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Original Article

An empirical investigation of nuclear energy consumption and carbon dioxide (CO_2) emission in India: Bridging IPAT and EKC hypotheses

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ABSTRACT

The transition toward clean energy is an issue of great importance with growing debate in climate change mitigation. The complex nature of nuclear energy-CO_2 emissions nexus makes it difficult to predict whether or not nuclear acts as a clean energy source. Hence, we examined the relationship between nuclear energy consumption and CO_2 emissions in the context of the IPAT and Environmental Kuznets Curve (EKC) framework. Dynamic Auto-regressive Distributive Lag (DARDL), a newly modified econometric tool, is employed for estimation of long- and short-run dynamics by using yearly data spanning from 1971 to 2018. The empirical findings of the study revealed an instantaneous increase in nuclear energy reduces environmental pollution, which highlights that more nuclear energy power in the Indian energy system would be beneficial for climate change mitigation. The results further demonstrate that the overarching effect of population density in the IPAT equation stimulates carbon emissions. Finally, nuclear energy and population density contribute to form the EKC curve. To achieving a cleaner environment, results point out governmental policies toward the transition of nuclear energy that favours environmental sustainability.

1. Introduction

The industrialization has led to increases in energy supply and demand as a result of economic growth and development. As stated by Sarkodie and Adams, (2018), modernization is expected to at least double the world energy supply from 2016 to 2030 as a result of changing lifestyles and increased need for modern energy access. However, several environmental problems have also emerged as a byproduct of better living conditions; for instance, out of them, climate change is among the most challenging problems the world is facing in the early 21st century [2]. Over the last century, the average world temperature has raised between 0.4 °C and 0.8 °C, and it is predicted that it could increase between 1.4 °C and 5.8 °C till 2100 [3]. In recent decades, climate change has created its problems such as accelerated melting of polar ice caps, rising sea levels, reduced availability of freshwater, heavy weather conditions, the rapid spread of disease, and loss of biodiversity [4]. As a responsible factor for climate change and global warming, the increased levels of greenhouse gases (GHGs) emissions worldwide are taken into consideration. In particular, among GHGs emissions, carbon dioxide (CO_2) emissions produced by fossil fuel combustion are accepted as a key factor behind global warming [5,6].

The widespread use of conventional energy sources such as coal, oil, and gas is the basis for climate change and global warming problems mentioned above. According to the estimates of the International Atomic Energy Agency [7], the production and consumption of energy are responsible for almost two-thirds of total GHGs emissions. In this context, increasing energy efficiency and switching to clean energy sources are considered as two main options for reducing the harmful effects of climate change [8]. Therefore, energy has (and will have) an essential role in the development process of the 21st century. Also, energy efficiency and environmental quality have a significant role in designing future policies for the planet [9]. To this aim, many countries have been searching for alternative energy sources to meet their increasing energy demand against the danger of global warming as well as avoiding the uncertainty in price fluctuation of fossil fuels [10]. As such, the increasing scarcity of fossil fuels and the growing

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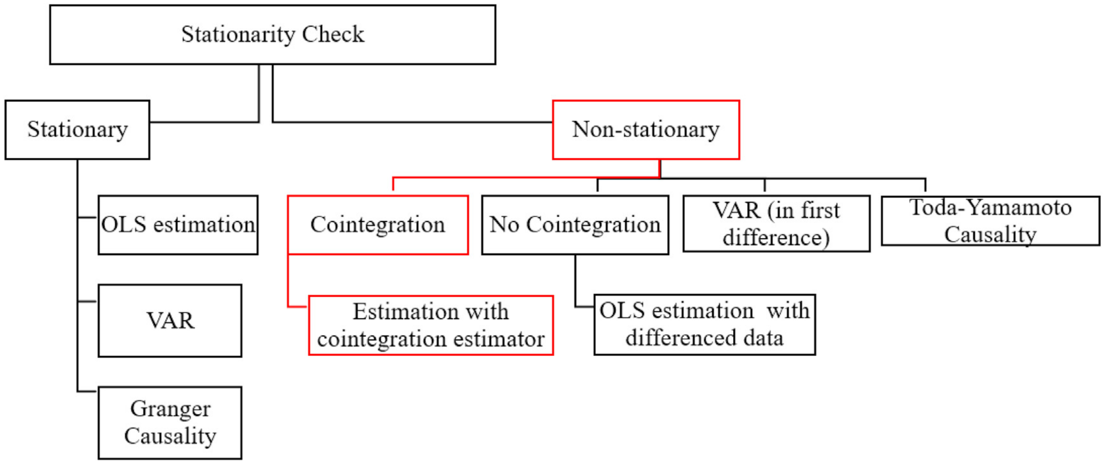

Fig. 1. The basic framework of empirical strategy.

Table 1
Result of unit root test.

Variables	Phillips-Perron		DF-GLS	
	Level	First difference	Level	First difference
$\ln CO_2$	2.086	−27.025 *	−0.935	−6.285 *
lnGDP	1.506	−40.548 *	−0.435	−8.377 *
$\ln GDP^2$	1.756	−34.467 *	−0.071	−8.377 *
lnNUE	0.655	−35.401 *	−1.619	−5.740 *
lnPOP	−0.725	4.841 *	1.270	−2.803 ***

Note: *, ** & *** means significance at level 1%, 5% and 10% respectively.

world energy demand have created a renewal of the discussions on future energy needs [9]. In this context, both renewable and nuclear energy sources have potential on the way to be the energy sources of the future. They are expected to provide solutions to the problems of energy security and climate change [11,12], which are the challenges facing many countries. GHGs emissions from nuclear and renewable energy sources are between one and two orders of magnitude below emissions from fossil fuel sources [13]. In this respect, both energy sources have gained prominence in the eyes of policymakers because of their cost-effective and environmentally friendly natures [1] since the substitution of scarce fossil fuel sources with renewables and nuclear energy is likely to provide environmental quality and to reduce the energy dependence of countries.

Given the importance of nuclear energy for a clean environment, we can assert that the Paris Agreement, adopted in 2015 and entered into force in 2016, has a special place in the development of nuclear energy. This agreement aims at keeping the increase in global average temperature to below 2 °C above pre-industrial levels, and nuclear energy that is a proven low carbon technology is accepted to make a significant contribution to the achievement of the climate change target of the Paris Agreement [7]. Particularly, nuclear energy has initially gained importance as a result of volatile fossil fuel prices (e.g., high oil prices), high dependence on foreign

Table 3
Result of dynamics ARDL.

Regressor	Coefficient	[prob.]
$\ln CO_{2,\ t-1}$	−0.3188 *	0.005
ΔlnGDP	0.7455	0.682
lnGDP	2.7306 *	0.006
$\Delta \ln GDP^2$	−0.0721	0.615
$\ln GDP^2$	−0.2012 *	0.003
ΔlnNUE	−10.943	0.144
lnNUE	−19.356 *	0.003
ΔlnPOP	25.188 **	0.039
lnPOP	0.3933 **	0.017
Constant	7.7731 *	0.008
R^2	0.91	
Sim	5000	
F-statistic	8.14	0.0000
Diagnostic test		
DW	2.25	
$\chi^2_{LM\text{-}ARCH}$	0.887	0.346
$^2_{LM\text{-}B\text{-}G}$	1.604	0.205
$\chi_{Ramsey\ RESET}$	0.45	0.717

energy sources, concerns about the security of energy supply, and global climate change [13,14]. After the oil crisis in 1973, oil-importing countries attached much more importance to the security of energy supply, and nuclear became the main competitor of oil in electricity generation [15]. However, in the 1990s, several countries cancelled their nuclear projects because of electricity market deregulations, a slower increase in electricity demand, and the public opposition after the accidents at Three Mile Islands in 1979 and Chernobyl in 1986 [16]. Moreover, the noteworthy role of nuclear energy use in economic growth has led policymakers to employ nuclear energy as an alternative source for their growing energy needs [17].

Nuclear energy is at the heart of zero-emission scenarios because it is the most precious energy in terms of resources, carbon emissions, and economics [18]. Nuclear energy, by producing low-

Table 2
Results of Bayer-Hanck cointegration and bound test cointegration test.

Bayer-Hanck cointegration test			
Estimated Model	EG-JOH	EG-JOH-BO-BDM	Decision
$LnCO_2 = f(\ln GDP, \ln GDP^2, \ln NUE, \ln BIO, \ln POP)$	15.690948	25.456171	Cointegration

Notes: Critical values for EG-JOH and EG-JOH-BO-BDM are 10.637 and 20.486 respectively.

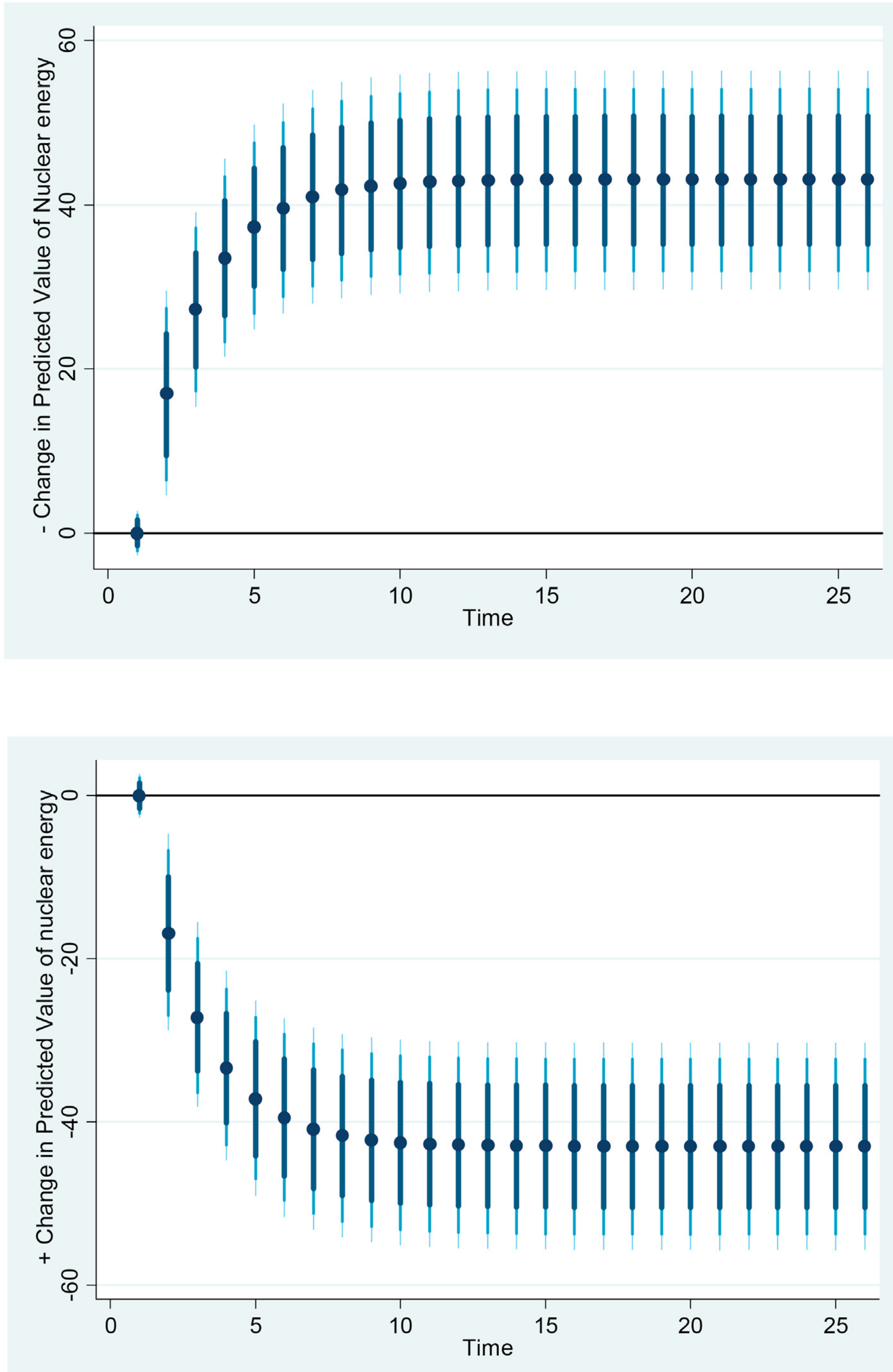

Fig. 2. Predicted emissions with ± Change in Nuclear energy.

carbon electricity, has achieved a global interest as one of the most effective tools for limiting pollution [3]. In recent times, nuclear power plants have saved 1.5–2 billion tons of GHGs emissions every year since 1990 [2]. [19] estimated that emissions from electricity generation and total energy-related emissions between 1971 and 2018 would have been almost 20% and 6% higher without nuclear power. Besides, nuclear energy makes a significant contribution to the world's electricity generation; for instance, %10 and % 18 of the electricity production, respectively, in the world and advanced countries were met by nuclear sources.[1] Therefore, currently, nuclear energy provides an important contribution to electricity generation with low-carbon emission, particularly in developed countries. Additionally, it is planned to increase the amount of electricity produced from nuclear energy to 25% of the world electricity by 2050 [1].

Besides its advantage above-mentioned, electricity generation from nuclear energy involves some potential risks though it is a

[1] See https://www.world-nuclear.org/information-library/current-and-future-generation/world-energy-needs-and-nuclear-power.aspx (Access date: 29.05.2020).

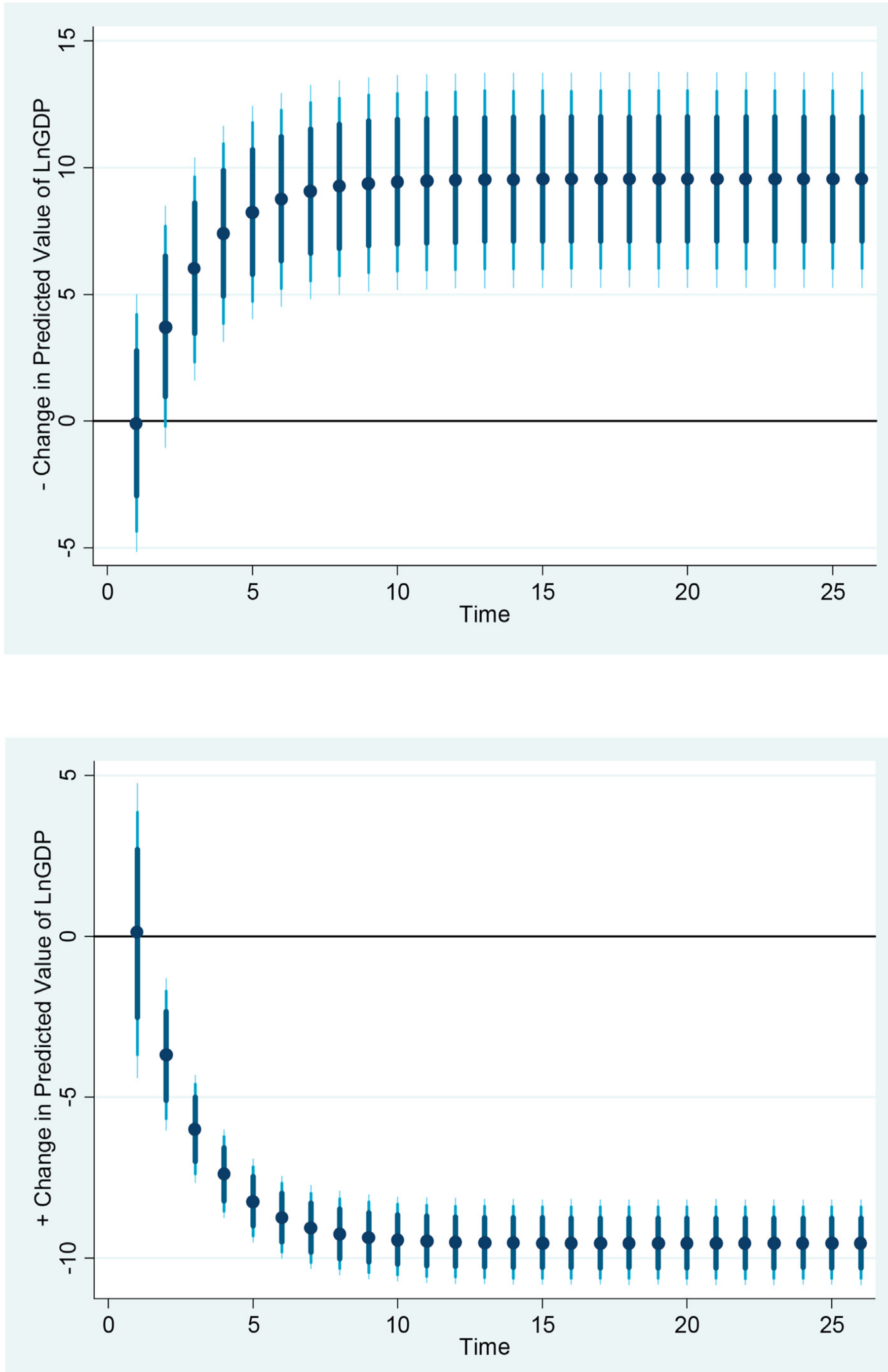

Fig. 3. Predicted emissions with ± Change in per capita GDP.

carbon-free source of energy generation. There are discussions and doubts amongst the public and policymakers on the implementation of nuclear power plants [20]. In this respect, there exist some concerns about nuclear power plants such as economic performance, the proliferation of dangerous material, the peril of terrorism, operation safety, and radioactive waste disposal, which contribute to a low social acceptation [13,15,17]. Additionally, the risks of reactor accidents with widespread environmental and health effects and the diversion of nuclear technologies for military or terrorist purposes are the essential drawbacks of nuclear energy [21]. Moreover, nuclear power generation includes high external costs to secure nuclear facilities against terrorist attacks, store highly radioactive waste, pay for insurance against the cost of sudden accidents, and apply safeguards to sensitive activities such as fuel-making [22,23]. When we evaluate its pros and cons together, it appears that nuclear energy will continue to have a unique role in the energy mix of countries.

The major contributions of this study are threefold: First, to the best of our knowledge, there is no study analyzing the impact of nuclear energy on air pollution for India in the literature. As is

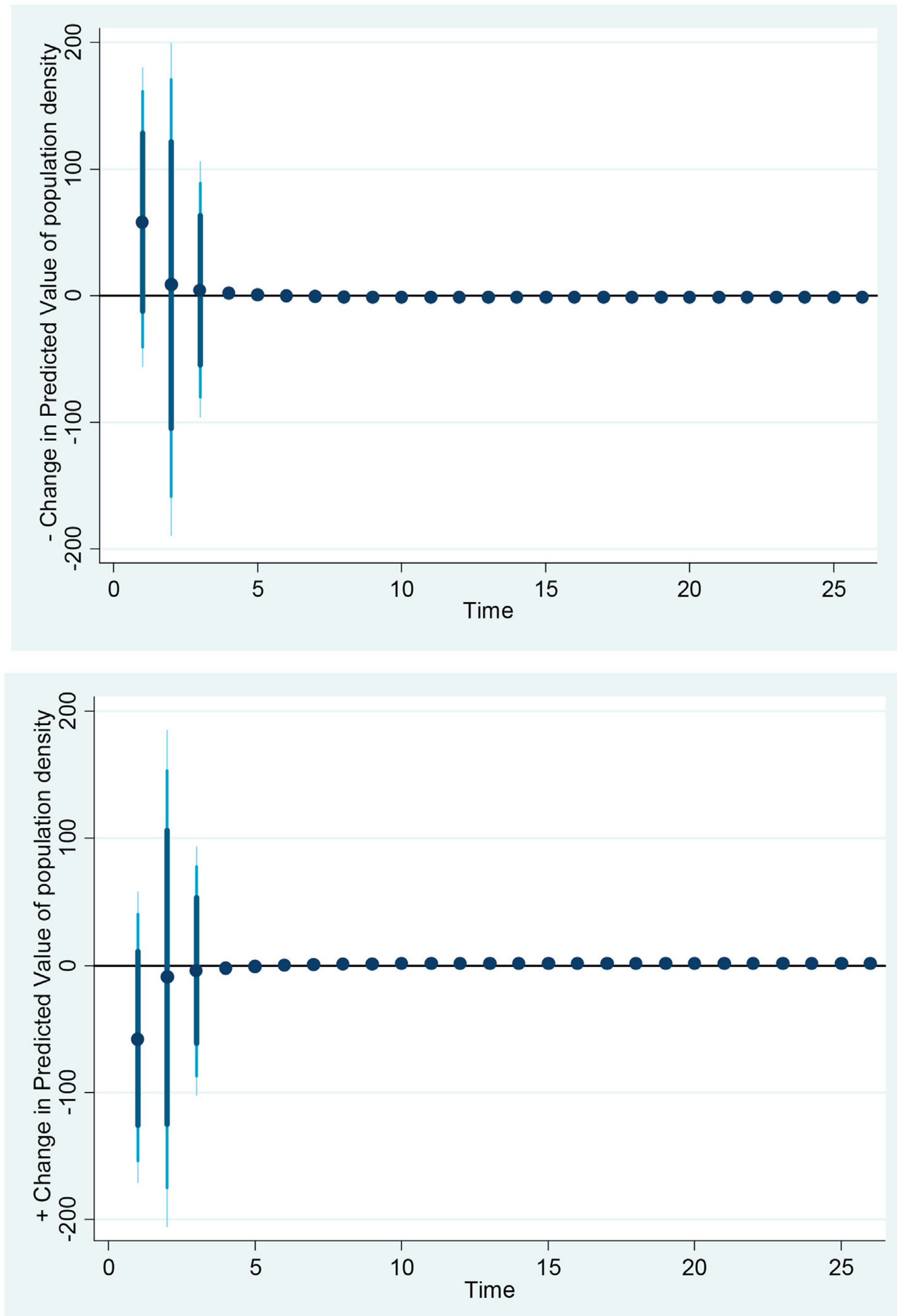

Fig. 4. Predicted emissions with ± Change in Population density.

explained below, India deserves a special research interest since it has a vast and growing population that creates heavy pressure on the environment. Most Indian people are living in rural areas and have a large dependence on fossil fuels for cooking, heating, and so on, which, in turn, results in increased air pollution. In 2018, India was the third-largest CO_2 emitter, following China and the U.S. However, India also has a large nuclear energy potential with its twenty-two operable nuclear reactors. Therefore, if India designs a proper and wise nuclear energy strategy, its air pollution problem is likely to be solved in the coming years. Second, besides nuclear energy-environmental pollution nexus, the traditional EKC hypothesis, which undertakes an inverted U-shaped relationship between pollution and income, is also tested for India in this study. Third, different from the available literature, this study applies a newly developed econometric approach, dynamic autoregressive distributed lag (DARDL) simulation, by following the EKC and IPAT models extended with nuclear energy. This method obtains, stimulate, and automatically plot estimations of deceptive change in one dependent variable on the response variable keeping other factors constant. Besides, this method helps to decrease the multifaceted nature and interpretation related issue of the existing ARDL model.

The remainder of the paper is organized as follows. Section 2 explains the situation of nuclear energy in India; Section 3 provides a literature review; Section 4 describes data and methodology; Section 5 provides empirical results and discussion, and finally, Section 5 concludes the study with some policy suggestions.

2. Literature review

Over the last few decades, the relationship between nuclear energy, CO_2 emissions, and economic growth has been the issue of numerous academic researches [14]. The related studies can be classified based on their samples, i.e. single country studies (time-series studies) versus multi-country studies (panel data studies).

The first research strand includes time-series studies, and most of them employed an autoregressive distributed lag (ARDL) testing approach to check the cointegration relationship between study variables and to estimate cointegration parameters [1,5,20,22,24–28]. Of them, for Japan [24], revealed that nuclear energy consumption contributes to carbon emissions mitigation only in the short-run over the period 1970–2010. For China [25], analyzed the impacts of fossil fuels, nuclear energy, and renewable energy on CO_2 emissions for the period 1993–2016. They confirmed the EKC[2] hypothesis and indicated that nuclear energy consumption reduces carbon emissions in both the long-run and the short-run. For France [26], analyzed the relationships between electricity generation sources and economic growth using monthly data from January 2010 to November 2014. They found that nuclear energy contributes to economic growth and lowers CO_2 emissions. They obtained that nuclear energy reduces CO_2 emissions only in Finland, Japan, Korea, and Spain while confirming the EKC relationship only in Finland. For Korea [28], tested the EKC hypothesis by considering energy consumption, electricity production from fossil fuels, and nuclear energy for the periods 1971–2007 and 1978–2007. They confirmed the EKC and found that nuclear energy decreases CO_2 emissions in both the short- and the long-run. Likewise, for the US [5], explored the role of nuclear and renewable energy consumption in environmental pollution for the period 1960–2010. They obtained that nuclear energy reduces CO_2 emissions in both the short-run and the long-run; however, they couldn't provide evidence for the EKC relationship. For Pakistan [20], analyzed the relationships between nuclear energy and CO_2 emissions between the years 1973 and 2017. Their results indicated that nuclear energy increases CO_2 emissions and confirmed a feedback relationship between nuclear energy and CO_2 emissions. For South Africa [1], examined the effects of disaggregate and aggregate energy consumption, economic development, urbanization, and institutional quality on CO_2 emissions using data from 1971 to 2017. They found that nuclear energy increases emissions in the short-run and confirmed the EKC hypothesis.

Other than the ARDL approach to check the cointegration relationship and estimate cointegration parameters, a few time-series studies employed different methods. For instance, using a multivariate cointegrated vector auto regression (CVAR) model and Johansen cointegration approach [6], found that nuclear energy lowers CO_2 emission in the US, France, Japan, Canada, Spain, and Korea. However [29], found that CO_2 emissions are in an insignificant relationship with nuclear energy consumption by using the Johansen cointegration test and Granger causality test. For China, based on an input distance function between the years 1981 and 2015 [30], found that nuclear energy can replace fossil fuels better than renewable energy since it has a more reducing effect on CO_2 emissions. For Iran [31], based on two scenarios, found that the Bushehr nuclear power plant will decrease CO_2 emissions level in the Iran power sector. Lastly, a city-level analysis was employed by Ref. [18] for Madrid during the period 2014–2024. They revealed that the number of saved emissions would be quite a lot of the electricity consumed for recharging the batteries of hypothetical battery electric vehicles (BEVs) was produced from nuclear power.

The second research line consists of panel data studies mostly used panel cointegration tests [32,33], long-run panel estimators (fully modified ordinary least squares (FMOLS), dynamic ordinary least squares (DOLS), and pooled mean group (PMG) and panel Granger causality test (see Refs. [2,10,11,14,17,34–38]). Only a few the panel studies employed different econometric approaches (see Refs. [3,39].

Some panel data studies focused on developed and developing country samples (see Refs. [2,11,14,17,36,37]. However, for a panel consisting of 18 developed and developing countries from 1990 to 2013 [37], couldn't find any significant relationship between nuclear energy and CO_2 emissions and couldn't support the EKC hypothesis. Likewise [14], for nine developed countries over the period 1990–2013, showed an insignificant relationship between nuclear energy and CO_2 emissions, whereas [2] obtained that nuclear energy reduces GHGs and carbon emissions for a panel of 35 developed countries from 1975 to 2012. Additionally, in a similar testing methodology [36], obtained that nuclear energy does not decrease carbon emissions for 30 countries from 1990 to 2014. Moreover, they confirmed the short-run bidirectional causality between nuclear energy consumption and carbon emissions. [17], for a panel including 25 developed and developing countries for the period 1993–2010, confirmed a strong form of causality running from nuclear energy to CO_2 emissions for developed countries, no significant relationship was achieved between nuclear energy and CO_2 emissions while for developing countries.

Similarly [3], using data from 1995 to 2015 for 18 OECD countries, confirmed the importance of nuclear energy in reducing carbon emissions while confirming the EKC hypothesis. Lastly, few studies selected major NE generating or consuming countries as samples (see Refs. [10,34,38]. For instance, for 30 major nuclear energy-consuming countries [10], found that nuclear energy consumption doesn't affect CO_2 emissions during the years 1990–2010. Using a similar testing approach for 12 major nuclear-generating countries [34], obtained that nuclear energy reduces CO_2 emissions, and the EKC hypothesis is not valid for the period 1980–2009. For a panel of 18 countries with more than four nuclear reactors [38], confirmed the EKC hypothesis for France, Germany, and Switzerland and revealed that a 1% increase in nuclear energy generation reduces CO_2 emissions about a 0.26–0.32% for the whole sample during the period 1970–2015.

In the related literature, there is not any study analyzing the nexus of income-nuclear energy and the environment for India. As stated before, India is a special and good case because it is one of the largest carbon emitters and also has large nuclear energy potential. Revealing the link between nuclear energy and air pollution will likely shed some light on policymakers to design proper energy and environmental policies.

3. Materials and methods

3.1. Model specification

Energy and CO_2 emission studies are analyzed by using several model combinations, including the IPAT model firstly formulated by Ref. [40], which investigates the impact of the population (P), affluence (A), and technology (T) on CO_2 emissions (I). Earlier studies have ignored the IPAT hypothesis while investigating nuclear energy and CO2 emission nexus [20,25]. Following [41] the IPAT approach can be stated as STIRPAT in case of parameter estimations based on stochastic processes "Stochastic Impacts by Regression on Population, Affluence, and Technology", and can be

[2] The EKC hypothesis assumes the presence of an inverted U-shaped relationship between economic development and environmental pollution. It suggests that economic development initially causes environmental deterioration, however, beyond a certain level of per capita income, this deterioration starts decreasing along with economic growth.

combined with the EKC concept by including the square of per capita income variable to represent affluence for an economy [42]. In this study, the environmental impact (I) is determined by the level of per capita income, which stands for affluence or economic prosperity (A), the population density (P), and the nuclear energy that can be used to represent technology (T) in a country [43] since it can be produced by advanced technology [44]. Population density is a demographic factor that needs adequate attention in India. Higher population density may have an adverse impact on environmental quality. Population density means the measurement of population per unit area or exceptionally unit volume. Population density influences the quality of the environment through the rise in energy demand and expands the transport sector. Due to the expansion of cities along with the population density, water supplies, sewage treatment, sanitation and drainage systems, and the electricity supply jointly affect the environmental quality [45]. On the other hand, it is claimed that population growth may induce technological innovation, which, in turn, may reduce the negative impact on the environment [46].

Nuclear energy is a new way to use a proxy for technology in the IPAT model. It is considered a high-tech investment and can be produced through advanced technological systems [43,44]. Nuclear energy, by producing low-carbon electricity, has achieved a global interest as one of the most effective tools for limiting pollution [3], and nuclear energy consumption provides a promising solution for greenhouse gas and carbon emission reduction [47]. For instance, nuclear energy-reduced nearly 564 million metric tons of CO_2 emissions in 2015, equivalent to CO_2 emitted from nearly 128 million transport sector.[3] On the other hand, nuclear energy minimizes costs for fossil fuel importing countries and their current account deficits as well as decreasing energy dependence and security problems. Nuclear energy is a clean energy source that is required to achieve sustainable development targets [48]. Nuclear energy is a continuous and safe energy supply encouraging economic growth through the reduction in problems of energy supply [49]. In the context of the EKC framework, the IPAT model for the current study is specified as:

$$CO_{2,t} = a_0 + +a_1 GDP_t + a_2 GDP_t^2 + a_3 NUE_t + a_4 POP_t + \mu_t \tag{1}$$

and the empirical form of the model with the logarithmic transformation (ln) is:

$$lnCO_{2,t} = a_0 + a_1 lnGDP_t + a_2 lnGDP_t^2 + a_3 lnNUE_t + a_4 lnPOP_t + \mu_t \tag{2}$$

Where CO_2 is carbon dioxide emission that represents the environmental impact (I) and POP is the representation of population standing for P in the IPAT equation. Y and Y^2 are per capita GDP and the square of per capita GDP respectively and represent affluence (A). NUE is the acronym for nuclear energy which is a representative indicator of technology (T) in the context of the IPAT framework t is the sample period considered in the study. Finally, μ is the error term that captures either unmolded effects or random noise.

3.2. Econometric strategy

In line with the current literature [50,51], this study applies an innovative time-series econometric tool, namely dynamic ARDL. The dynamic ARDL simulation proposed by Jordan and Philips (2018) is expressed as:

[3] https://www.nei.org/advantages/climate (Access date: 01.06.2020).

$$\Delta(y)_t = \alpha + \delta_0 (y)_{t-1} + \delta_1 (x_1)_{t-1} + \ldots + \delta_k (x_k)_{t-1} + \sum_{i=1}^{p} \alpha_i \Delta(y)_{t-1} + \sum_{j=0}^{q_1} \beta_{1j} \Delta(x_1)_{t-j} + \ldots + \sum_{j=0}^{q_k} \beta_{kj} \Delta(x_k)_{t-j} + \mu_t \tag{3}$$

where the increases or decreases in the response variable (y) in time t are explained by a constant term (α), lagged and firs difference lagged values of the response variable in time $t-1$, explanatory variables ($x_1 \ldots x_k$) and their lagged and first difference lagged values beginning from $t-1$, and finally a stochastic error term (μ).

The present inquiry implements an innovative dynamic ARDL simulation method which can estimate, stimulate, and automatically plot predictions of decisive change in one independent variable on the response variable keeping all other factors constant. This method contributes to understanding the multifaceted nature and issue related to the interpretation of the already existing ARDL model. Following the empirical expression in Eq (3), the estimation of error correction forms of ARDL bound model for Eq (2) which represents the IPAT and EKC framework is shown in Eq (4),

$$\Delta lnCO_{2,t} = a_0 + \delta_0 lnCO_{2,\,t-1} + \delta_1 lnGDP_{t-1} + \delta_2 lnGDP_{t-1}^2 + \delta_3 lnNUE_{t-1} + \delta_4 lnPOP_{t-1} + a_1 \Delta lnCO_{2,t-1} + \beta_1 \Delta lnGDP_{t-1} + \beta_2 \Delta lnGDP_{t-1}^2 + \beta_3 \Delta lnNUE_{t-1} + \beta_4 \Delta lnPOP_{t-1} + \mu_t \tag{4}$$

In general, the error correction form of the ARDL model involves complex dynamic specifications, such as multiple lags, first differences, and lagged first differences [52]. This makes interpretation of the effects of changes more complicated —particularly short- and long-run changes—in the regressors. To counter this problem, the dynamically simulate a variety of ARDL models is introduced, including the error-correction model. The DARDL automatically draw a graph for that capture the spurious change in one regressor keeping all else equal through stochastic simulation techniques.

3.3. Data

The current study gathered annual data from 1971 to 2017 comprising per capita GDP (constant 2010 U S. dollar), nuclear energy (million tons per capita), population density (per sq. km of land area), and CO_2 emissions (metric tons per capita) of India. The data on per capita GDP and the population density were extracted from the World Bank. The data on CO_2 emissions and nuclear energy were mined from the British Petroleum (BP) statistics database.

4. Results and discussions

The dynamic ARDL empirical procedure involves several steps. Initially, it is important to check the level of stationary of study variables and also important that the dependent variable must be stationary at the first difference I(1) while explanatory variables may be stationary at first difference or level, I(1) or I(0). However, explanatory variables must not have an integration level higher than I(1). Fig. 1 provides a brief framework for empirical steps followed by the study.

For the unit root analysis, the study applied Phillip-Perron (P.P.) and DF-GLS unit root tests. The results of both tests are reported in Table 1 which indicates that the null hypothesis of unit root cannot be rejected for all variables at the level I(0), but after considering the first differenced data for the study variables they become stationary. In other words, the study variables meet the required integration order condition to check the cointegration relationship and to estimate cointegration parameters.

After confirmation of the stationary level of variables, the next step is to confirm cointegration among the indicated variables of this study. For this purpose, in the current study, we performed [53] combined the co-integration test to see the level of relationship (co-integration) among indicated variables selected for the study. This test syndicates existing approaches of cointegrating tests (i.e. [54–57] to get efficient and reliable estimates. The combined cointegration procedure solves the problem of inconsistency in results associated with other co-integration methods and gives robust results in comparisons of *t*-test. The [53] co-integration procedure can be formulated as follows:

$$EG - JOH = -2\left[Log(P_{EG}) + Log(P_{JOH})\right] \quad (5)$$

$$EG - JOH - BO - BDM = -2Log[(P_{EG}) + (P_{BO}) + (P_{BDM})], \quad (6)$$

In Bayer and Hanck's co-integration test, calculated statistics are compared with critical values. If the calculated F-statistic value is greater than the critical values, then we reject a null hypothesis and vice versa. The combined integration test results are shown in Table 2. Results indicate that there is a cointegration relationship between study variables for India by considering the calculated statistics. Thus, we proceed to employ the dynamic ARDL method to estimate cointegration parameters.

The dynamic ARDL results are shown in Table 3. The long-run coefficients of per capita *GDP* and the square of per capita *GDP* are in favour of theoretical expectations within the EKC concept, which confirm the environmental Kuznets curve hypothesis for India, since the per capita *GDP* and the square of per capita *GDP* have positive and negative signs, respectively. For the role of nuclear energy on CO_2 emissions, the findings of dynamic ARDL are in favour of our expectations. Nuclear energy has a significant and negative effect on CO_2 emissions. According to the obtained coefficient of nuclear energy variable (electricity generation from nuclear energy), a 1% rise in nuclear energy would decrease CO_2 emissions by 19.356% in the long-run. In other words, nuclear energy leads to executing a considerable reduction in CO_2 emissions. So, it can be a better alternative tool instead of conventional energy sources to improve environmental quality [3]. The transition of clean energy sources for electricity generation such as nuclear energy is crucial for the reduction of greenhouse gases as well. Further, nuclear energy can facilitate to modernize energy sector in India. The inclusion of nuclear energy will reduce dependency on energy imports and fossil consumption. Consequently, with this measure, CO_2 emissions can be eradicated. Thus, empirical findings of this study support that nuclear energy is necessary to avoid the detrimental effects of pollutant gases driving global warming and climate change, and it can be a better alternative energy source in India since expansion and usage of nuclear energy are beneficial economically and ecologically as well. This recommends the higher quantitative composition of nuclear energy in the Indian energy system, and nuclear energy almost crosses the threshold level to reduce pollution. Our findings are consistent with the findings obtained by Refs. [3,5,22,25,34]. The result certainly supports the privilege that nuclear plant operation does not produce CO_2 emissions when the energy sector shifts from fossil fuel to nuclear power that could help in greenhouse gas mitigation. It worth mentioning that even though nuclear energy reduces carbon emission, nuclear power plants always involve crucial risks; relying on wide cross-country variations in social, economic, and political factors. While discussing the environmental and health impacts of nuclear energy generation, these risks should be carefully considered and minimized [5,34].

Concerning the role of population density, in the long-run, the results recommend that the impact of population density on CO_2 emissions is positive and statistically significant. Hence, population density plays an incremental role in carbon emission in the case of India. Population density is accredited as a concern for projecting future emissions, somewhat due to huge uncertainties related to human behaviour. These concerns are valid for India because it has the world's second large population. Population density leads to a rise in energy consumption. Together all these cause to increase in pollution.

Figs. 2–4 show responses from CO_2 emissions based on $\pm1\%$ shock to the nuclear energy, per capita GDP, and population density. The figures for dynamic ARDL simulations reveal that a -1% shock to nuclear energy consumption increases CO_2 emissions and, however, a $+1\%$ change in nuclear energy consumption reduces CO_2 emissions. Further, -1% change in per capita GDP escalates CO_2 emissions and contributes to environmental pollution. On the other hand, a $+1\%$ change in income level mitigates CO_2 emissions. Finally, either negative or positive shock in population density shows no impact in CO_2 mitigations.

5. Conclusion and policy implications

The current study complements the existing studies on the nuclear energy and carbon emission relationship via IPAT and environmental Kuznets hypothesis in the Indian context. This study explores the relationship between the underlying variables over the period from 1971 to 2018. The cointegration test confirms the level of the relationship between the outlined variables. Later, the novel long-run estimation tool dynamic ARDL suggests a negative but statistically significant relationship between nuclear energy consumption and environmental pollution. Both nuclear energy consumption and pollution density form the Environmental Kuznets Curve in India. On the contrary, an inverse relationship is found between population density and carbon emissions over the sampled period**.**

The study findings directed essential policy recommendations. The positive role of nuclear energy in pollution reduction is noticeable. The policy analyst and government officials should pay attention to generate as much electricity from nuclear energy sources as it cleans the environment. The adverse role of population density means rising as it increases energy demand and India relay on energy imports and dirty sources to meet the growing need for energy. In such a condition, nuclear energy can play a significant role not only to meet energy demand due to the population to boost economic growth but suitable for sustainable development. More probably, Government of India should focus on to control the rapid population growth rate. More investment and technological innovation in generating electricity from nuclear source should be encouraged.

Like other studies, this work also has some limitations. First, this inquiry examined the nuclear energy and emissions nexus for India. This leaves a room for the future to carry out research work for other developing and under developing economies for both time series and panel data. Secondly, this study uses annual data and employs CO_2 emissions as an indicator of environmental degradation. However, alternative pollution indicators such as the ecological footprint or alternative econometric techniques would contribute to expanding the literature. On the other hand, the so-called pollution haven hypothesis is ignored for developing countries; since due to demand for clean environment rich countries transfer their dirty technology to poor countries allowing poor countries to produce more pollution-intensive goods, thus worsening environmental quality. This should be addressed in future research.

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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