	Coefficient	Std. Error	p-value	Coefficient	Std. Error	p-value
Constant	−0.242	0.030	0.000			
ΔNEC_{it}	−0.034	0.009	0.000	−0.046	0.025	0.073
ΔY_{it}	8.861	0.953	0.000	19.979	2.350	0.000
ΔTRD_{it}	0.014	0.007	0.041	0.035	0.026	0.173
FDI_{it}	0.009	0.013	0.454	−0.069	0.057	0.227
N	270			52		
R^2	0.389					
F-stat	26.62 [0.000]					

Note: F-stat indicates F statistics for testing whether the all-regression coefficients are significant. [.] is the p-value.

The panel threshold regression model results are presented in Table 7. Although the first regime can be named a low innovation regime, we call the second regime a high innovation regime. According to results in Table 7, negative statistically significant estimated coefficients for nuclear energy in both regimes indicate that an increase in nuclear energy significantly reduces carbon emissions. It should be noted that the estimated coefficient for nuclear energy in the second regime is found to be lower than the estimated coefficient for nuclear energy in the second regime and this finding indicates that nuclear energy reduces carbon emissions more than after a certain innovation level. More specifically, we calculate the mean elasticity for nuclear energy as 6.29% in the first regime and this result suggests that a one percent increase in nuclear energy reduces carbon emissions by nearly as 6%.[1] In the second regime, the mean elasticity for nuclear energy is 8.27% and hence one percent increase in nuclear energy reduces carbon emissions by nearly 8%. Therefore, it can be said that nuclear energy reduces carbon emissions by 2% more after a certain level of innovation. Our empirical finding suggests that innovations in nuclear energy power plants provide a significant accelerating effect on reducing carbon emissions.

Also, growth in the per capita GDP negatively affects environmental quality in both regimes. In other words, an increase in the per capita GDP leads to a rise in carbon emissions and this effect is higher in the second regime than in the first regime. We find that the impact of trade openness on carbon emissions varies according to regimes where an increase in trade openness causes to rise in carbon emissions in the first regime. On the other hand, the impact of trade openness on carbon emissions is not statistically significant in the second regime. We cannot determine a significant relationship between foreign direct investment and carbon emissions in both regimes.

Although our econometric model is different from the EKC model, the analysis results can be interpreted in line with the EKC hypothesis when the number of patents for nuclear fusion reactors is considering as an indicator of technological progress. Therefore, it can be said that positive and significant relationship between carbon emissions and per capita GDP in both regimes is contradictory with the EKC hypothesis. However, the insignificant relationship between carbon emissions and foreign direct investment in both regimes and the positive and significant relationship between carbon emissions and trade in the first regime can be explained by the scale effect. On the other hand, the insignificant relationship between carbon emissions and trade in the second regime is inconsistent with the EKC hypothesis. This finding may have been obtained due to using the number of patents for nuclear fusion reactors as a threshold variable.

Table 8
Threshold effect test for alternative and nuclear energy consumption.

H_0	H_1	Threshold	SSR	LM Statistics	Decision
None	Single	85.50	32.844	26.27 [0.001]	Reject
Single	Double	2.50	32.007	7.06 [0.765]	Accept

Note: SSR is the sum of squared residuals.

5. Robustness checks

In this section, we examine the robustness of our findings by using the alternative nuclear energy consumption measurement. To that end, as in Ozturk [72] and Alam et al. [51] we consider the alternative and nuclear energy as a percentage of total energy use as a proxy for nuclear energy consumption. The data for alternative and nuclear energy is obtained from World Development Indicators.[2] We start the analysis by first testing the presence of the threshold effect by using the LR test. The test results in Table 8 show that the null hypothesis of no threshold effect can be rejected at a 1% significance level. On the other hand, we cannot find evidence in favor of the double threshold effect because the null hypothesis of a single threshold cannot be rejected. As in per result in Table 6, the threshold value is determined as 85.5 and this finding again indicates that the relationship between alternative/nuclear energy and carbon emissions can be examined into two regimes depending on whether the number of patents for nuclear fusion is smaller or larger than 85.5.

The panel threshold model results are presented in Table 9. The results in Table 9 show that the impact of nuclear energy on carbon emissions is not statistically significant in the first regime. On the other hand, the weight for nuclear energy is estimated as negative and statistically significant at a 5% level in the second regime. These findings suggest that although there is no significant relationship between nuclear energy and carbon emissions in the first regime, increase the share of nuclear energy in the total energy consumption significantly reduces carbon emissions in the second regime. Overall, it can be said that the relationship between carbon emissions and nuclear energy consumption is asymmetric and also depends on a certain level of innovations for the nuclear energy plants and hence process improvements for nuclear energy power plants not only increases energy efficiency but also positively contribute for environmental quality.

5. Conclusion and policy implications

In this study, the effect of nuclear energy consumption and technological innovation on CO_2 emissions was investigated for the period 1970–2015 by using the Panel Threshold Regression Model in G7 countries. The number of patents for nuclear power plants was taken as the threshold variable. Empirical findings indicated

[1] The mean elasticity for nuclear energy is calculated as $\beta \times (\overline{NEC} / \overline{CO2})$.

[2] The integration level of alternative and nuclear energy consumption series is found to be one according to unit root test results.

Table 9
Threshold model results for alternative and nuclear energy consumption.

	First regime ($\gamma \leq 85.5$)			Second regime ($\gamma > 85.5$)		
	Coefficient	Std. Error	p-value	Coefficient	Std. Error	p-value
Constant	−0.278	0.031	0.000			
$\Delta ANEC_{it}$	0.031	0.021	0.143	−0.219	0.104	0.038
ΔY_{it}	8.933	0.973	0.000	20.490	2.403	0.000
ΔTRD_{it}	0.015	0.007	0.033	0.030	0.026	0.253
FDI_{it}	0.024	0.012	0.060	−0.061	0.058	0.288
n	270			52		
R^2	0.366					
F-stat	24.48 [0.000]					

Note: F-stat indicates F statistics for testing whether the all-regression coefficients are significant. [.] is p-value.

that the relationship between nuclear energy consumption and carbon emissions differs in terms of innovation for nuclear power plants. It was also concluded that nuclear energy consumption reduces carbon emissions more after a certain level of innovation. More specifically, when the number of patents for nuclear power plants in these countries is below 85.5, a 1% increase in nuclear energy consumption reduces carbon emissions by about 6%. In addition, when the number of patents is above 85.5, a 1% increase in nuclear energy consumption reduces carbon emissions by approximately 8%. These results indicate the effect of technological innovation on reducing CO2 emissions. The fact that nuclear energy consumption has a positive effect on environmental quality and that expenditures on technological investments further increase this effect is the point that policymakers should not ignore. Prominent policy recommendations on increasing the benefiting nuclear energy and encouraging technological investments in nuclear energy are as follows:

The position of nuclear energy in alternative energy sources should be preserved. However, it should be emphasized that positive contributions of an energy source to environmental quality do not require dependence on this energy source. Each country should implement a resource diversification strategy by evaluating the potential of its energy resources. Instead of being dependent on a single energy source, policymakers should take measures to reduce the environmental costs of each energy source by increasing technological investments.

G7 countries should allocate more resources to technological investments that strengthen the CO_2-reducing effect of nuclear energy. Researches on nuclear fusion reactors need to be encouraged to contribute to reducing the environmental costs of nuclear energy. The main property of the nuclear fusion reactor is producing more energy by using less fuel. This advantage brings a reduction in environmental degradation. Technological development in nuclear energy contributes to the reduction of risks in nuclear energy and the improvement of the negative perception of the public, as well as energy savings and an increase in environmental quality.

Reducing construction and financial costs are very important. Although great labor cost savings can be achieved through the application of innovative technologies in construction processes, further reductions in the costs of construction processes are required. Such large investments cannot be fulfilled without government interventions. Government loan guarantees can be a good support in infrastructure construction processes. Suppliers such as pressure vessels for housing nuclear reactors and the cooling systems must be constructed to extremely high standards that can eliminate the risks of accidents. Besides, the presence of experienced, skilled, and trained workers is very important in minimizing the risks. Training and qualification programs to protect both the reactor and the environment must be included in all nuclear energy production facilities.

Research findings showing that the increase in nuclear energy consumption in developed economies and technological investments in the field of nuclear energy make positive contributions to environmental quality are also important for developing economies as they guide the policies to be implemented.

In this study, the effects of nuclear energy consumption and nuclear energy-related innovation technological innovation on environmental quality were investigated. There are many reasons affecting the level of nuclear energy consumption such as GDP, population, prices of other energy resources, allocation of resources, and legal regulations. In the future studies, the effects of those factors on nuclear energy consumption can be investigated. In addition, the G7 countries were included in our study. Since the developing countries need more energy as their economies grow, fast developing countries such as China and BRICS, can be included to analyses. Finally, the Panel Threshold Regression Model was preferred for the econometric analysis. Similar analyses can be made by different econometric models.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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