Energy Efficiency and Green Innovation and Its Asymmetric Impact on CO2 Emission in China: A New Perspective

Yue Li
China University of Geosciences
Chuan Zhangchuan
China University of Geosciences
ShiXiang Li
China university of Geosciences
Ahmed Usman (voice.of.usman.au@gmail.com)
Government College University Faisalabad

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Abstract

Green innovation undoubtedly plays a significant role in creating employment opportunities, boosting green economic activity, and improving environmental sustainability. This study scrutinizes the effect of energy efficiency and green innovation on CO_2 emissions in China over the 1992–2014 period using NARDL. Findings show that energy efficiency and green innovation contribute to reducing CO_2 emissions in China. Energy efficiency and green innovation are also important asymmetric determinants of CO_2 emissions. An increase in energy efficiency and green innovation lowers CO_2 emissions, while a decrease in energy efficiency and green innovation increases CO_2 emissions in China in the long run. Some policy measures are suggested to attain carbon neutrality.

Introduction

In the context of global climate change and protecting the ecosystem from greenhouse gas emissions, understanding the link between CO_2 emissions and economic growth is very pertinent. This relationship has been extensively tested in the light of the Environmental Kuznets Curve (EKC) by many empirical studies; however, the seminal work in this regard was conducted by Grossman and Kreuger (1991). In this regard, Dinda (2004) and Al-mulali et al. (2016) review all the studies on the topic of EKC regarding various countries and regions. The literature on the EKC hypothesis is large enough, and multiple factors such as industrialization, urbanization, ICT, trade openness, renewable energy, and globalization have come out as determinants of environmental quality alongside economic growth (Ullah et al. 2021). However, energy efficiency and green innovations, which could be essential factors in mitigating CO_2 emissions, are not studied extensively as promoters of sustainable development and a clean environment. The relationship between these factors and CO_2 emissions is mainly observed over a long period of time. Therefore, in this study, we aim to observe the relationship between energy efficiency and green innovations on environmental quality in China.

Energy is served as an essential input in production; hence, the main contributor to the industrialization and economic development of developed and emerging economies. On the other side, this process of modernization and development is not free of cost, and an environmental cost is attached to this process (Chang et al., 2018). Several empirical studies have tried to find the role of energy consumption on the economic development of various countries and regions, and most of them have accounted for the problems of environmental pollution and CO_2 emissions (Arouri et al., 2012; Ozturk & Al-Mulali, 2015). Moreover, various studies have also highlighted that the adverse effects produced by energy consumption can be countered by increasing energy efficiency (Filippini and Zhang, 2016). Therefore, several past studies have considered energy efficiency as a key element in increasing energy security, driving economic growth, and reducing environmental problems.

Given the importance of energy efficiency, many developed and emerging economies have incorporated energy efficiency policy into their energy-related strategies, targets, and overall national agendas. (IEA, 2014). To achieve targets of high environmental quality alongside high economic growth, the world has to invest heavily in green technology (Wurlod and Noailly, 2018). Another way to successfully achieve the targets mentioned above is to improve the countries' institutional quality that could effectively contribute to the implementation of energy policies. Although many nations have implemented the energy efficiency policy, the efficacy of these policies largely varies from country to country depending upon the difference in their level of institutions, relative factor prices, degree of specialization, and status of their technological development (Usman et al., 2012).

Following the Oil crisis in the 1970s, energy efficiency has grabbed global attention (Florini & Sovacool 2009). Ever since the oil crisis of 1970, a plethora of studies have tested the impact of energy efficiency on environmental quality with regards to the use of energy in various sectors and for different countries. Literature, in the context of energy efficiency, can be divided into two main classifications. The first group of studies focuses on the techniques to measure energy efficiency. The second group of studies focuses on the factors that can affect energy efficiency. The first group of studies includes many studies, but they haven't reached a consensus on the definition of energy efficiency (Filippini and Hunt, 2015). However, this group of studies provided several definitions relying on the simple ratio from production to the energy input used in production. In order to observe a rise in energy efficiency, miscellaneous measurable variables are primarily used, including a thermodynamic indicator, physical thermodynamic indicator, economic indicator, etc. (Patterson, 1996).

Green innovations have also gained popularity during recent years, and they can help achieve green economic growth, which is the need of the hour. One of the most pertinent benefits of green innovations is that they can significantly cut carbon emissions, which is a significant cause of environmental degradation, by increasing energy efficiency and developing more sophisticated and modern technologies (Cantore et al. 2012). Therefore, during the Paris agreement various countries have agreed to work together that leads them towards the path of green economic growth. Despite all these efforts, there are several hurdles still exist in the implementation of green technology not only at the domestic but international level (Maskus, 2010). The decision of the countries regarding investment in green technologies will depend on whether the green technology help reduces energy inefficiency and increases productivity or not. In this context, empirical studies provided mixed results. Palmer et al. (1995) indicated that green technology might cause energy efficiency and productivity to fall. On the other side, Lin and Moubarak (2014) and Wurlod and Noailly (2018), highlighted that green technology improves energy efficiency and also increases productivity.

China is the second-largest economy in the world, the largest consumer of energy, and the biggest contributor to global CO2 emissions (Aslam et al. 2021). China is an emerging economy, which is growing at a great pace. The demand for controlling CO2 emissions in China is on the rise. The pressure is mounting on China domestically and internationally (Yuelan et al. 2021). Energy efficiency and green innovations can help reduce CO2 emissions without compromising economic growth. Not much studies are available that have particularly targeted China in this context. Therefore, in this study, we try to analyze the nexus between energy efficiency, green innovations, and environmental quality in China. This study is different from all previous studies because it relies on the asymmetry assumption, which provides us an opportunity to separately calculate the impact of positive and negative changes in energy efficiency and green innovations on CO2 emission in China. To that end, the analysis applied linear and non-linear ARDL models. To the best of our knowledge, this is a first-ever study that tried to capture the asymmetric impact of energy efficiency and green innovations on CO2 emissions in China.

Model, Methods, And Data

This study aims to investigate the impact of energy efficiency and green innovation on CO_2 emissions in China. Therefore, to analyze the nexus between CO2 emissions, energy efficiency, and green innovation in China, we derived the following equation (1) from the literature.

$$CO_{2,t} = \alpha_0 + \alpha_1 Gsize_t + \alpha_2 Csize_t + \alpha_3 Trade_t + \alpha_4 EC_t + \mu_t \quad \text{-------} \ (1)$$

Where carbon dioxide emissions (CO2) in China depends on the energy efficiency (EE), green innovation (GI), GDP per capita (GDP), foreign direct investment (FDI), and randomly distributed error term (μ_t). Specification (1) is a long-run equation and is only able to provide us with long-run results. In order to get short as well as long-run estimates we will redefine the equation (1) in an error correction specification format as shown below:

$$\Delta CO_{2,t} = \pi + \sum_{p=1}^{n1} \pi_{1p} \Delta CO_{2,t-p} + \sum_{p=0}^{n3} \pi_{2p} \Delta Gsize_{t-p} + \sum_{p=0}^{n4} \pi_{3p} \Delta Csize_{t-p} + \sum_{p=0}^{n5} \pi_{4p} \Delta Trade_{t-p} + \sum_{p=0}^{n5} \pi_{5p} \Delta EC_{t-p} + \beta_1 CO_{2,t-1} + \beta_2 Gsize_{t-1} + \beta_3 Csize_{t-1} + \beta_4 Trade_{t-1} + \beta_5 EC_{t-1} + \mu_t \quad \text{---------} \ (2)$$

This format of error correction is known as ARDL model of Pesaran et al. (2001). In this method, we can get short and long-run estimates at the same time. In the above equation (2) estimates of first-differenced variables provide the short-run results, and the estimates attached to β_2-β_5 normalized on β_1 provide us the long-run results. The validity of the long results relies on the test of co-integration known as the F-test for the joint significance of the lagged level variables. Pesaran et al. (2001) developed critical values for this test. This method has another advantage over other methods. It doesn’t require pre-unit root testing because it can account for integrating properties of the variables and add a mixture of I(0) and I(1) variables. Moreover, it can also provide efficient estimates if the number of observations is small.

Apart from the symmetric analysis, we have also performed asymmetric analysis to know whether the effects of energy efficiency and green innovation on CO2 emissions are symmetric or asymmetric. To that end, we break the variables of energy efficiency and green innovation into positive and negative components using the partial sum procedure. The process of partial sum procedure in mathematical form is shown below:

$$\mathrm{Gsize}^{+}{}_{t} = \sum_{n=1}^{t} \Delta \mathrm{Gsize}^{+}{}_{t} = \sum_{n=1}^{t} \max\ (\mathrm{Gsize}^{+}{}_{t}, 0) \qquad (3a)$$

$$\mathrm{Gsize}^{-}{}_{t} = \sum_{n=1}^{t} \Delta \mathrm{Gsize}^{-}{}_{t} = \sum_{n=1}^{t} \min\ (\Delta \mathrm{Gsize}^{-}{}_{t}, 0) \qquad (3b)$$

$$\mathrm{Csize}^{+}{}_{t} = \sum_{n=1}^{t} \Delta \mathrm{Csize}^{+}{}_{t} = \sum_{n=1}^{t} \max\ (\Delta \mathrm{Csize}^{+}{}_{t}, 0) \qquad (4a)$$

$$\mathrm{Csize}^{-}{}_{t} = \sum_{n=1}^{t} \Delta \mathrm{Csize}^{-}{}_{t} = \sum_{n=1}^{t} \min\ (\Delta \mathrm{Csize}^{-}{}_{t}, 0) \qquad (4b)$$

Positive changes in the variables of energy efficiency and green innovations are represented by equations 3a & 4a; whereas, the negative changes are represented by equations 3b & 4b. After breaking the variables into positive and negative components, we need to incorporate these partial sum variables in place of original variables in equation (2), and the resulting equation will become NARDL as prescribed below:

$$\Delta \mathrm{CO}_{2,t} = \omega_0 + \sum_{k=1}^{n} \pi_{1k} \Delta \mathrm{CO}_{2,t-k} + \sum_{k=0}^{n} \pi_{2k} \Delta \mathrm{Gsize}^{+}{}_{t-k} + \sum_{k=0}^{n} \pi_{3k} \Delta \mathrm{Gsize}^{-}{}_{t-k} + \sum_{k=0}^{n} \pi_{4k} \Delta \mathrm{Csize}^{+}{}_{t-k} + \sum_{k=0}^{n} \pi_{5k} \Delta \mathrm{Csize}^{-}{}_{t-k} + \sum_{k=0}^{n} \pi_{6k} \mathrm{Trade}_{t-k} + \sum_{k=0}^{n} \pi_{7k} \mathrm{EC}_{t-k} + \omega_1 \mathrm{CO}_{2,t-1} + \omega_2 \mathrm{Gsize}^{+}{}_{t-1} + \omega_3 \mathrm{Gsize}^{-}{}_{t-1} + \omega_4 \mathrm{Csize}^{+}{}_{t-1} + \omega_5 \mathrm{Csize}^{-}{}_{t-1} + \omega_6 \mathrm{Trade}_{t-1} + \omega_7 \mathrm{EC}_{t-1} + \varepsilon_t \qquad (6)$$

The NARDL is proposed by Shin et al. (2014), which is an advanced form of linear ARDL. Therefore, the co-integration and diagnostic tests of the linear ARDL model are equally applicable for the non-linear ARDL model. However, asymmetric tests are required before we can decide whether the effects of our concerned variables are symmetric or asymmetric. Firstly, to confirm the short-run impact asymmetry, we need to prove that $\sum \pi_{2k} = \sum \pi_{3k}, \sum \pi_{4k} = \sum \pi_{5k}.$ with the help of the Wald-SR test. Then, to confirm the long-run asymmetric effects, we need to prove that $\frac{\omega_2}{-\omega_1} = \frac{\omega_3}{-\omega_1}, \frac{\omega_4}{-\omega_1} = \frac{\omega_5}{-\omega_1}$ with the help of Wald-LR.

The study explores the impact of energy efficiency and green innovation on carbon emissions for China for time period 1990 to 2019. For that purpose, CO2 emission is used as a dependent variable, energy efficiency and green innovation are focused variables, while GDP per capita growth and FDI are control variables in Table 1. CO2 emission is measured by Carbon dioxide emissions in kilogram. Energy efficiency is measured as GDP per unit of energy use and green innovation is measured as the development of environment-related technologies as a percent of all technologies. GDP per capita growth is taken in annual percentage, and foreign direct investment inflows are taken as a percentage of GDP. All the data to be used in this study is extracted from the World Bank.

Table 1
Data definitions and sources

Variables	Symbol	Definitions	Sources
CO_2 emissions	CO_2	CO_2 emissions (kt)	World bank
Energy efficiency	EE	GDP per unit of energy use (constant 2017 PPP $ per kg of oil equivalent)	World bank
Green innovation	GI	Development of environment-related technologies, % all technologies	OECD
GDP per capita growth	GDP	GDP per capita growth (annual %)	World bank
Foreign direct investment	FDI	Foreign direct investment inflows (% of the GDP)	World bank

Results And Discussion

A preliminary analysis, stationarity properties of data have been confirmed by adopting traditional unit root tests. For that purpose, unit root without and with break tests are used to provide for more reliable results and the outcomes of these tests are presented in Table 2. The findings suggest that all the variables are either stationary at I(0) or at first difference I(1). Moreover, none of the variables is stationary at I(2). Thus, the study adopted ARDL approach to figure out the dynamics of energy efficiency and green innovation on CO_2 emissions in case of China. The study also proceeds to investigate the asymmetric impact of energy efficiency and green innovation on CO_2 emissions by adopting NARDL approach. Table 3 presented the short-run and long-run coefficient estimates of ARDL and NARDL models.

Table 2: Unit root testing

	Unit root without break			**Unit root with break**				
	I(0)	**I(1)**		**I(0)**	**Break date**	**I(1)**	**Break date**	
CO_2	-0.638	-3.105**	I(1)	-5.155	2002			I(0)
EE	-1.264	-3.047	I(1)	-2.102	2006	-4.356	2003	I(1)
GI	-1.372	-6.215	I(1)	-3.142	2000	-8.235	2001	I(1)
GDP	-1.712	-6.145	I(1)	-3.023	2007	-6.015	2010	I(1)
FD	-4.156		I(0)	-6.695	2004			I(0)

Note: ***$p<0.01$; **$p<0.05$; and *$p<0.1$

The long-run findings of ARDL model reveal that energy efficiency exerts a negative and significant impact on CO_2 emissions revealing that environmental quality improves due to increasing in energy efficiency. The coefficient estimate shows that in response of 1 percent increase in energy efficiency, CO_2 declines by 0.589 percent. However, green innovation has no significant impact on CO_2 emissions in the long-run. In terms of control variables, long-term impact of GDP per capita growth on CO_2 emissions is significant and positive in China with elasticity of 0.074 while FDI produced an insignificant impact. The short-run estimates of ARDL model demonstrate that energy efficiency, green innovation, and GDP per capita growth produce no significant impact on CO_2 emissions; however, the impact of FDI is significant and positive on CO_2 emissions in China. In the third panel of Table 3, findings of some important diagnostic tests are given which are imperative to perform to confirm the validity of ARDL estimates. Statistically significant coefficient estimates of F-statistics and ECM confirm the existence of long-run cointegration among variables. No issues of heteroskedasticity and autocorrelation are found in LM and BP tests. The model is correctly specified as confirmed by the findings of Ramsey RESET test. CUSUM and CUSUM sq test report that stability exists in the model.

The long-run coefficient estimates of NARDL model demonstrate that positive shock in energy efficiency has significant and negative impact on CO_2 emissions confirming that environmental quality is enhances due to an upsurge in energy efficiency. The findings reveal that due to 1 percent upsurge in positive shock of energy efficiency, CO_2 emissions declines by 0.045 percent. In terms of negative shock of energy efficiency, findings reveal that a decline in negative shock of energy efficiency results in increasing CO_2 emissions in the long-run. In other words, due to 1 percent decline in negative shock of energy efficiency, CO_2 emission increases by 1.573 percent.

This finding is also consistent with Bayar and Gavriletea (20190), who noted that energy efficiency permits savings of energy in the process of production for goods and services. Energy efficiency and environmental strategy are key factors used by various organizations pursuing to attain sustainability of the environment. Likewise, the energy efficiency contribution is also imperative with a negative coefficient estimate, indicating the significance of energy efficiency in the reduction of carbon emissions in China. Empirical and theoretical literature also supports the findings (Pardo et al. 2011; Wu et al. 2012; and artínez-Moya et al. 2019). Therefore, the proposed contribution of the study is well verified empirically, and energy efficiency can be beneficial towards the growth of China. Furthermore, energy efficiency is beneficial with outstanding market potential, thus facilitating energy security and endorsing sustainable development. Thus, a continuous upsurge in the carbon emissions of China can be controlled by adopting energy efficiency. Energy efficiency is gradually becoming a measure of green growth strategies of governments, aiming to control CO_2 emissions by enhancing energy consumption and achieving environmental targets. Energy efficiency is a key measure to attain decarbonization at a worldwide level (Tajudeen et al. 2018).

In the case of green innovation, it is found that positive shock of green innovation produces no significant impact on CO_2 emissions, while a decline in negative shock of green innovation produces a significant and positive impact on CO_2 emissions. It reveals that due to 1 percent decline in negative shock of green innovation, CO_2 emissions rise by 0.168 percent in the long-run. Green innovation helps in reducing energy consumption and resultantly reduces energy use that leads to the achievement of sustainable growth.

Therefore, green innovation is found to be favorable in reducing carbon emissions in China (Hussain et al., 2020).

Green innovation is such technology that is used in the processing or production of goods without any damage to the environment. Hussain & Dogan (2021) highlighted the contribution of green innovation in the execution of efficiency-based models to attain sustainable societies. Furthermore, sustainable growth via green innovation is also supported by growing investment in the environmental research and development sector (Ulucak, 2020). The findings confirm the encouraging contribution of green technologies in green growth environmental targets (Mensah et al., 2019 and Ullah et al. 2021). Moreover, consumption-based carbon emissions are controlled due to the adoption of green innovations and energy efficiency in China, thus providing smooth measures of sustainable growth (Hussain et al., 2020). Furthermore, energy efficiency and green innovation can contribute a significant role in correcting environmental pollution. Furthermore, green innovations are imperative for sustainable growth of economic, social, and energy systems and carbon mitigation of the economies.

Table 3: ARDL and NARDL estimates

	ARDL				NARDL			
	Coefficient	Std. Error	t-Stat	Prob.	Coefficient	Std. Error	t-Stat	Prob.
Short-run								
D(EE)	-0.023	0.093	0.243	0.812				
D(EE(-1))	-0.061	0.111	0.554	0.590				
D(EE(-2))	-0.195***	0.074	2.629	0.024				
D(EE_POS)					-0.094	0.103	0.909	0.390
D(EE_POS(-1))					-0.339	0.122	2.786	0.024
D(EE_NEG)					-1.056***	0.339	3.118	0.014
D(EE_NEG(-1))					0.956***	0.358	2.673	0.028
D(GI)	-0.007	0.010	0.723	0.485				
D(GI_POS)					0.001	0.018	0.035	0.973
D(GI_NEG)					-0.132***	0.046	2.896	0.020
D(GI_NEG(-1))					-0.152**	0.069	2.201	0.059
D(GDP)	0.009	0.006	1.568	0.145	0.031***	0.011	2.977	0.018
D(GDP(-1))	-0.001	0.008	0.136	0.894	0.016	0.012	1.345	0.216
D(GDP(-2))	-0.024	0.007	3.248	0.008				
D(FDI)	0.144***	0.054	2.671	0.022	-0.224*	0.133	1.693	0.129
D(FDI(-1))	0.038	0.043	0.890	0.393				
D(FDI(-2))	0.073*	0.039	1.879	0.087				
Long-run								
EE	-0.589***	0.101	5.842	0.000				
EE_POS					-0.045*	0.024	1.875	0.089
EE_NEG					-1.573**	0.733	2.145	0.064
GI	-0.017	0.020	0.837	0.420				
GI_POS					-0.001	0.018	0.035	0.973
GI_NEG					-0.168***	0.028	5.956	0.000
GDP	0.074***	0.024	3.129	0.010	0.003	0.012	0.226	0.827
FDI	0.108	0.094	1.146	0.276	0.724***	0.125	5.812	0.000

C	10.02***	1.880	5.334	0.000	-2.747***	3.116	0.881	0.404
Diagnostics								
F-test	4.252*				3.954*			
ECM(-1)	-0.426***	0.142	3.009	0.012	0.692*	0.407	1.700	0.100
LM	1.654				2.512			
BP	0.689				0.721			
RESET	1.845				1.234			
CUSUM	S				S			
CUSUM-sq	S				S			
Wald-SR-EE					1.235			
Wald-LR-EE					6.655***			
Wald-SR-GI					0.265			
Wald-LR-GI					5.654***			

Note: ***$p<0.01$; **$p<0.05$; and *$p<0.1$

In terms of control variables, findings reveal that GDP per capita growth produces an insignificant impact on CO2 emissions, while the long-term impact of FDI on CO2 emissions is significant and positive in China with an elasticity of 0.724. The short-run findings of NARDL model demonstrate that positive shocks in energy efficiency and green innovation produce no significant impact on CO2 emissions, however, negative shocks in energy efficiency and green innovation have a significant and positive impact on CO2 emissions in China. In terms of control variables, findings reveal that GDP produces a significant positive impact on CO2 emissions, while FDI produces a significant and negative impact on CO2 emissions in the short-run. The findings of diagnostic tests show that long-run cointegration exists among variables as shown by statistically significant coefficient estimates of F-stat and ECM. The findings of LM and BP tests confirm the non-existence of autocorrelation and heteroskedasticity issues. The findings of Ramsey RESET test confirm the correct specification of the model. The stability condition is also fulfilled in the model as shown by findings of CUSUM and CUSUM-sq tests. The asymmetries are only observed in the long run. Table 4 reports the symmetric and asymmetric causality results. Findings show that energy efficiency has a bidirectional causality relationship with CO2 emissions, which implies that energy efficiency significantly causes CO2 emissions. The existence of unidirectional Granger causality running from CO2 to green innovation indicates that there is green innovation enhances during high carbon emissions in China.

Table 4: Symmetric and asymmetric causality tests

Symmetric causality			Asymmetric causality			Decision	
Null Hypothesis:	F-Stati	Prob.	Null Hypothesis:	F-Stat	Prob.	Symmetric causality	Asymmetric causality
EE → CO2	2.290	0.125	EE_POS → CO2	3.153	0.064	No	Yes
CO2 → EE	5.105	0.015	CO2 → EE_POS	3.970	0.035	Yes	Yes
GI → CO2	3.237	0.059	EE_NEG → CO2	0.925	0.412	Yes	No
CO2 → GI	0.283	0.756	CO2 → EE_NEG	3.575	0.046	No	Yes
GDP → CO2	2.069	0.150	GI_POS → CO2	5.335	0.013	No	Yes
CO2 → GDP	2.437	0.111	CO2 → GI_POS	0.772	0.475	No	No
FDI → CO2	0.368	0.696	GI_NEG → CO2	0.057	0.945	No	No
CO2 → FDI	5.060	0.016	CO2 → GI_NEG	1.731	0.202	Yes	No
GI → EE	0.161	0.852	GDP → CO2	2.069	0.150	No	No
EE → GI	0.992	0.387	CO2 → GDP	2.437	0.111	No	No
GDP → EE	0.148	0.863	FDI → CO2	0.368	0.696	No	No
EE → GDP	2.206	0.134	CO2 → FDI	5.060	0.016	No	Yes
FDI → EE	2.242	0.130	EE_NEG → EE_POS	2.113	0.146	No	No
EE → FDI	0.490	0.619	EE_POS → EE_NEG	2.457	0.110	No	No
GDP → GI	0.223	0.802	GI_POS → EE_POS	0.314	0.734	No	No
GI → GDP	0.183	0.834	EE_POS → GI_POS	3.347	0.055	No	Yes
FDI → GI	1.004	0.382	GI_NEG → EE_POS	0.434	0.653	No	No
GI → FDI	3.232	0.059	EE_POS → GI_NEG	3.307	0.056	Yes	Yes
FDI → GDP	0.630	0.542	GDP → EE_POS	0.174	0.842	No	No
GDP → FDI	6.512	0.006	EE_POS → GDP	2.307	0.124	Yes	No
			FDI → EE_POS	2.172	0.139		No
			EE_POS → FDI	1.448	0.258		No
			GI_POS → EE_NEG	8.945	0.002		Yes
			EE_NEG → GI_POS	0.140	0.870		No
			GI_NEG → EE_NEG	7.535	0.003		Yes
			EE_NEG → GI_NEG	0.319	0.731		No
			GDP → EE_NEG	0.799	0.463		No

	EE_NEG → GDP	0.577	0.570	No
	FDI → EE_NEG	1.540	0.238	No
	EE_NEG → FDI	3.618	0.045	Yes
	GI_NEG → GI_POS	1.213	0.317	No
	GI_POS → GI_NEG	10.264	0.001	Yes
	GDP → GI_POS	1.328	0.287	No
	GI_POS → GDP	0.293	0.749	No
	FDI → GI_POS	1.147	0.337	No
	GI_POS → FDI	0.781	0.471	No
	GDP → GI_NEG	0.514	0.605	No
	GI_NEG → GDP	0.472	0.630	No
	FDI → GI_NEG	1.848	0.182	No
	GI_NEG → FDI	0.869	0.434	No
	FDI → GDP	0.630	0.542	No
	GDP → FDI	6.512	0.006	Yes

Note: ***p<0.01; **p<0.05; and *p<0.1

Conclusion And Implications

The existing empirical literature researching the energy efficiency, green innovation, CO2 emission nexus provides no consistent and sufficient empirical findings. Moreover, the asymmetric effect of energy efficiency and green innovation on CO2 emission has not been fascinating yet enough attention. Therefore, our study considers the asymmetric impact of energy efficiency and green innovation on CO2 emissions of China selected from 1991 to 2019 by controlling GDP and FDI in empirical analysis. The cointegration outcomes confirm that there is a long-run relationship between energy efficiency, green innovation, and CO2 emissions.

Generally, findings show that energy efficiency and green innovation have an asymmetric effect on CO2 emissions in China. An increase in energy efficiency stimulated environmental quality, but a decrease in energy efficiency promoted environmental quality in China in long-run. The effect of positive change in green innovation has negative insignificant, while a negative change in green innovation has a positive significant impact on CO2 emissions in long-run in China. Energy efficiency and green innovation have also asymmetrically influenced CO2 emissions in short-run. The coefficients on positive shock in energy efficiency and green innovation indicate insignificant effects on CO2 emissions, while negative shocks coefficient have also positive impacts on CO2 emissions in short-run. The estimate of negative shocks in energy efficiency and green innovation is greater than positive shocks in non-linear models. The results show that energy efficiency and green innovation significantly reduce CO2 emissions and improve environmental quality in long-run.

Policy instruments such as subsidies, rebates, feed-in tariffs, incentives can be employed in order to promote and inspire renewable energy investments without compromising the environment and economic growth. Governments must change their policy approaches in order to meet growing clean energy demands and also sustainable energy-efficient technologies to produce and save energy. China should design and implement green growth-oriented policies and programs to achieve carbon neutrality. Government should allocate a large share of green public spending on green environmental innovation. China can promote environmental awareness by using smart technologies. China should more investment in environmental technology to clean its environment. The possible extensions of empirical research are to examine the asymmetric impacts of energy efficiency and green innovation at the provincial level. Authors should also conduct similar research for other high-polluted economies and conducted at the sectoral level is needed. Future studies can produce more reliable parameter estimates with alternative indicators, datasets, and econometric techniques that can substantially enrich our empirical findings.

Declarations

Ethical Approval: Not applicable

Consent to Participate: I am free to contact any of the people involved in the research to seek further clarification and information

Consent to Publish: Not applicable

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