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Causal relationship between nuclear energy, carbon-di-oxide emission and economic growth. Empirical evidence from China

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The present study aims to explore the role of nuclear energy production in aiding the sustainable economic growth of Chine by exploring the underlying causal relationship between reducing Carbon-di-oxide emissions and nuclear energy production. The study also aims to explore the relationship between economic growth and nuclear energy production in the Chinese context. Besides that, the present research also provides evidence in favor of nuclear energy in terms of controlling the overall emissions target of the Chinese government. The main aim of the present research is to investigate the effect of the use of nuclear energy on the Chinese Carbon-di-oxide emissions and its contribution to the growth of Chinese Gross Domestic Product by utilizing the data from 1992 to 2020. Using a modified Granger causality test, the present research identified one-way causation between the usage of nuclear energy and emissions of Carbon-di-oxide. Based on the research findings, it can be argued that by utilizing nuclear power, China can control the emissions of greenhouse gasses, to meet the global emission targets.

KEYWORDS

CO2 emission, economic growth, China, energy, nuclear

Introduction

The first nuclear power plant was established in the U.S.A., the EBR-I and initially produced four 200-W electricity, followed by "Obninsk APS-1" in 1954. This first Russian nuclear reactor produced 5 MW of electricity (Osif, Baratta, & Conkling, 2004). Given its potential, nuclear energy was once considered the solution for global warming as it was carbon neutral. Considering the negative press nuclear power has received in the past and continues to receive in the present day, it is worth noting that nuclear energy production is

responsible for reducing Carbon-di-oxide emissions by an average of 1.2 Giga tones per year if the data for the past 50 years is analyzed. The total tonnage (60 gigatons) accounts for almost 2 years of Carbon-di-oxide emissions related to energy production (F. Birol, 2010). The role of nuclear energy in powering sustainable economic growth in developed economies cannot be disputed. Still, with time's passage, nuclear energy seems to fade out, owing to advancements in the production of renewable energy sources and the international backlash. If this trend continues by 2040, almost two thirds, and its economic and social consequences as it applies, there would be a gap of almost 13%, amounting to 1,600 TWh (Marchal et al., 2021; Jones, 2022). Although one cannot dispute the potential hazards associated with the use of nuclear energy at the same time, its merits also need to be considered as it can be used in conjunction with other sources to reduce net carbon emissions and avoid the global climate emergency (Rogelj et al., 2018).

Chinese government stated production of nuclear energy in mid-80's, with establishment of two nuclear power plant at Daya Bay and Qinshan. First one was established near Hong Kong while latter was established in south Shanghai. This initiative was a part of Chinese government policy for ensuing sustainable and secure energy production. The Chinese energy security policy mainly revolves around production of clean, economical and sustainable energy production and in this regard the fossil fuel-based energy production was complemented by renewable energy production which included production of nuclear energy (Hore-Lacy, 2014).

China has abundant natural resources when it comes to energy production, but major issues faced by Chinese government remains to be uneven regional distribution of these resources. Along this given the large population the per capital share of such resources is very low. Another major issue is the fragility of the eco system of the resource rich regions of China, which to most extent has hindered their optimum exploitation. This coupled with rapid industrial growth leading to ever increased demand of energy has created a gap between the energy production and consumption. Nuclear energy seems to have plugged this gap, ensuring the Chinese energy security, which is center of their strategic economic policy as well. The rapid increase in the nuclear energy capacity can be assessed from following figure.

As the indicated by the above graph one can see the rapid increase in the.

On the contrary to western policies, China has consistently increased its nuclear energy production, given that it is considered one of the largest producers of "Green House Gases". The above notion holds for developed economies such as the U.S.A, E.U. and Australia etc. In the Chinese case, the nuclear energy production is rapidly growing, and it has been estimated that in with next 10 years, China will overtake the U.S.A. as the global leader in development and export of technology related to nuclear energy (DeWit, 2022).

As part of the Chinese commitment to reducing the emissions level to zero, the Chinese government plans to substitute all of its coal-based power plants with renewable energy sources like wind and solar will take over the nation's energy supply to achieve this goal. Tsinghua University researchers performed a study last year that found nuclear power to be a close third. According to the researchers, nuclear power is more expensive than other forms of energy but is more trustworthy. The reactor is the most expensive part of generating atomic energy; hence, this has a big impact on the final cost, significantly influencing the overall cost. Even though nuclear power costs around $42 per megawatt-hour, it is much less expensive than coal and natural gas in many regions, even when borrowing rates are as low as 1.4 per cent. In nations such as China and Russia, this is the bare minimum need for infrastructure development. The cost of nuclear power in developed countries might reach $97 per kilowatt-hour if the economy grows at a pace of 10 per cent each year (N. Zhou et al., 2019). Chinese nuclear power analysts, including those at Bloomberg NEF and the IAEA, between $2,500 and $3,000 a kilowatt; the government is expected to build reactors for a fraction of past initiatives in the France and United States. China keeps the production cost concealed, but IAEA has estimated the abovementioned cost based on their analysis and available international data (Andrews-Speed, 2020).

Around 40 years ago, China launched a process of economic reforms and trade liberalization that has transformed the country from a stagnant and impoverished economy to one that now plays a key role in the world economy. The Chinese economy has witnessed one of the most stable and sustained economic growths in history since 2008, with annual growth rates averaging 9.5 per cent every year since 2008. Because of growing trade and investment with the rest of the world, China's economy has risen at a real annual Gross Domestic Product rate of 9.5% since 1979. As reported by the World Bank, China's rapid economic growth has raised the living standard of Over 800 million people from abject poverty to middle-class, resulting in the transformation of the Chinese economy from a mere agrarian economy to its status of second-largest economic power. It is the world's most powerful economy because of trade and foreign exchange. The United States has benefited from this. China is the third-largest market for U.S. exports and a significant trading partner, as it is the largest investor in securities issued by the U.S. Treasury. This factor has allowed the Federal Reserve to keep U.S national interest rates low, even in crises Figure 1 for energy consumption.

According to the I.M.F, the real Gross Domestic Product growth rate of China will decline from 14.2% in 2007 to 5.5% in 2024. According to the Chinese government, slowing economic growth has become the "new normal," and the country must shift to a new development model that is more reliant on private consumption and innovation than on fixed investment and exports to maintain its competitiveness. "The middle-income trap" occurs when a country's economic progress approaches an

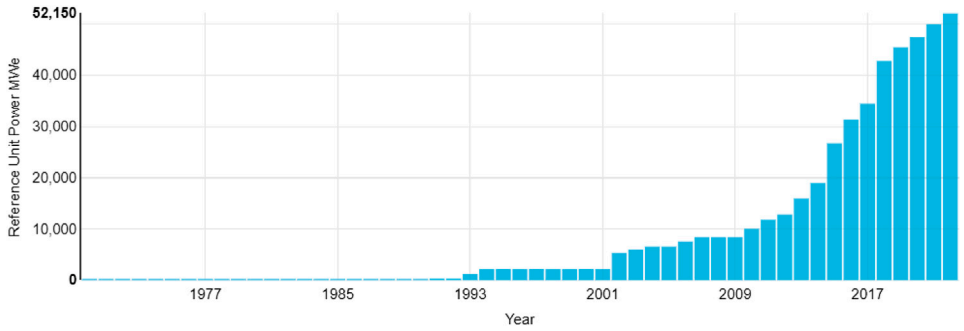

FIGURE 1
Nuclear energy consumption in China from 1998 to 2021.

impasse. The country is incapable of adopting new technologies, which could result in continuity of economic growth, such as technical innovation, resulting in dramatically lower growth rates than would otherwise be the case, so far the economic policies of the Chinese government have enabled China to avoid this trap, given the rapid increase in its middle class as a result of economic liberalization (Liu & Diamond, 2005).

Chinese firms were involved in four of the world's five largest renewable energy transactions in 2016 (Alola, Adebayo, & Onifade, 2022). The top five manufacturers of solar modules manufacturing companies are based in China, as does the world's largest maker of wind turbines (Jaeger, Joffe, & Song, 2017) Figure 2 for nuclear power plants in China and Figure 3 for Historical Gross Domestic Product Growth rate of China.

There are two fundamental issues confronting humanity: economic progress and conserving the environment. However environment has come to the forefront of contemporary issues for both developed and developing countries since the deterioration of environmental quality raises concerns about global warming and climate change arising mainly from greenhouse gases (GHGs) emissions, of which Carbon di Oxide is most abundant as its emmsion is considered to be the main cause of green house effect, leading to rise in global temertuare and distortion of climatic patterns. These distortion have lead to severe drought scrop failures and extereme weather phenomemnos (Boston & Lempp, 2011). Figure 4 shows declining trend in the net consumption of renewable energy in China.

As it is evident from the graph above that per capita Carbon di Oxide emmsions of China has steadily increased over the period of 1992–2020, as compared to its neighbour India the increase is much more rapid owing to the rapid industrailisation. While the per capita Carbon di Oxide of U.S.A. has fallen considerblily. The main cause of this can be attributed to U.S. governments green initaives. Figure 5 shows per capita CO2 emissions.

Figure 6 indicates the percentage change in per capita of Carbon di Oxide emissions of the China, which provides even paints even more bleak picture of the situation as the Chinese per capita Carbon di Oxide emissions have increased by over 200%, indicating eminent environmental consequences as the demand of energy is met by use of fossil fuel and carbon based energy sources such as coal (Ummalla & Goyari, 2019). Given the fact that majority of these natural resources are in the fragile ecosystems and combined with the fact that such increase in Carbon di Oxide emissions present a great challenge for Chinese government as it strives towards the goals of climate change. One must keep in mind the adverse impact of environmental degradation on economic sustainable sustainability, of which energy security is off utmost importance (Udemba et al., 2022).

Keeping in view the above scenario, it is of paramount importance that the role of nuclear energy in the economic development of China should be studied. The present study aims to explore the role of nuclear energy production in aiding the sustainable economic growth of China by exploring the underlying causal relationship between the reduction of Carbon-di-oxide emissions and the production of nuclear energy. The study also aims to explore the relationship between economic growth and nuclear energy production in the Chinese context. The present study adopted the Toda and Yamaoto's version of the Granger non-causality test. The present study's focus is also, whereas previous research has focused on energy use and Gross Domestic Product It has long been well-known that nuclear energy consumption and growth in Gross Domestic Product have a bidirectional causal association in many developed and developing countries in the long term.

The study comprises five main chapters first part consists of an introduction encompassing the brief history and some interesting facts about nuclear energy and its development in China, along with the main motivation of the study. The second part consists of a detailed literature review on the said topic. The third part explains the research methodology and model, while the fourth contains the results obtained from statistical tests. The fifth part consists of a conclusion; this part encompasses a brief conclusion, the study's contribution, limitations, and future research direction.

FIGURE 2
Location of planned or under-construction nuclear power plants in China.

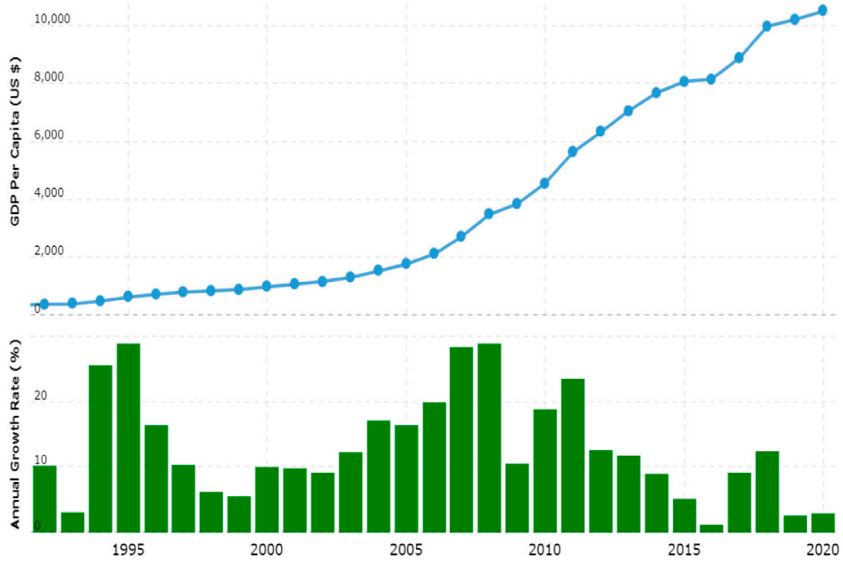

FIGURE 3
Historical Gross Domestic Product growth rate of China from1992 to 2020.

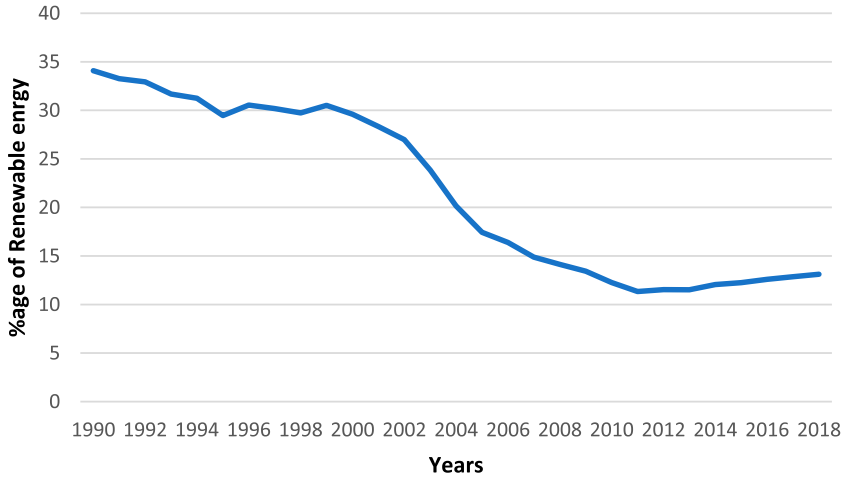

FIGURE 4
Graph depicting declining trend in the net consumption of Renewable energy in China.

Literature review

Using nuclear and renewable energy is becoming a more compelling option due to the Kyoto Protocol's requirement that signatories drastically reduce their Carbon-di-oxide emissions to tackle climate change's ever-growing menace. Since 1990, when the Kyoto Protocol was signed, all countries had agreed to reduce their greenhouse gas emissions by at least 20% below 1990 levels by 2012 (King, 2015). Carbon dioxide emissions can be reduced by utilising renewable and nuclear energy sources. Menyah and Wolde-Rufael (2010) suggested that nuclear and renewable energy, which are essentially carbon-free power sources, may be critical in the fight against global warming and the maintenance of long-term energy stability. One of the major reasons for adopting renewable energy sources is the rising prices of oil and gas, which are the main sources of fossil fuels used to

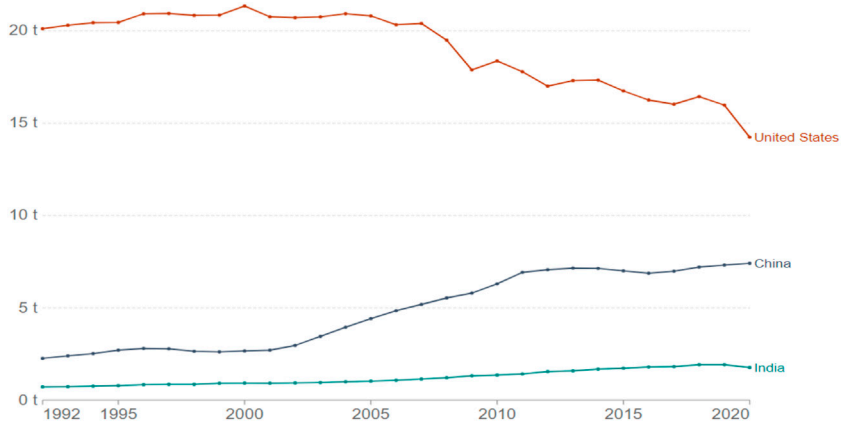

FIGURE 5
Per capita CO_2 emissions.

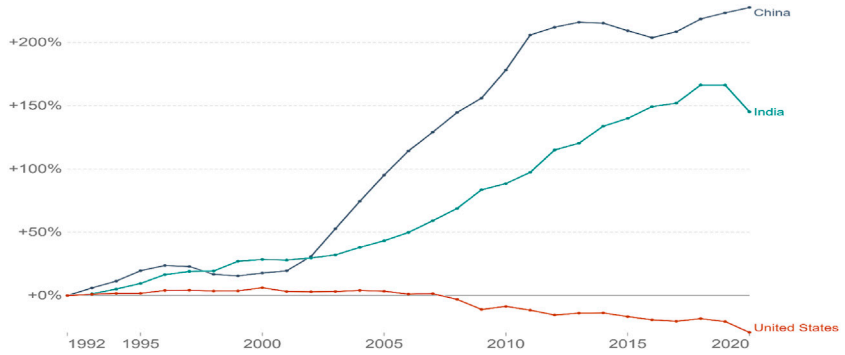

FIGURE 6
Change in per capita CO_2 emissions.

produce energy globally (Adamantiades & Kessides, 2009). Once wary of nuclear power, governments are increasingly interested in improving energy security, reducing carbon emissions, and replacing fossil fuels. Nuclear energy has the potential to become an alternative to hydrocarbons, diversify energy supplies, and improve global energy security (Wolde-Rufael, 2012). The improvement and development of renewable energy sources in the United States are now more realistic than previously imagined, even though no concrete plans for further nuclear power plants have been disclosed. Nuclear power is claimed to play a substantial role as a source of greenhouse gas emissions reduction, with nuclear reactors now accounting for around 10% of Carbon-di-oxide emissions from global energy use (Paltsev, Morris, Cai, Karplus, & Jacoby, 2012).

The adverse impact of climate change has been felt across the globe, and global climate change is considered to be one of the most prominent global issues, especially for the countries with a large population and its impact is especially pronounced in developing economies such as BRICS countries (Ummalla & Goyari, 2019). The ever-rising emissions have generated great demand from public and international pressure groups to developing countries such as China to develop environmentally friendly energy sources to further their economic growth. Nuclear energy can be considered a viable source (Gokmenoglu & Kaakeh, 2018). Renewable and Nuclear energy has been referred to as one of the major sources of reducing Carbon di Oxide emissions as it is economically and technically viable (Baron, 2013). Still, one cannot ignore the importance of developing other renewable sources of energy such as hydro, solar, and wind power (Yoo and Ku, 2009; Ummalla & Samal, 2018).

In recent decades, climate change has been the most important issue facing several countries have to deal with. This issue has prompted policymakers in developed and developing countries to find green energy sources to meet their energy needs and reduce CO2 emissions. Through the benefits of CO2 reduction, green energy sources will reduce dependence on foreign energy suppliers. The empirical literature emphasizes decarbonization of the energy sector, as it is easier to achieve than decarbonization of other sectors such as transport and industry (Shirizadeh and Quirion, 2021). In this regard, the main energy strategy in developed and developing countries is to promote renewable and nuclear energy sources to decarbonize the energy sector. One of the major reasons seldom discussed by the researcher regarding the use or adoption of green or renewable energy relates to reduced reliance on foreign countries for energy production. Therefore decarbonizing the energy sector is prioritised in the empirical research because it is more feasible than decarbonizing other sectors like transportation and industries. It is one of the crucial considerations as far as any primary energy policy of both developing and developed countries, serving both objectives of self-reliance and reduction in Carbon di Oxide emissions (Samour, Moyo, & TurgutTursoy, 2022; Udemba et al., 2022).

Meanwhile, others argue that renewables have little impact on environmental damage (Pata & Ahmed, 2022; Udemba and Tosun, 2022). In this respect, according to IAEA, the introduction of nuclear energy in the existing energy mix of developing countries can result in the reduction of global average temperature by two degrees centigrade (Philip et al., 2022; Udemba and Tosun, 2022); at the same time, this introduction would also result in a 15% reduction in the global Carbon di Oxide emission by 15% by 2050, (D. F. Birol, 2021). Carbon emissions have been taken by a majority of the researcher (Pata & Ahmed, 2022; Philip et al., 2022; Samour et al., 2022; Udemba et al., 2022; Udemba and Tosun, 2022) as standard or proxy for determining the level of pollution, but this proxy has been criticised in the past in favor of ecological footprint (Pata and Caglar, 2021). The major issue with using the ecological footprint is its inability to determine the pollution level as it can only be used to determine the adverse human impact on the environment caused by human exploitation of natural resources, but it fails to account for biocapacity.

Because of the rise in emissions of greenhouse gases and the volatility in the prices of fossil fuels, many nations are looking to alternate forms of energy to meet their energy needs, resulting in the adoption of nuclear power as an alternative. A rising trend that has lasted for 40 years has begun with an increase of almost 37% in global nuclear energy usage during the previous 4 decades. The major reason for opting for nuclear energy is to decrease their dependency on fossil fuel imports. Some countries have set themselves the objective of boosting their usage of nuclear energy. Research into how energy consumption impacts Gross Domestic Product is very widespread; however, very few studies examine how Carbon-di-oxide emissions are connected to Gross Domestic Product growth and how nuclear energy usage is tied to nuclear energy consumption, both of which are important considerations (de Castro, Gracia, Peiró, Pietrantoni, & Hernandez, 2013). There is no debate on the harmful impact of Greenhouse gasses. Farhani and Shahbaz (2014). Carbon-di-oxide emissions rise due to burning fossil fuels, producing manufacturing smoke, and burning wood. Other industries, such as agriculture and forestry, are negatively impacted by carbon dioxide emissions. Several studies by Pao, Yu, and Yang (2011); Radmehr, Henneberry, and Shayanmehr (2021) link energy usage to economic growth and long-term degradation of the environment. It is important to remember that most studies have been done in countries like the United States and Europe (Radmehr et al., 2021). One of the main hurdles in this regard is the consensus of policymakers and academics about the viable options. Many renewable energy sources are in development and therefore cannot be adopted globally. Until these options become, mature or widely available nuclear energy can be used as an alternative. It has great potential to curb the rapidly deteriorating Green House Gas situation globally (Sailor, Bodansky, Braun, Fetter, & van der Zwaan, 2000).

According to early research, economic expansion and increased energy use are the primary causes of Carbon-di-oxide emissions. According to the IAEA, nuclear power plants have reduced greenhouse gas emissions produced by OECD countries' electrical industries for more than 40 years. One of the major reasons has been the anti-nuclear energy lobbies and scientists (Mez, 2012). Such activists also include many prominent scientists who openly reject the nuclear option for curtailing Carbon-di-oxide emissions yet fail to present viable alternatives (Muellner et al., 2021). Many scientists still consider nuclear energy a low-carbon alternative to fossil fuel-based energy sources and profess that the overall benefits of nuclear energy are greater than the economic advantages of intermittent renewable energy sources (Knapp & Pevec, 2018). Based on the facts, nuclear power is a much better and more viable alternative to coal-based power plants in both environmental and financial terms. First is their limited carbon footprint. The second relates to the additional environmental taxes on coal-based power plants (Knapp & Pevec, 2018). At the same time, some researchers deem nuclear energy the only viable option for achieving the climate-related goals of the Paris agreement (Parsons, Buongiorno, Corradini, & Petti, 2019). IAEA has also pointed out many climate-friendly aspects of nuclear energy, such as low emissions, nuclear waste recycling, etc. IAEA has also pointed out these (Alam, Sarkar, & Chowdhury, 2019).

One of the main reasons for many countries not opting for nuclear power generation stems from the international embargos and the initial cost related to nuclear power generation (Buongiorno, Corradini, Parsons, & Petti, 2019). Due to the worldwide restructuring of the electrical industry, which is increasingly emphasizing economic rivalry, this problem has

become even more severe. Investors are increasingly being held accountable for financial risks formerly borne only by the public. Because of the risks involved with competitive power markets, as observed by the IAEA, "investors prefer to adopt less capital-intensive and more flexible technologies." In evaluating the economics of various power production technologies, standardized energy costs are frequently used as a tool. Every future financial flow, including expenditures and revenues (from the projected sale of energy), must be discounted to arrive at an arbitrarily chosen date of reference that is predefined but not fixed. To calculate the Levelized energy cost, the discounted cashflows spent on energy production must equal the potential cashflows generated due to the energy distribution to consumers. There are several ways to determine the price of electricity and an overview of them. Construction of the power production facility, annual fuel and operations, maintenance costs, and waste management fees decide how much it costs to generate electricity. The decommissioning of nuclear reactors is also considered a component of nuclear energy. Even though decommissioning and dealing with radioactive waste are expensive endeavors, the discounted costs of both operations, even at a discount rate other than zero, will be insignificant because most of the expenses will be incurred over an extended period (Tsapaki et al., 2018). Research on the underlying relationship between the usage of nuclear energy and economic growth presented by the increase in Gross Domestic Product is well documented.

According to past studies, a bi-directional relationship between the use of nuclear energy and the growth of the Gross Domestic Product is evident. Although nuclear energy consumption has a one-way causal link to Gross Domestic Product growth, India's Gross Domestic Product growth is influenced by nuclear energy in the long term, as held by (Wolde-Rufael, 2012). There were no significant differences between the findings of Heo, Yoo, and Kwak (2011). Similar findings were held in the cases of Switzerland. While in the cases of Pakistan and France, only a one-way relationship was evident. Using nuclear power in South Korea has been directly associated with Gross Domestic Product growth (Wolde-Rufael, 2012). Argentina's and Germany's usage of nuclear energy has never been linked to economic development (Goldemberg, 2009).

.,.,According to the findings of Lee and Chiu (2011), nuclear energy usage in Japan, the Netherlands, Canada, and Sweden directly correlated with Gross Domestic Product growth in the United States. Investigations (Lee & Chiu, 2011) also uncovered many findings in industrialized countries. According to Lee and Chiu (2011), most OECD economic growth was found to have no relationship with nuclear energy. Researchers in the United States, and Taiwan, such as A. Payne and Frow (2005) and Wolde-Rufael (2012), came to the same conclusion on the same subject. A few studies have examined only nuclear power utilization, Gross Domestic Product growth, and Carbon-di-oxide emissions. According to S. Zhou and Zhang (2010), China's use of nuclear energy is directly linked to its economic growth and its emissions of carbon dioxide. Wolde-Rufael (2012) also held a similar conclusion in the case of the United States.

According to the literature, many research conclusions vary depending on the location and country under inquiry. This disagreement might be explained because the study utilized different methodologies and periods, resulting in incompatible conclusions. Most studies attribute the rise in Carbon-di-oxide emissions to industrialization, which leads to economic growth, which is important for understanding and improving development patterns in emerging economies. It is possible for a nation blessed with vast natural resources to cut fossil fuel imports and carbon dioxide emissions significantly. According to Hassan, Baloch, and Tarar (2020), establishing an energy plan can help limit non-renewable energy sources' use. Non-renewable energy sources, on the other hand, have a considerable influence on the composition of the energy mix. This section discusses in depth how renewable and non-renewable energy sources may be sustained over the long term. There are long-term equilibrium links between environmental deterioration and energy use, according to (Mahmood, Wang, & Zhang, 2020). According to the findings, a 7% and a 20% increase in environmental degradation was seen as the variance decomposition analysis. They determined that Sierra Leone's environmental impact might be minimized by adopting clean energy in the future (Asumadu-Sarkodie & Owusu, 2017).

Furthermore, it is stated that if nuclear power had not been deployed, carbon dioxide emissions from OECD power plants would have been around one-third higher (Abdel-Wahab et al., 2013). Production of nuclear power in OECD countries enabled them to cut the annual Carbon-di-oxide emissions by approximately 1,200 million metric tons, or 10%, compared to other energy sources. According to the European Union (2006), the E.U. would have been unable to substantially impact carbon-di-oxide emissions if nuclear energy had not been available (Tsapaki et al., 2018). Several studies indicate that nuclear energy can be a practical substitute for fossil fuels and dramatically cut greenhouse gas emissions. In contrast, others argue that the immense hazards associated with nuclear energy exceed any advantages it may give (Adamantiades & Kessides, 2009). Nuclear power generation accounts for saving around 2% of the annual GHG emissions at the global level (Mez, 2012).

Research methodology

The present research relies upon the version of the Granger non-causality test established by Toda, following in the footsteps of (Menyah & Wolde-Rufael, 2010). The main advantage of this approach mainly lies in the underlying methodology as this approach perfectly fits the typical auto-regression vector

model on variables other than the first-order differential. Allowing the incorporation of the impact of long-term information into the system. This information is mainly required for differencing and pre-whitening rather than only comparing the differences between the variables, as held by the conventional methodology (Clarke & Mirza, 2006) and (Iyer, Rambaldi, & Tang, 2006). The Toda and Yamamoto test application allows restriction parameters related to V.A.R. (k), in which k represents the length of lag in the equation. The entire Toda and Yamaoto test is the modified version of the Wald test, commonly known as (MWALD). The Toda and Yamaoto test mainly allows for the correct assessment of the value k by artificially augmenting the integrational maximal order of $d_{max.}$ Once the $(k + d_{max})^{th}$ order V.A.R. is established and employing estimation, the coefficient pertaining to the last values lagged d_{max} vector can be ignored as suggested by the true Order (k) approach artificially increases the true order (k) by the greatest order of integration (d_{max}), according to the T.Y. method. The V.A.R. is computed to the $(k + dmax)^{th}$ order, and the latest delayed d_{max} vector coefficients are removed as suggested by (Pittis, 1999).

Given that the main aim of the research is to assess the underlying relationship between the consumption of nuclear and renewable energy and its impact on the level of Carbon-di-oxide emission in China, the corresponding equations for the three variables are stated as under:

$$\begin{aligned} ln\,Co_{2t} &= \alpha_0 + \sum_{i=1}^{k} \alpha_{1i} ln\,Co_{2t-1} + \sum_{j=k+1}^{dmax} \alpha_{2j} ln\,Co_{2t-j} \\ &+ \sum_{i=1}^{k} \beta_{1i}\, lnNu_{t-1} + \sum_{j=k+1}^{dmax} \beta_{2j}\, lnNu_{t-j} \\ &+ \sum_{i=1}^{k} \gamma_{1i}\, lnRE_{t-1} + \sum_{j=k+1}^{dmax} \gamma_{2j}\, lnRE_{t-j} \\ &+ \sum_{i=1}^{k} \varphi_{1i} lnY_{t-1} + \sum_{j=k+1}^{dmax} \varphi_{2j}\, lnY_{t-j} + \varepsilon_{1t} \end{aligned} \quad (1)$$

$$\begin{aligned} ln\,Co_{2t} &= \gamma_0 + \sum_{i=1}^{k} \delta_{1i} ln\,Co_{2t-1} + \sum_{j=k+1}^{dmax} \delta_{2j} ln\,Co_{2t-j} \\ &+ \sum_{i=1}^{k} \lambda_{1i}\, lnNu_{t-1} + \sum_{j=k+1}^{dmax} \lambda_{2j}\, lnNu_{t-j} \\ &+ \sum_{i=1}^{k} \pi_{1i}\, lnRE_{t-1} + \sum_{j=k+1}^{dmax} \pi_{2j}\, lnRE_{t-j} \\ &+ \sum_{i=1}^{k} \omega_{1i} lnY_{t-1} + \sum_{j=k+1}^{dmax} \omega_{2j}\, lnY_{t-j} + \varepsilon_{2t} \end{aligned} \quad (2)$$

$$\begin{aligned} ln\,Co_{2t} &= \theta_0 + \sum_{i=1}^{k} \theta_{1i} ln\,Co_{2t-1} + \sum_{j=k+1}^{dmax} \theta_{2j} ln\,Co_{2t-j} \\ &+ \sum_{i=1}^{k} \varphi_{1i}\, lnNu_{t-1} + \sum_{j=k+1}^{dmax} \beta_{2j}\, lnNu_{t-j} \\ &+ \sum_{i=1}^{k} \zeta_{1i}\, lnRE_{t-1} + \sum_{j=k+1}^{dmax} \zeta_{2j}\, lnRE_{t-j} \\ &+ \sum_{i=1}^{k} \rho_{1i} lnY_{t-1} + \sum_{j=k+1}^{dmax} \rho_{2j}\, lnY_{t-j} + \varepsilon_{1t} \end{aligned} \quad (3)$$

Where lnREt represents the natural log of renewable energy consumption (measured in billion Btu), ln NUt is the natural log of nuclear energy consumption (measured in billion Btu). When ln Yt is the natural log of real Gross Domestic Product (measured in US$), the equation is completed (a proxy for economic growth). From 1992 to 2020, all data were collected every year, with no exceptions. Global Development Indicators for 2020, published by the World Bank, served as the source of these numbers. The data relating to China's nuclear energy production was obtained from the "World Nuclear Association." World Bank data on renewable energy generation and China's Gross Domestic Product was taken from the World Bank database. According to Apergis and Payne (2010), renewable energy consumption is the net consumption of electric power generated from geothermal, solar, wind, and other renewable natural sources. It is included because it has been proved to be a substantial driver of renewable energy use short and long term, along with Carbon-di-oxide emissions (Sadorsky, 2009). According to the World Bank, a country's per capita income impacts global Carbon-di-oxide emissions. Several factors have significantly influenced the usage of renewable energy sources (Sadorsky, 2011). The amount of Carbon-di-oxide emitted is also greatly impacted by the income per capita. Given (Eq. (1)), it implies that Carbon-di-oxide emissions (ln Co_{2t}) are caused by nuclear energy consumption (ln NUt) when the Granger causation from renewable energy consumption (ln REt) is taken into consideration.

In Eq. 1, the use of nuclear energy represented by ln Nu_t, Granger causes the emission of Carbon-di-oxide represented by ln Co_2only in case if $\beta_{1i} \neq O\forall I$, while the causality from ln RE_t to ln Co_2will occur in the case of $\gamma_{1i} \neq O\forall_I$. In Equation (2), the use of nuclear energy represented by ln Nu_t, Granger causes the emission of Carbon-di-oxide represented by ln Co_2only in case if $\delta_{1i} \neq O\forall I$, while the causality from ln Nu_t to ln Co_2will occur in the case of $\pi_{1i} \neq O\forall_I$. In Eq. 3, the use of nuclear energy represented by ln Nu_t, Granger causes the renewable energy represented by ln RE_t only in case if $\theta_{1i} \neq O\forall I$, while the causality from ln Nu_t to lnRE_{2t} will occur in the case of $\varphi_{1i} \neq O\forall_I$.

Results and discussion

As a preliminary step, the natural log of the data was taken to remove any exponential variances and enabled the researcher to lift every non-zero observation as suggested by (Ummalla & Samal, 2018; Ummalla & Goyari, 2019; Ummalla, Samal, & Goyari, 2019), who conducted similar studies using the similar variables. Before conducting any causality testing, it is necessary to find the suitable lag length k [in Eqs (1) and (2), and 3)] to eliminate the possibility of deducing false causality or concluding the absence of causality when it is present (Clarke & Mirza, 2006). We determined that all series were *I*th series after conducting various unit root tests. For example, according to Hatemi-J and Irandoust (2000), the lag length (mlag) and the number of endogenous variables (m) in system (T) should be related to the sample size by the formula m*mlag = T 1/3 Konya (2004) to establish the optimal lag length for a given testing parameter. Table 1 shows statistics along with selection criterion choice of V.A.R model. Hatemi-J and Irandoust (2000) used the A.I.C,

TABLE 1 Test statistics along with selection criterion choice of V.A.R. model.

Lags	Likelihood-log	Aic	SBC	Likelihood ratio test	Adjusted likelihood ratio test
3	382.74	330.74	278.74	-	-
2	351.38	317.42	283.46	CHSQ (16) = 59.58 [0.00]	CHSQ (16) = 40.18 [0.00]
1	341.54	312.43	283.32	CHSQ (32) = 79.68 [0.00]	CHSQ (32) = 55.12 [0.00]

TABLE 2 Granger causality test.

Causality direction	Chi-squared	*p*-Value	Sum of lagged values coefficient causing variables
$ln\,Nu_t \rightarrow ln\,Co_{2t}$	6.095	0.070*	-0.045
$ln\,Co_{2t} \rightarrow ln\,Nu_t$	3.240	0.366	-0.195
$ln\,RE_t \rightarrow ln\,Co_{2t}$	1.359	0.683	-0.040
$ln\,Co_{2t} \rightarrow ln\,RE_t$	13.958	0.002***	0.551
$ln\,Y_t \rightarrow ln\,Co_{2t}$	7.921	0.042**	0.149
$ln\,Co_{2t} \rightarrow ln\,Y_t$	12.340	0.007***	0.300
$ln\,RE_t \rightarrow lnNu_t$	6.301	0.098*	0.400
$ln\,Nu_t \rightarrow lnRE_t$	4.365	0.141	0.132
$ln\,Y_t \rightarrow lnNu_t$	4.981	0.146	0.315
$ln\,Nu_t \rightarrow ln\,Y_t$	1.915	0.763	0.000
$ln\,Y_t \rightarrow ln\,RE_t$	8.354	0.040**	-0.431
$ln\,RE_t \rightarrow lnY_t$	4.952	0.306	0.491

S.B.C, L.R, and diagnostic tests to determine the length of time delayed in each circumstance. To choose between the S.B.C. and A.I.C. criteria, we utilise the L.R. test to compare the two orders of delays provided by the criteria (M. Pesaran & Pesaran, 1997). After that, we performed diagnostics to see if our chosen lag order had worked properly. It was possible to establish whether or not our models were dependable by a set of diagnostic tests, including autocorrelation, normality, and heteroskedasticity tests. None of those above tests was identified as having an insignificant impact when taken as a whole.

Table 2 depicts the results of the Granger causality test. It is apparent from the results that the direction of the Granger Causality is running N.U. To Carbon-di-oxide, without any feedback.

It has been long argued that nuclear energy tends to control or decrease the emission of greenhouse gasses such as Carbon-di-oxide. This notion applies that the lag values of the coefficient would be negative, but as far as our research is concerned, this is not the case. According to the results increase in RE did not lead to a significant rise in the emission of Carbon-di-oxide. Still, the inverse unidirectional causality between emissions and the use of renewable energy was found. According to the present research results, renewable energy, unlike nuclear, does not appear to have reduced Carbon-di-oxide emissions. Many reasons may have led to an absence of causation amongst the RE and emissions of Carbon-di-oxide.

When looking at the series beyond 1992 to 2020, the causality test described above provides no method to assess the comparative strength of Granger causality across the different series (Shan & Morris, 2002). Therefore, we resorted to applying the generalized impulse response approach developed by M. H. Pesaran, Shin, and Smith (1999). This methodology is invariant to the order of variables in a V.A.R. and does not need shock orthogonalization of the earlier described (J. E. Payne & Mervar, 2002). We split the prediction error variance of Carbon-di-oxide emissions into components attributable to shocks in every variable in the system, including the system itself, using our non-augmented V.A.R. estimation method (k lags only), allowing us to better understand the Granger causality test as a result.

According to Table 3, the use of nuclear energy accounts for about 18.3% of the expected error variance in Carbon-di-oxide emissions. According to the latest available data, renewable energy utilization may account for more than 19.2% of the expected error variance in Carbon-di-oxide emissions. However, the prediction error variance of Gross Domestic

TABLE 3 Generalized forecast error variance decomposition.

Decomposition of generalized forecast error	Horizon	Emission of carbon-di-oxide	Consumption of nuclear energy	Consumption of energy from renewable sources	Gross domestic product
Emission of Carbon-di-oxide	1	90.5	15.7	18.7	4.5
	5	87.1	18.3	19.2	7.3
	10	88.2	17.5	18.5	6.4
	15	89.4	17.3	18.5	6.4
Consumption of Nuclear Energy	1	16.4	93.7	18.7	2.2
	5	16.5	87.8	17.2	6.3
	10	16.9	87.2	17	6.3
	15	16.9	87.2	17	6.3
Consumption of Energy from Renewable Sources	1	27.2	21.9	77.2	4.1
	5	26.7	24.8	71.5	4.9
	10	26.9	24.5	70.9	5.3
	15	26.9	24.5	70.9	5.3
Gross Domestic Product	1	5.4	0.5	0.4	89.9
	5	6.7	1.5	3.5	85.8
	10	7.1	1.6	4.2	84.7
	15	7.1	1.6	4.2	84.1

Product, on the other hand, accounts for just 7.3% of the forecast error variance of carbon dioxide emissions. Renewable energy consumption, which accounts for 18.7% of the variance in nuclear energy consumption projections, may help explain the expected erroneous variation in nuclear energy consumption. Nuclear power facilities are responsible for a staggering 27.2% of the predicted error variance in renewable energy use. Based on this evidence, there may be a bidirectional relationship between nuclear energy use and renewable energy consumption. While interpreting the results of Table 3, one must keep in mind that in contrast to orthogonalized cases, in the present research, the total of rows depicting the generalized decompositions does not add to 100. As for the present research, we have applied the generalized version of the model, which provides the 'optimal 'measure of the errors for the given time series as held by 19) and further validated by Sari and Soytas (2007).

First and foremost, the proportion of overall energy consumption derived from renewable sources is steadily declining, notwithstanding significant increases in overall renewable energy production. The main reason is that the Chinese economy's energy requirement is increasing daily, even though China is the largest investor and producer of renewable energy. The demand for power-hungry and the ever-growing economic sector has outstripped renewable energy production.

Consuming renewable energy has no impact on environmental quality. The statistics demonstrate that the current usage of renewable energy is insufficient to address the environmental challenges faced by China, given the scale of the Chinese energy demand. As it is evident from the above statistics that there is a decline in the overall production of renewable energy compared to the overall energy demand. One of the prime reasons for the increase in nuclear energy production is the decrease in fossil fuels imported from politically volatile regions of the world. It is evident from the rapid increase in nuclear energy production by establishing several nuclear reactors based on the latest technology. There are also plans by the Chinese government to export nuclear technology by establishing partnership-based ventures in regional developing countries. When it comes to nuclear energy production, compared to European countries like Germany and France, the Chinese nuclear power plants and overall infrastructure is state of the art and considered one of the most efficient.

While using nuclear power improved Chinese Carbon di Oxide emissions, nuclear energy production increased from 1992 to 2020. Based on the results, it can be concluded that in the given scenario, nuclear energy has provided the Chinese government with the opportunity to decrease its dependence on foreign sorces of energy and reduce its carbon footprint.

Conclusion, policy implications, limitations, and future implications

One of the major challenges faced by China relates to producing cheap and balancing the energy production so that they also ensure the security of energy to power the continuous

growth of its economy. Such measures will also ensure that China meets its zero-emissions targets by 2060. The present research used the Granger causality test to analyze the hypothesis that nuclear power and renewable sources tend to decrease the emission of greenhouse gases such as Carbon-di-oxide. The statistical evidence indicates the presence of negative, unidirectional causality amongst the emissions of Carbon-di-oxide and utilization of nuclear energy when there is no feedback available, leading us to conclude that nuclear energy consumption will control Carbon-di-oxide emissions by reducing emissions. Meanwhile, no causality was found between renewable energy and emissions of Carbon-di-oxide. Still, the unidirectional causality was discovered between the emissions of Carbon-di-oxide and the consumption of renewable energy. These results indicate that China can control and reduce its Carbon-di-oxide emissions by incorporating nuclear energy into its existing energy infrastructure. These results support current Chinese policies regarding building new nuclear power plants in different locations. Our results align with those held by Menyah and Wolde-Rufael (2010) and contradict those of Sovacool (2008), who stated that nuclear energy production does not reduce the overall Carbon-di-oxide emissions. At the same time, our findings support the findings of (Gokmenoglu & Kaakeh, 2018), who studied the causal relationship between Spain's economic growth and nuclear energy use.

It is impossible to overstate the importance of transforming low-carbon technologies that seek to reduce emissions and promote sustainable economic development. Thanks to these measures, the green economy is maintained, and the environment is protected. There is a need for regulations that encourage people to put their money towards renewable energy sources like solar, wind, and natural gas over more environmentally damaging options like coal, petroleum, and their derivatives. Promoting energy efficiency is important since it would lead to greater energy security and lower CO2 emissions without stunting economic development. The rising population makes it difficult to slow the growth of energy use. Thus people must become more conscious of their impact on the environment. The environmental degradation issue may be solved if community awareness and government regulatory pressure work together. Increased efforts to prevent deforestation by local populations are warranted since it serves to re-release Carbon di Oxide emissions into the atmosphere. It is important to establish industry-specific emission standards and implement emission monitoring systems to guarantee that those criteria are met. Since Carbon di Oxide is not a local pollutant but a global one, perhaps international cooperation would help reduce its emissions. The growth of financial markets in these countries can help boost investment in research and development of modern energy-efficient technologies, ensuring lower emissions. The efficiency of environmental rules may be improved if these nations form a union to adopt uniform environmental acts. That doesn't discount the need for separate national environmental laws and regulations; however, if China is going to progress in combating global warming, it must look for other energy sources than the ones now available from fossil fuels. The two major challenges for Chinese economic progress relate to Energy security and climate change. These issues can be addressed by combining nuclear and renewable energy sources. Nuclear power can be used as an alternative to coal-based power generation and can be switched to renewable energy sources.

Contribution of the study

This study contributes to the existing literature on the topic by highlighting the often-ignored facts about nuclear energy, such as its contribution to reducing and limiting Carbon-di-oxide emissions globally. Besides this, given that the study analyzed the use of nuclear energy exclusively in China, it also elaborates on the positive aspects of using and expanding nuclear energy production. This study also statistically proves how nuclear energy production contributes to the Chinese government's commitments to climate change.

Unfortunately, there is a shortage of research on how nuclear power affects Gross Domestic Product and Carbon di Oxide emissions. This research not only addresses a previously unaddressed issue but also adds three significant new findings to the current body of literature. This analysis contrasts the impacts of China's increasing use of nuclear power on the country's Gross Domestic Product growth and carbon dioxide emissions. For several reasons, China is an excellent test case for examining the interconnections between nuclear power and other energy sources. To begin, China has signed the Paris Agreement, creating a worldwide framework to mitigate climate change's potentially disastrous impacts by keeping average global temperatures below two degrees Celsius. China is next only to the United States and France regarding nuclear power capacity, with 49 reactors totaling 47.5 GW and another 17 are now in the works, totaling 18.5 GW of power. None of them have been shut down as of yet. The nuclear sector now accounts for just 2% of China's electrical power, but the nation intends someday to surpass all other sources. To this day, China must contend with the effects of climate change. Finding ways to minimize pollution is crucial to China's long-term economic success. In this light, France has introduced new legislation mandating climate change analysis and disclosure in annual reports to institutional investors. This statute acknowledges that institutional investors are deemed essential to effective climate change measures.

Policy implications

According to experts, increasing sea levels, more violent storms, and longer heat waves are all expected to affect China in the next decades due to climate change. The National Climate Center of China published a report in 2020 that found that China's average temperature and sea level have increased more rapidly than the world average. Renewable energy is critical to China's efforts to curb its emissions. The government has already made significant strides in the country's move away from coal and toward this energy source. Compared to a decade ago, renewable energy sources produced only 7% of China's energy, but by 2019 they accounted for around 15% of the country's total energy mix. One of the major reasons for constructing many nuclear power plants relates to energy security issues for China. Besides that, the present research also provides evidence in favor of nuclear energy in terms of controlling the overall emissions target of the Chinese government. As Stern (2012) stated, if global warming results in a 25 percent reduction in Gross Domestic Product, then mitigating its impacts will cost around 1 percent of global Gross Domestic Product to implement. Another aspect relates to China's energy security as most global oil reserves are located in regions facing volatile situations.

With the advent of Ukraine–Russia, war prices of global energy have skyrocketed; along with this, the volatility in the oil and gas prices along with prices of essential commodities such as wheat and cooking oil has once again reminded the developed and developing countries of the importance of energy and food security. This notion holds especially true for most Populus nations of China, as the use of nuclear energy can ensure its energy security, and this energy security can also enhance its local food production as well. Thus, securing its future economic progress and the social well-being of its public.

Limitations

One of the present research's major limitations is the issues related to the stationarity of the data, which can be an issue if the data is comprised of long-time series. Future researchers can apply other statistical techniques to address such problems.

Regarding future research directions on the topic, the researchers can conduct the research using the same techniques or by applying different statistical methods using the data of other countries to test similar hypotheses.

Another major limitation relates to the availability of the data, as data for many variables are not readily available for all countries as many countries might consider the data regarding the production of nuclear energy secret.

Future direction of research

In the future, the researchers can use other statistical methods to assess the causal relationship between the economic growth, production, and consumption of nuclear energy, along this they can add other macro-economic variables such as energy security and the impact of nuclear energy on the consumption of fossil fuel, etc. Besides those researchers can also conduct regional analysis, by including different countries that use nuclear energy, and identifying whether the causal relationships vary from country to country or over time.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

All authors contributed to conceptualization, formal analysis, investigation, methodology, writing and editing of the original draft, and read and agreed to the published version of the manuscript.

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Conflict of interest

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