Environmental Science and Pollution Research (2023) 30:82760–82769
https://doi.org/10.1007/s11356-023-27927-w

RESEARCH ARTICLE

Energy taxes, energy innovation, and green sustainability: empirical analysis from a China perspective

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Received: 7 March 2023 / Accepted: 22 May 2023 / Published online: 19 June 2023

Abstract
The idea that energy taxes and innovation may contribute to lowering greenhouse gas emissions and fostering the development of a more sustainable energy future is gaining popularity. Therefore, the study's main goal is to explore the asymmetric impact of energy taxes and innovation on CO2 emissions in China by employing linear and nonlinear ARDL econometric methods. The outcomes of the linear model demonstrate that long-term increases in energy taxes, energy technological innovation, and financial development cause CO2 emissions to reduce, while increases in economic development cause CO2 emissions to climb. Similarly, energy taxes and energy technological innovation cause CO2 emissions to fall in the short run, while financial development promotes CO2 emissions. On the other hand, in the nonlinear model, the positive energy changes, positive energy innovation changes, financial development, and human capital help reduce the long-run CO2 emissions, and economic development increase the CO2 emissions. In the short run, the positive energy and innovation changes are negatively and significantly connected to CO2 emissions, while financial development is positively linked to CO2 emissions. The negative energy innovation changes are insignificant in both the short and long run. Therefore, Chinese policymakers should try to promote energy taxes and innovations as tools to achieve green sustainability.

Keywords Energy taxes · Energy innovation · Green sustainability

Introduction

Greenhouse gas (GHG)-induced climate change has grown into a serious issue that needs an immediate fix. Energy conservation and lowering CO2 emissions have drawn a lot of attention and have been the subject of many studies (Wang et al. 2012; Su et al. 2020). Strategies for green sustainability have been the focus of research by many academics (Secundo et al. 2020). A lot of policy measures have been investigated or put into practice to help achieve a green sustainable economy, including resource taxes (Sun et al. 2021), carbon taxes (Yu et al. 2023), and pollution trading schemes (Huang et al. 2021).

Taxes have the power to govern resource allocation, income distribution, and business organization (Saez and Zucman 2020). Taxes on energy production or consumption industries may be useful for maximizing energy efficiency, lowering carbon footprints, and enhancing green sustainability. According to Sohail et al. (2023) analysis of the impacts of various ecological tax return rates on China's economy, environmental taxes are not destructive to the economy. In addition, they may successfully reduce the release of SO2 from industries with high pollution levels. Kaplowitz and McCright (2015) used eight survey procedures to evaluate how certain policy elements and persuasive messaging impact support for an increase in the gas tax. Numerous research, including those by Mardones

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and Baeza (2018) and Wang et al. (2022) have concentrated on the economic or ecological effects of a CO2 tax.

Studies on the impact of tax reform on the energy sector have been published (Lin and Jia 2019; Angga et al. 2022). Deroubaix and Lévèque (2006) investigated the political debates brought on by the energy tax restructuring program and the reasons it ultimately failed in the hopes that it would assist in resolving the political challenges associated with enacting environmental legislation. Energy tax directive reform's possible effects on pricing levels in different businesses across 27 EU nations were examined by Rocchi et al. (2014). Using the computable general equilibrium (CGE) model, Orlov (2015) examined the overall economic impacts of lowering the export duties on crude oil and petroleum-related goods, which were then made up by raising the royalty on crude oil. The study discovered that the strategy offers a little increase in "allocative efficiency", but that the approach is not better. Thampapillai et al. (2014) provided an example of how reinvesting resource rent tax and other mining-related government income might slow down the decline in the value of the mine. To conclude the above discussion, we can say that energy taxes may significantly promote green sustainability by stimulating the adoption of renewable energy sources, lowering the emission of greenhouse gasses, and improving energy efficiency. Energy tax designs and the accessibility of green alternatives may impact how well they promote sustainability.

The main contribution of energy taxes is the promotion of energy innovations, which are vital for achieving green sustainability. Energy innovation is viewed as a crucial tool for achieving a green economy as a reaction to the rise in global temperatures. Innovation in energy technology is the process of generating new knowledge to advance energy-related research and technology (Gu et al. 2019; Li et al. 2022). According to Gallagher et al. (2006), "energy technology innovation" also describes product innovation that supports the commercial use of innovative energy-related ideas. Energy innovations may be divided into "renewable energy technology innovation and fossil energy technology innovation" (Alvarez-Herranz et al. 2017). Innovations in energy are influencing the world's system of energy usage. As an illustration, the advancement of clean energy technologies, such as solar, biomass, and wind encourages the shift of the coal economy by modernizing the model of energy use (Chien et al. 2021) and offers an achievable strategy to lessen regional reliance on carbon fuels (Fri and Savitz 2014). As a result, several researchers have shed light on the unfavourable correlations that exist between the development of renewable energy technologies and carbon footprints. Therefore, innovation in the energy sector has the potential to be very important in tackling the world's energy problems, fostering sustainable economic growth, and assuring a green and sustainable future (Chen et al. 2023).

Against this backdrop, the primary motive of the analysis is to analyze the impact of energy taxes and energy-related innovations on green sustainability. Although certain studies have focused on examining the relationship between carbon taxes and environmental sustainability, some other studies have also looked at the influence of environmental-related taxes on energy production and consumption; however, not many have studied the effect of energy taxes on green sustainability. A few other studies have also emphasized the importance of energy innovation, but none of them have looked at how China's CO2 emissions may be affected by both energy taxes and innovation. Additionally, no previous research has looked at the asymmetries between energy taxes and innovation and green sustainability in China. The main research question of the study is that, how do energy taxes and energy innovation influence CO2 emissions?

This research attempts to close the aforementioned gaps in the literature, making it novel in many ways. To start, this is the first empirical research that has, as far as we are aware, looked at the effects of energy taxes and technologies on CO2 emissions in China Second, this is the first effort to investigate the asymmetric impact of energy taxes and innovation on CO2 emissions has been made. The fact that previous research relied heavily on linear paradigms to predict how energy innovations and taxes would impact CO2 emissions is one of their main shortcomings. However, most macroeconomic variables show nonlinearities, especially those related to the business cycle (Bahmani-Oskooee et al. 2020; Orlando et al. 2021). The fundamental drawback of linear models is that they only show how the variable has an influence linearly (Usman et al. 2021). According to a study by Kahneman and Tversky (1979), asymmetries and human behaviour are closely intertwined. As a result, studying asymmetries in social sciences is important since human behavior is involved. Thirdly, the research demonstrates interest in both the short-run connection between the variables and the long-run relationship between them. To that end, we have relied on linear and nonlinear ARDL, which can simultaneously provide short and long-run estimates. Last but not least, because energy innovations and energy taxes are essential for reducing the consequences of climate change, the analysis's findings are important for defining the role of energy innovations and energy taxes in supporting green sustainability. They also contribute to safeguarding the world's sustainable future.

Model and methods

Energy taxes have a significant impact on reducing CO2 emissions by encouraging the use of renewable energy sources and discouraging the use of high-carbon energy sources. When energy taxes are implemented, they increase the cost of energy from high-carbon sources, making them less attractive compared to lower-carbon alternatives

(Grubler et al. 2018). This creates a market incentive for businesses and individuals to switch to cleaner and more efficient energy sources, which results in a reduction in CO2 emissions. Additionally, energy taxes stimulate energy efficiency, which further decreases carbon intensity by decreasing energy consumption (Pan et al. 2019). Alola and Onifade (2022) noted that energy taxes play a significant role in reducing CO2 emissions by incentivizing the use of low-carbon energy sources, discouraging the use of high-carbon sources, promoting energy efficiency, and funding research and development in clean energy technologies. Energy innovation also plays a critical role in reducing carbon intensity by enabling the development, distribution, and consumption of energy with lower carbon emissions. Such innovations can lead to the production of new renewable energy technologies, resulting in a decline in the carbon intensity of energy production and consumption (Balsalobre-Lorente et al. 2019). Technological innovation theory suggests that innovation drives economic growth and development, and energy innovation, in particular, can facilitate the development of cleaner and more efficient energy sources, thereby reducing carbon emissions (Ullah et al. 2021; Ahmed et al. 2023). The relationship between energy taxes, energy innovation, and carbon emissions is examined using technological innovation and environmental theories (Porter 1991; Grossman and Krueger 1995). This model is:

$$CO_{2,t} = \tau_0 + \tau_1 ET_t + \tau_2 ETI_t + \tau_3 FD_t + \tau_4 ED_t + \tau_5 HC_t + \varepsilon_t \quad (1)$$

Equation (1) is CO2 emissions (CO2) that relies on energy taxes (ET), energy technology innovation (ETI), financial development (FD), economic development (ED), and human capital (HC)**.** Equation (1) provides only estimates for the long-run coefficients of the variables. However, this study aims to obtain both short-term and long-term estimates, requiring us to include the short-term dynamics in the specification (1). To achieve this, we designate specification (1) as an error correction structure and utilize the bounds-testing method for cointegration and error-correction modeling of Pesaran et al. (2001), as described in Eq. (2), following the methodology used in previous studies.

$$\Delta CO_{2,t} = \tau_0 + \sum_{k=1}^{n} \delta_{1k} \Delta CO_{2,t-k} + \sum_{k=0}^{n} \delta_{2k} \Delta ET_{t-k} + \sum_{k=0}^{n} \delta_{3k} \Delta ETI_{t-k} + \sum_{k=1}^{n} \delta_{4k} \Delta FD_{t-k} + \sum_{k=0}^{n} \delta_{5k} \Delta ED_{t-k} + \sum_{k=0}^{n} \delta_{6k} \Delta HC_{t-k} + \tau_1 CO_{2,t-1} + \tau_2 ET_{t-1} + \tau_3 ETI_{t-1} + \tau_4 FD_{t-1} + \tau_5 ED_{it-1} + \tau_6 HC_{t-1} + \varepsilon_t \quad (2)$$

Model (2) is advantageous as it allows for the simultaneous estimation of short and long-term effects. Short-term effects are captured by the coefficients of first-difference (Δ) variables, while the long-term effects are indicated by the coefficients τ1- τ6. For the long-term relationship to be valid, cointegration must occur among the variables. Pesaran et al. (2001) introduced a new set of critical values for the F-test, which can be used to test for cointegration. The null hypothesis of no cointegration can be rejected only if the estimated F-statistic exceeds the critical values of Pesaran et al. (2001). Unit root analysis is not necessary since the critical values consider the level of integration of the variables, which may include a mix of I(0) and I(1) series (Aslam et al. 2021; Sohail et al. 2021). ARDL model is robust to small sample sizes, which can be a common problem in economic research.

However, specification (2) only provides symmetric or linear estimates of the primary independent variables of energy taxes and energy technology innovation. NARDL is useful when the relationship between variables is asymmetric. To obtain asymmetric estimates, we have employed the partial sum procedure of Shin et al. (2014) by dividing the variables of energy taxes and energy technology innovation into positive and negative changes, as demonstrated below:

$$ET^{+}_{t} = \sum_{n=1}^{t} \Delta ET^{+}_{t} = \sum_{n=1}^{t} \max\left(ET^{+}_{t}, 0\right) \quad (3a)$$

$$ET^{-}_{t} = \sum_{n=1}^{t} \Delta ET^{-}_{t} = \sum_{n=1}^{t} \min\left(\Delta ET^{-}_{t}, 0\right) \quad (3b)$$

$$ETI^{+}_{t} = \sum_{n=1}^{t} \Delta ETI^{+}_{t} = \sum_{n=1}^{t} \max\left(ETI^{+}_{t}, 0\right) \quad (3c)$$

$$ETI^{-}_{t} = \sum_{n=1}^{t} \Delta ETI^{-}_{t} = \sum_{n=1}^{t} \min\left(\Delta ETI^{-}_{t}, 0\right) \quad (3d)$$

Series (3a and 3c) represent only positive changes, while series (3b and 3d) represent only negative changes in the energy taxes and energy technology innovation variables. Once these partial sum variables are substituted into the specification (2), the resulting equation will be as follows:

$$\Delta CO_{2,t} = \tau_0 + \sum_{k=1}^{n} \delta_{1k} \Delta CO_{2,t-k} + \sum_{k=0}^{n} \delta_{2k} \Delta ET^{+}_{t-k} + \sum_{k=0}^{n} \delta_{3k} \Delta ET^{-}_{t-k} + \sum_{k=0}^{n} \delta_{4k} \Delta ETI^{+}_{t-k} + \sum_{k=0}^{n} \delta_{5k} \Delta ETI^{-}_{t-k} + \sum_{k=0}^{n} \delta_{6k} FD_{t-k} + \sum_{k=0}^{n} \delta_{7k} ED_{t-k} + \sum_{k=0}^{n} \delta_{8k} HC_{t-k} + \tau_1 CO_{2,t-1} + \tau_2 ET^{+}_{t-1} + \tau_3 ET^{-}_{t-1} + \tau_4 ETI^{+}_{t-1} + \tau_5 ETI^{-}_{t-1} + \tau_6 FD_{t-1} + \tau_7 ED_{t-1} + \tau_8 HC_{t-1} + \varepsilon_t \quad (4)$$

Equation (4) is referred to as the nonlinear ARDL framework when the creation of partial sum variables results in a nonlinear equation. In contrast, model (2) is referred to as the linear ARDL framework. Shin et al. (2014) demonstrate that the nonlinear system can be estimated using the same methodology as the linear model, using Pesaran et al. (2001).

While the baseline model is the nonlinear ARDL framework, we have also utilized the nonlinear QARDL model to verify the robustness of our findings. The nonlinear QARDL model provides accurate estimates when non-normality is present.

Data and descriptive analysis

Our study aims to explore the impact of energy taxes and energy innovation on green sustainability in China. To conduct this analysis, we have collected time-series data for the period 1990 to 2021 and the information regarding data is presented in Table 1. The green sustainability variable is measured through CO2 emissions in metric tons per capita. Energy taxes (ET) and energy technology innovation (ETI) are focused variables in this study. Energy taxes (ET) are measured by energy-related tax revenue as % of total environmental tax revenue. Energy technology innovation (ETI) is measured in terms of patents on energy-related technologies. Following previous studies, our study includes three control variables in the model (Liu et al. 2022; Ozturk and Ullah 2022). These variables have the tendency to influence environmental sustainability in China. These are financial development (FD), economic development (ED), and human capital (HC). An index is used to measure financial development, while GDP per capita at current US$ is used to measure economic development. Human capital (HC) is measured by average schooling years at age 15 & above. Table 1 also reports the descriptive statistics for all variables. Mean scores are reported as: 4.882 for CO2, 3.608 for ET, 7.243 for ETI, 0.474 for FD, 3.355 for ED, and 7.157 for HC. Whereas, S.D scores are reported as: 2.219 for CO2, 0.321 for ET, 2.005 for ETI, 0.119 FD, 0.505 for ED, 0.640 for HC. The J-B statistics reject the null hypothesis of normality for all variables. It shows that none of the data series is normally distributed in our model.

Empirical results

To avoid drawing incorrect conclusions from using non-stationary variables, the initial and most significant phase in the time series modeling procedure is to determine if the factors chosen are stationary. Three well-reputed tests are applied in this analysis, namely Augmented Dickey-Fuller (ADF), Phillips and Perron (PP), and DF-GLS. The results of the unit root tests are shown in Table 3, which demonstrates that except for the HC rest of the variables become stationary after 1st differencing (Table 2). Thus, the variables included in the investigation belong to mixed order of integration, i.e., I(0) and I(1).

We employ the linear and nonlinear ARDL arrangement, which can deal with I(0) and I(1) variables in line with the unit root results. As seen in Table 3, this approach allows for simultaneous estimation of both short and long-term results. The linear ARDL confirms the negative effect of ET, ETI, and FD on long-run CO2 emissions. A 1% upsurge in ET,

Table 1 Definitions and descriptive statistics

Variables	Definitions	Mean	Median	Max	Min	S.D	Skewness	Kurtosis	J-B	Prob
CO2	CO2 emissions (metric tons per capita)	4.882	4.912	8.508	1.993	2.219	0.103	1.393	13.55	0.001
ET	Energy-related tax revenue, % total environmental tax revenue	3.608	3.614	4.151	2.857	0.321	−0.426	2.310	6.222	0.044
ETI	Patents on energy-related technologies	7.243	7.461	9.787	3.759	2.005	−0.213	1.506	12.49	0.003
FD	Financial development index	0.474	0.467	0.676	0.274	0.119	0.158	1.762	8.447	0.016
ED	GDP per capita (current US$)	3.355	3.321	4.145	2.501	0.505	−0.082	1.595	10.33	0.006
HC	Average years of total schooling, age 15+, total	7.157	7.332	8.009	5.679	0.640	−0.695	2.400	11.91	0.002

Table 2 Results of unit root test

	ADF		PP		DF-GLS	
	Level	1st Difference	Level	1st Difference	Level	1st Difference
CO2	−0.989	−3.075**	−1.772	−5.374***	0.375	−1.682*
ET	−0.515	−3.335**	−0.554	−5.197***	−0.258	−3.161***
ETI	−0.981	−2.612**	−0.232	−6.345***	−0.235	−2.064**
FD	−0.234	−5.335***	−0.370	−6.672***	1.415	−2.075**
ED	−0.946	−2.745*	−1.387	−3.875***	0.689	−2.230**
HC	−2.814*		−3.021**		−1.745*	

Table 3 Estimates of ARDL and NARDL

Variable	ARDL Coefficient	Std. Error	t-Statistic	Prob	NARDL Coefficient	Std. Error	t-Statistic	Prob
Long-run								
ET	−0.602***	0.080	−7.549	0.000				
ET_POS					−0.393***	0.079	−4.997	0.000
ET_NEG					−0.057	0.404	−0.140	0.889
ETI	−1.315***	0.079	−16.74	0.000				
ETI_POS					−2.110***	0.549	−3.841	0.000
ETI_NEG					−0.425	0.268	−1.587	0.116
FD	−1.452***	0.091	−16.02	0.000	−1.605***	0.071	−22.67	0.000
ED	1.468***	0.077	19.00	0.000	0.911***	0.049	18.52	0.000
HC	−0.548	0.339	−1.616	0.109	−0.164*	0.098	−1.687	0.094
Short-run								
ET	−0.255**	0.104	−2.451	0.016				
ET_POS					−0.579**	0.278	−2.080	0.040
ET_NEG					−0.004	0.032	−0.140	0.889
ETI	−0.216*	0.105	−2.053	0.043				
ETI(-1)	0.339*	0.183	1.849	0.067				
ETI(-2)	−0.214*	0.109	−1.952	0.052				
ETI_POS					−0.173***	0.063	−2.777	0.006
ETI_POS(-1)					−0.145	0.200	−0.726	0.470
ETI_NEG					0.246	0.226	1.086	0.280
ETI_NEG(-1)					−0.005	0.023	−0.214	0.831
FD	0.791*	0.469	1.688	0.094	1.303**	0.508	2.566	0.012
FD(-1)	−1.070**	0.512	−2.091	0.039	−1.582***	0.538	−2.941	0.004
ED	0.244	0.156	1.568	0.120	0.877	0.545	1.610	0.110
ED(-1)					−1.117**	0.503	−2.219	0.029
HC	−0.352	0.718	−0.490	0.625	−0.744	1.345	−0.553	0.582
HC(-1)	0.233	0.294	0.790	0.431	0.432	0.864	0.500	0.618
C	1.240***	0.093	13.38	0.000	0.999***	0.304	3.290	0.001
Diagnostics								
F-test	10.25***				7.895			
ECM(-1)*	−0.706***	0.244	−2.891	0.004	−0.741**	0.334	−2.215	0.028
LM	1.542				0.698			
RESET	0.658				1.025			
CUSUM	S				S			
CUSUM-sq	S				S			
Wald-ET-LR					8.689***			
Wald-ET-SR					4.056*			
Wald-ETI-LR					9.055***			
Wald-ETI-SR					2.325			

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

ETI, and FD deters long-run CO2 emissions by 0.602%%, 1.315%, and 1.452%, respectively. In contrast, the long-run estimated coefficients of ED are positively and significantly linked to CO2 emissions – a 1% rise in the ED causes the CO2 emissions to rise by 1.468%. In the short run, the linear model suggests that a 1% growth of ET and ETI reduces CO2 emissions by 0.255% and 0.216%, and FD increases CO2 emissions by 0.791%.

In the nonlinear model, the estimates of ET_POS, ETI_POS, FD, and HC negatively influence CO2 emissions – a 1% increase in ET_POS, ETI_POS, FD, and HC reduces CO2 emissions by 0.393%, 2.110, 1.605%, and 0.164%, respectively; however, the estimates of ET_NEG and ETI_NEG are insignificant, while 1% increase in ED increases CO2 emissions by 0.911%. This finding is in line with Wang et al.'s (2012) research. Doğan et al. (2022) described that energy taxes reduce CO2 emissions by increasing the cost of fossil fuels and other high-carbon energy sources, energy taxes make low-carbon alternatives relatively more attractive, encouraging consumers and producers to switch to cleaner energy sources and technologies. Cheng et al. (2021) revealed that energy taxes encourage energy efficiency improvements, as higher prices for energy can create an incentive for individuals and businesses to use energy more efficiently. This leads to reductions in energy consumption and, in turn, CO2 emissions. Moreover, energy taxes generate revenue that is used to support investment in clean energy technologies. This includes funding for research and development, subsidies for the deployment of renewable energy sources, or support for energy efficiency improvements. Finding also infer that energy taxes promote the development and deployment of clean energy technologies, which in turn reduce CO2 emissions (Zhang et al. 2022). Energy taxes lead to behavioral change, as individuals and businesses change their energy use patterns in response to higher energy prices, which leads to a reduction in CO2 emissions. This also means that energy taxes also raise public awareness of the environmental impacts of energy use and the need to reduce CO2 emissions. This can create a cultural shift toward more sustainable energy use practices and support for policies that reduce CO2 emissions (Yuelan et al. 2019). In contradiction, Li et al. (2018) reported that energy taxes also have substitution effects, where consumers or businesses switch to alternative energy sources that may have a higher carbon intensity than the taxed source.

Our finding is also consistent with the studies conducted by Alvarez-Herranz et al. (2017) and Alola and Onifade (2022), who noted that technological progress plays a key role in mitigating climate change. Energy technology innovation leads to improvements in energy efficiency, which help reduce energy consumption. This results in lower greenhouse gas emissions per unit of output. Energy technology innovation helps reduce the cost of low-carbon technologies, such as wind and solar power, making them more competitive with fossil fuels. This can lead to increased adoption of these technologies, which can help reduce greenhouse gas emissions (Baloch et al. 2022). Energy technology innovation enables the development of new low-carbon technologies, which help reduce greenhouse gas emissions from the transportation sector (Cheng et al. 2021). Energy technology innovation facilitates the integration of renewable energy sources into the grid by improving the reliability and efficiency of energy storage systems. This help reduces CO2 emissions by enabling greater use of renewable energy sources like wind and solar power.

In the short run, the estimates of the ET_POS, ETI_POS, and ED negatively influence CO2 emissions, and the FD positively influences the CO2 emissions – a 1% increase in ET_POS, ETI_POS, and ED reduces CO2 emissions by 0.579%, 0.173%, and 1.117%, respectively and the FD increases CO2 emissions by 1.303%. Our estimations have been validated as being accurate by a number of diagnostic tests, including LM, RESET, CUSUM, and CUSUM-sq. Table 3 shows that the LM and RESET tests cannot detect serial correlation and misspecification in the models. The CUSUM and CUSUM-SQ tests provide further evidence of our parameters' stability. The F-test and ECM(-1) tests are used to examine the cointegration between the parameters, and both results validate the validity of the variables' long-term connection. The Wald-LR estimates are significant, indicating that in the long-run, the aggregate of positive shock estimates of ET and ETI is significantly different from the aggregate of the negative shock estimates of ET and ETI.

To analyze our main findings' robustness, we have employed the nonlinear QARDL model, which is available in Table 4. The long-run estimates of ET_POS are negatively significant from the 60th to 95th quantiles, and the estimates of ET_NEG are significantly negative from the 70th to 90th quantiles, implying that the rise in energy taxes reduces CO2 emissions and the fall in energy taxes increases CO2 emissions at higher intensities of CO2 emissions. The estimated coefficients of ETI_POS and ETI_NEG are significantly negative from the 30th to 95th quantiles. The long-run estimates of HC are significant and negative through all quantiles, and the estimates of FD are significant and negative from the 70th to 95th quantiles, while the estimates of ED are significant and positive and significant from the 5th to 95th quantiles. In the short run, the estimates of the ET_POS and ETI_POS are negatively significant from the 80th to 95th quantiles; however, the estimates of ET_NEG do not influence CO2 emissions, while the estimates of ETI_NEG are negatively significant from the 60th to 95th quantiles. The estimates of ED are positive and significant, while the estimates of HC are significant and negative in more than half of the quantiles.

Conclusion and implications

The idea that energy tariffs and innovation may contribute to lowering greenhouse gas emissions and fostering the development of a more sustainable energy future is gaining traction. By making energy usage more costly, energy taxes may aid in reducing energy use. The result may be a decrease in energy use on the part of consumers and enterprises, which might aid in lowering greenhouse gas emissions. On one side, investment in energy-saving and renewable energy technology may be encouraged through energy taxes; on the other side, energy innovation may encourage a more sustainable energy future and assist in lowering greenhouse gas emissions. More effective energy production and usage may assist in cutting emissions. In addition to reducing our dependency on fossil fuels, energy innovation may also create new renewable energy

Table 4 Estimates of QARDL

	Long-run estimates							Short-run estimates								
	ET_POS	ET_NEG	ETI_POS	ETI_NEG	FD	ED	HC	ET_POS	ET_NEG	ETI_POS	ETI_NEG	FD	ED	HC	C	ECM
0.05	0.257	−0.222	−0.404	−0.512	−0.719	3.433**	−1.928***	0.203	0.100	−0.062	−0.699	1.593	1.054	−0.193	2.007	−0.382***
	1.540	−1.063	−1.465	−1.070	−0.293	2.552	−8.688	0.622	1.071	−0.321	−1.599	1.597	1.243	−0.092	0.761	−3.648
0.10	0.334	−0.176	−0.291	−0.824	−1.440	3.996**	−1.898***	−0.011	0.010	−0.069	−0.408	1.041	0.409	−0.294	0.622	−0.446***
	1.325	−0.706	−1.320	−1.646	−0.515	2.503	−7.096	−0.048	0.040	−0.226	−1.457	1.167	0.095	−0.775	0.210	−2.852
0.20	0.280	−0.119	−0.370	−1.002*	−0.721	3.470**	−1.839***	−0.025	0.025	−0.344	−0.034	1.963	0.330	−0.415***	1.409	−0.304*
	1.270	−0.462	−1.473	−1.694	−0.239	2.112	−6.863	−0.126	0.318	−1.308	−0.908	1.277	1.086	−2.938	0.432	−1.793
0.30	0.303	−0.030	−0.500***	−1.173***	−0.408	2.733***	−1.789***	−0.080	0.033	−0.425	−0.564	2.326	0.295	−0.572***	2.887	−0.209*
	1.186	−0.130	−2.883	−4.416	−0.232	3.266	−9.554	−0.651	0.566	−1.461	−0.952	0.876	1.483	−4.103	1.483	−1.691
0.40	0.250	−0.144	−0.539**	−1.223***	−1.522	3.372***	−1.991***	−0.076	0.046	−0.365	−0.328	2.191	0.237**	−0.621***	2.757	−0.210*
	0.860	−0.645	−2.280	−5.782	−1.137	4.053	−10.33	−0.733	0.808	−1.616	−1.050	0.645	1.965	−4.820	1.233	−1.936
0.50	−0.215	−0.369	−0.827***	−1.329***	−1.771	3.441***	−2.250***	−0.053	0.061	−0.330	−0.264	2.351	0.495**	−0.787***	4.283**	−0.160**
	−1.433	−1.438	−4.713	−8.021	−1.366	3.228	−8.048	−0.510	1.066	−1.426	−0.711	1.051	2.618	−3.776	2.079	−2.058
0.60	−0.454*	−0.381	−0.879***	−1.442***	−1.928	3.795***	−2.384***	−0.042	0.041	−0.302	−0.175*	1.826	0.577***	−0.890***	4.283*	−0.141**
	−1.895	−1.601	−6.404	−6.821	−1.419	2.875	−8.713	−0.001	0.648	−1.384	−1.890	1.255	2.696	−2.833	1.733	−2.270
0.70	−0.378**	−0.232*	−0.985***	−1.538***	−1.493*	2.804*	−2.401***	−0.025	0.029	−0.194	−0.449*	1.421	0.725**	−0.784***	6.680*	−0.199**
	−2.083	−1.770	−6.050	−3.967	−1.697	1.691	−5.580	−1.177	0.534	−1.008	−1.931	1.397	2.511	−3.147	1.947	−2.376
0.80	−0.198**	−0.102**	−1.109***	−1.135***	−1.103**	1.913*	−2.482***	−0.050**	0.072	−0.233*	−1.009**	0.556	1.014**	−0.678***	9.458***	−0.277**
	−2.292	−2.347	−6.956	−3.280	−2.119	2.038	−3.775	−2.030	1.078	−1.892	−2.704	0.734	2.463	−3.297	4.382	−2.457
0.90	−0.227**	−0.074**	−1.213***	−1.040***	−1.006***	2.271*	−2.753***	−0.110***	0.117	−0.554**	−1.453***	0.558	1.202**	−0.576***	10.75***	−0.311***
	−2.406	−2.187	−4.782	−2.505	−3.001	2.310	−3.789	−2.944	1.152	−2.550	−3.257	1.052	2.119	−2.849	3.462	−3.082
0.95	−0.234**	−0.083**	−1.260***	−0.844***	−0.809***	2.343**	−2.820***	−0.247***	0.217	−1.384***	−1.661***	0.222	1.343*	−0.461***	11.25***	−0.431***
	−2.463	−2.259	−5.891	−3.645	−3.264	2.478	−6.314	−3.212	1.396	−3.004	−3.685	0.336	1.911	−3.086	4.394	−4.558

T-stat is below the estimated coefficient. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

technology. Consistent with these viewpoints, the study's main goal is to explore the impact of energy taxes and innovation on CO2 emissions in China. In contrast to most earlier analyses, which relied on the linear assumption, this study relies on the asymmetry assumption. This research used linear and nonlinear ARDL econometric methods to achieve that goal. The outcomes of the linear model demonstrate that although long-term increases in ET, ETI, and FD cause CO2 emissions to reduce, increases in ED cause CO2 emissions to climb. Similarly, ET and ETI cause CO2 emissions to fall in the short run, while FD promotes CO2 emissions. On the other hand, the nonlinear model, the ET_POS, ETI_POS, FD, and HC help reduce the long-run CO2 emissions, and the ED increase the CO2 emissions. In the short run, the ET_POS and ETI_POS are negatively and significantly connected to CO2 emissions, while the FD is positively linked to CO2 emissions.

These findings are essential for advising Chinese officials on achieving green sustainability. The positive and negative changes in energy taxes and innovation have different influences on CO2 emissions; therefore, policy experts must focus on the rise and fall in energy taxes and innovation while making policies for green sustainability. In addition, to induce companies and people to cut their emissions, policymakers should try to make emitting greenhouse gases more costly by increasing the price of carbon emissions by firms and households. Investments in sustainable energy technologies like solar and wind power may be made using the money raised through energy taxes. It may also be utilized to increase energy efficiency in residential and commercial buildings. Further, the tax should be created in a manner that does not stifle investment and economic expansion. Low-income families should not be disproportionately affected by the design of the tax system. On the other hand, the Chinese government may spend money on research and development to create new energy technologies like solar and wind energy. This may aid in lowering the cost of renewable energy and increasing its ability to compete with fossil fuels. Further, businesses that invest in energy innovation may get tax rebates and other incentives from the government. This may hasten the creation and use of new energy technologies crucial for achieving green sustainability.

Indeed the analysis has made many contributions to the existing literature, but it has some limitations. For instance, the analysis has only selected China as a sample country; thus, the inference drawn from the study has limited effects. The upcoming studies should perform the analysis by collecting data across a panel of different countries. Further, the analysis selected CO2 emissions as a measure of green sustainability; however, it would be more appropriate if future studies used green growth or sustainable development as a measure of green sustainability because these variables cover both environmental and economic aspects.

Authors contributions **Zhu Chunhui:** Idea, software, Methodology, Writing-Original draft preparation, Reviewing and Editing; Methodology; Investigation, Reviewing and Editing; **Ning Yuncai**: Conceptualization, Methodology, Writing-Original draft preparation; **Sun Xudong:** Reviewing and Editing; **Muhammad Abdullah:** Investigation, Reviewing.

Funding Projects Supported by the Fundamental Research Funds for the Central Universities (Grant No. 2010YG03)

Data availability The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

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

Competing interests The authors declare that they have no conflict of interest.

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