Clean energy consumption and CO₂ emissions: does China reduce some pollution burdens through environmental regulation?

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Abstract
Environmental regulations are considered a prerequisite for environmental performance. However, very limited studies have explored the asymmetric relationship between clean energy consumption, environmental regulation, and CO₂ emissions. This study scrutinizes the asymmetry phenomenon in environmental regulation-clean energy consumption and environmental quality nexus in China by using the time series nonlinear ARDL approach by covering the period 1993–2019. The result reveals that the impact of environmental regulation on clean energy consumption and CO₂ emissions is asymmetric. A positive change in environmental regulation has a positive effect on clean energy consumption but a negative impact on CO₂ emissions in the long run. While a negative change in environmental regulation has insignificant effects on clean energy consumption and CO₂ emissions in the long run. The study suggests that China should need to revisit environmental regulation policies that could help in improving environmental quality.

Keywords Environmental regulation · Clean energy · Environmental quality · China

Introduction

Environmental issues are attracting worldwide attention as climate change and environmental degradation are increasingly disrupting ecosystems including human life. Preserving environmental quality without sacrificing economic performance has become a key concern all over the world. Mainly emerging countries face the issue of sustaining their growth and the environment simultaneously. Against this backdrop, China is not properly managing economic growth, clean energy, and the environment. The growth of the Chinese economy largely depends upon its increasing industrialization which is the key cause of high pollution as well. Meanwhile, controlling environmental pressure has become a worldwide agenda. The United Nations (UN) sustainable development goals (SDGs) have more focus on the environment. SDG 13 is particularly focused on climate action. China is a fast-growing polluting economy and contributed around 28.8% to global CO₂ emissions (BP 2020). Lately, China has approved an “environmental protection tax law in 2018”, to limit pollution emissions (Jia 2018). While pursuing SDGs, China needs to increase its environmental regulations and their implementations (Chen et al. 2018; Hao et al. 2018; Wu et al. 2020).

Exploring the nexus between environmental regulation, energy use, and CO₂ emissions is useful from different viewpoints. The results help to better reforms and management of environmental taxes, price controls, energy sector issues, sectoral energy policies, and environmental management at the country and global level. The role of environmental regulation is critical for the energy sector in the following manners. First, environmental taxes increase the cost of conventional sources of energy, and demand for alternative clean energy sources tends to increase. Second, carbon taxes set a certain constraint on emission trading and, contrary to this no limit, is set on emissions price (Chiu et al. 2015). In a recent study, Shahzad (2020) reviews the literature up to 2020 to explore relationships between environmental tax, energy demand, and environmental pollution. Shahzad...
(2020) concludes that the extant literature provides ambiguous findings and requires a more comprehensive study. These facts inspire us to explore the dynamics of the applications of environmental regulation taxes on clean energy demand and CO₂ emissions (Godil et al. 2020; Sinha et al. 2021).

The link between environmental regulation and carbon emissions has attracted worldwide attention in recent decades. Standard literature, however, suggests controversial findings. The earlier studies were of the strong view that environmental regulation can help to control environmental pollution (Porter and Van der Linde 1995; Laplante and Rilstone 1996; Marconi 2012; Cairns 2014). In this regard, Porter’s hypothesis suggests that strict environmental laws force firms to innovate eco-friendly production methods, thereby alleviating the environmental burden. This hypothesis is suggested by Porter and Van der Linde (1995) who assert that stringent environmental regulations can invigorate corporate innovation endeavors. Meanwhile, the subsequent “compensation effect” can partly or even entirely compensate the cost of environmental regulation, contributing to productivity.

Laplante and Rilstone (1996) showed favorable negative impacts of environmental regulation on pollution emissions in Canada. Likewise, Marconi (2012) analyzed the outcome of environmental regulations for China and EU 14. Their findings also confirm that regulations can mitigate emissions. Van der Ploeg and Withagen (2012) claimed that environmental regulation can have favorable effects on carbon reduction and green welfare. Likewise, Cairns (2014) also showed that environmental regulation helps to manage carbon emissions.

Meanwhile, a group of scholars doubted the favorable role of environmental regulation for emissions abatement (Sinn 2008; Smulders et al. 2014; Ritter and Schopf 2014). They argued that regulation may not mitigate pollution, generally referred to as the “green paradox” hypothesis. Sinn (2008) views that environmental regulation is positively associated with CO₂ emissions. He believes that carbon tax takes time to be implemented, and CO₂ emissions escalate. Similarly, research by Smulders et al. (2014) demonstrated that premature information about environmental regulations fosters CO₂ emissions. Similarly, Ritter and Schopf (2014) demonstrated that “green policy” fosters the mining of fossil fuels and enhances CO₂ emissions.

Some scholars consider that the “green paradox” and “emission reduction effect” of environmental regulation work at the same time (Zhang et al. 2020; Min 2018). In this regard, Min (2018) showed that initially, regulations support green paradox, but after a certain threshold point, emission reduction effect begins to dominate. Thus, an inverted U-shaped phenomenon is likely to take place. Similarly, employing the panel data of 30 regions in China and the threshold regression model, Zhang et al. (2020) validated an inverted U-shaped association between environmental regulation and CO₂ emissions. Empirical research is growing in this field. One group of the studies focused on “enterprise-level” evidence. For example, Gamper-Rabindran and Finger (2013) employed the panel data of 1759 enterprises over the period 1988 to 2001 and explored the environmental impact of self-regulation for enterprises that joined the “responsible care” alliance. Surprisingly, their results show that regulation has emission-escalating effect. The authors suggest the likely reason could be the absence of the certification by a third party. Contrary to this, Khanna and Kumar (2011) showed that high-intensity regulation improves environmental efficiency for enterprises.

One group of studies has revealed mixed effects of environmental regulation on carbon emissions in China (Chen et al. 2018; Hao et al. 2018; Wu et al. 2020). Chen et al. (2018) explored the regulation and environmental nexus in the presence of an informal economy in 30 provinces of China from 1998 to 2012. Their findings show mixed results. On the one hand, their estimates show that both the shadow economy and stringent environmental regulation enhance CO₂ emissions in China. On the other hand, they show that regulation can help to control pollution depending on a given level of the shadow economy.

Similarly, Hao et al. (2018) investigate the impact of environmental regulations on environmental quality by employing panel data of Chinese cities from 2003 to 2010. They use the first difference GMM to estimate the model. The results do not confirm the environmental improving effect of the regulations. However, the combined effect of FDI and environmental regulation turns out to be negative and significant suggesting the importance of FDI in achieving the benefit of environmental regulations. In the same manner, using the data for 30 provinces of China over the period 2006–2015 and the GMM approach of estimation, Wu et al. (2020) also found mixed evidence of environmental regulation and environmental quality nexus. Environmental regulation curbs emissions in central and eastern China while it did not curb emissions in the western region of China.

China is among the world’s largest consumers of energy around the globe. According to an estimate, China consumed 24% of world energy consumption in 2018. China ranked first in greenhouse gas emissions throughout the globe. China’s carbon emissions accounted for 9428.7 million tons, which was equal to 27.8% of the world’s total carbon emissions. The net growth in carbon emissions is recorded at 30.7%. Due to this intensification in CO₂ emissions, governments of various economies have formulated policies for environmental regulation. The Chinese government has successively implemented and promulgated various environmental protection laws and regulations such as the saving energy law, the prevention and control of air pollution.
law, and the environmental protection law. Thus, we have selected China for empirical analysis.

The key objective of the present study is to investigate the role of environmental regulation in clean energy and the environment in China from 1993 to 2019. This research is particularly important from the policy perspective because environmental regulation requires scientific evidence. Even though the new research work provides valuable insights on regulation, clean energy, and emissions, however, we could not find any famous study for China that has explored the asymmetric role of environmental regulation for clean energy and carbon emissions. Furthermore, the existing studies provide conflicting outcomes. Therefore, more research is required to provide new and more conclusive outcomes. The prior empirical studies mainly focus on evidence-based firm-level experience, city, or region-specific studies. The findings of these studies, however, cannot be generalized at an aggregate level for China. Besides, the existing studies assume linear relationships which can lead to misleading results.

This study contributes to the extant literature on regulation, clean energy, and pollution nexus in the following ways: First, this study explores the role of environmental regulation on both clean energy and pollution in a single study using both linear and nonlinear ARDL approaches. Second, it provides fresh evidence of environmental regulation on energy and emissions using updated time-series data (1993–2019) covering both the short- and long-run empirical outcomes. Third, it employs alternative measures of regulation namely environmental regulation and environmental monitoring to provide a clearer picture of the empirical results. Fourth, it explores the nonlinear hidden impacts of environmental regulation by isolating the positive and negative shocks in environmental regulation. Fifth, this study controls the effect of environmental technology and financial performance index which are important drivers of clean energy use and carbon emission. Sixth, in the framework of sustainable development goals, it is one of the few studies which are focusing on the policy side of the economy, i.e., regulation, energy, and CO₂ emissions, in the case of China. The study will offer appropriate policy suggestions for China and other emerging and developing economies.

The next section provides a literature review. “Model and method” describes the “methodology and model.” The "empirical results and discussion" are reported in “Results and discussion.” Finally, “Conclusions and policy” provides a “conclusion and suggests policy implications.”

### Literature review

Environmental regulation is an integral means of social regulation through which government authorities regulate the operation and production activities of producers through means of tax collection for pollution emissions, administrative penalties, emission permits, and administrative orders to ensure the sustainability of environmental and economic development. Environmental regulation tools can be divided into three categories such as voluntary participation, market incentive, and command control (Yang and Song 2019). In the command control regulation type, government authorities regulate the requirements and objectives of environmental regulations through legislation and rules that need strict compliance from all producers (Mehmood et al. 2021). In the market incentive regulation type, the government authorities encourage such market standards that protect the environment through various means such as environmental taxes, transaction fees for pollution emissions, and sewage charges (Shen et al. 2019). Market incentives indirectly enhance environmental quality through economic incentives to recover the transaction cost paid by pollution emitters (Chen et al. 2022). In the voluntary regulation type, the government authorities carry out education and publicity among the public through various ways that improve their social awareness regarding environmental protection (Yang and Song 2019). Voluntary regulations include citizen participation, consultation, and public opinion that provide more suitable external supervision and incentives for controlling pollution.

Industrial processes currently depend on the consumption of fossil fuels as economic development is directly linked with continuous energy demand (Mehmood et al. 2021; Lei et al. 2022). Thus, the consumption of renewable and clean energy sources has emerged on a large scale to overcome the issue of environmental degradation (Mehmood 2021). In this perspective, we are exploring the prevailing literature on the nexus of environmental regulations and clean energy consumption. Environmental regulations can be implemented as a policy tool to reshape the pattern of clean energy consumption to improve economic growth and environmental quality (Du et al. 2021; Lei et al. 2021). By exploring the scope of environmental regulations for the long term, He et al. (2021) suggested that clean energy consumption and environmental regulations can mitigate carbon emissions in polluted economies on a large scale. Carrera et al. (2015) reported that environmental regulations encourage producers to adopt clean energy sources in the process of production. Zhou et al. (2021) adopted environmental regulation as a measure of energy policy and reported that energy policy enhances renewable energy consumption and improves the efficiency of energy. Various researches suggest that environmental...
regulation’s impact generally depends upon the composition of economic structure (Zhang et al. 2022).

Mardones and Baeza (2018) denoted that increase in environmental tax helps in reducing the consumption of fossil fuels and promotes the consumption of clean energy sources. Tian et al. (2020) denoted that imposition of high environmental taxes results in a slowdown of the domestic economy. Furthermore, studies reveal that the imposition of environmental taxes and regulations can promote growth in the renewable and clean energy sector (Bi et al. 2014). In the case of emerging economies, Acemoglu et al. (2016) denoted that environmental regulations reduce carbon emissions that bring significant development in the clean energy sector that significantly leads to sustainable environmental and economic development. Liu et al. (2018) investigated the nexus between environmental regulations and energy consumption by incorporating the role of economic growth and revealed that the imposition of environmental constraints can help in reducing the depletion speed of energy resources.

In general, the basic objective of environmental policies and regulations is to protect the quality of the environment. Thus, the expected impact of environmental regulations on carbon emissions is positive. Most specifically, the imposition of environmental taxes on high pollution emissions enterprises can raise their costs of production, thus reducing energy demand and CO₂ emissions (Zhang et al. 2021; Li et al. 2022a, b). Studies report that environmental regulations can directly and indirectly influence carbon emissions through industrial structure, FDI, and technology innovation (Yin et al. 2015; Wang and Zhang 2022). Environmental regulation influences carbon emissions through the channel of technology innovation that reports both negative offset and positive compensation impacts. Environmental regulations produce compensation impact through the process of technology innovation that can mitigate CO₂ emissions by enhancing the productivity level, hence controlling CO₂ emissions (Yuelan et al. 2019; Neves et al. 2020). Wang and Wei (2020) denoted that green innovation contributes more to reducing carbon emissions and enhancing energy efficiency. The offsetting impact states that the transaction cost of enterprises intensified due to the imposition of environmental regulations. Thus, their fund’s utilization for technology innovation declines and the enterprises often enlarge their production capacity in order to raise their profits, hence contributing to increasing carbon emissions. In this scenario, environmental regulations cannot control CO₂ emissions (Cai et al. 2022).

Literature reports that environmental regulations influence CO₂ emissions through the channel of FDI as described by the pollution–halo hypothesis (Jafri et al. 2022). According to the pollution-haven hypothesis, developing economies relax their environmental regulations to attract FDI, and the developed economies used to transfer highly polluting industries to developing economies, thus raising pollution emissions (Li et al. 2022a, b). Environmental regulation’s impact on CO₂ emissions also varies due to industrial structure. The high pollution-intensive industries generate more pollution, thus leading to the intensification of CO₂ emissions (Yu et al. 2021). Strict imposition of environmental regulations can upgrade and optimize the industrial structure. Environmental regulations tend to raise environmental costs; hence, enterprises prefer to adopt eco-friendly technologies for environmental sustainability and promote the upgrading of industrial structure for a possible reduction in CO₂ emissions (Zhang et al. 2019).

Our study finds several studies exploring the association between CO₂ emissions and environmental regulation but failed to find enough studies on determining the impact of environmental regulation on clean energy consumption. Some other deficiencies are found in prevailing studies. There is a gap in the literature on the nexus between clean energy consumption and environmental regulations; thus, our study explores the impact of environmental regulation on CO₂ emissions and clean energy consumption. Another deficiency of existing literature is that it explores the symmetric impact on environmental regulations of CO₂ emissions. However, our study explores the asymmetric impact of environmental regulations on CO₂ emissions and clean energy consumption in China.

**Model and method**

In formulating the clean energy consumption and carbon emissions models, we follow the literature, e.g., Wang and Shen (2016) and Wang et al. (2019), by assuming that environmental regulation is the main determinant of clean energy and environmental quality. As such we showed Eqs. (1 and 2) are below as

\[
CEC_t = \rho_0 + \rho_1ER_t + \rho_2EM_t + \rho_3ET_t + \rho_4GDP_t + \rho_5FDI_t + \epsilon_t
\]

(1)

\[
CO_{2,t} = \rho_0 + \rho_1ER_t + \rho_2EM_t + \rho_3ET_t + \rho_4GDP_t + \rho_5FDI_t + \epsilon_t
\]

(2)

Equation (1) is China’s clean energy consumption and Eq. (2) is the environmental quality model and assumed to rely on the level of environmental regulation denoted by ER. Since increased environmental regulation leads to more clean energy consumption, we expect estimates of \( \rho_1 \) in Eq. (1) to be positive, while environmental regulation leads to more environmental quality; we expect estimates of \( \rho_1 \) in Eq. (2) to be negative. Equations (1 and 2) provide the long-run estimates only; however, we are concerned with both short-run and long-run estimates. To that end, we need to reconsider the above equation in the error correction format as displayed below:
\[ \Delta CEC_t = \beta_0 + \sum_{k=1}^{n_1} \beta_{k1} \Delta CEC_{t-k} + \sum_{k=1}^{n_2} \beta_{k2} \Delta ER_{t-k} + \sum_{k=1}^{n_3} \beta_{k3} \Delta EM_{t-k} + \sum_{k=1}^{n_4} \beta_{k4} \Delta ET_{t-k} + \sum_{k=1}^{n_5} \beta_{k5} \Delta GDP_{t-k} + \sum_{k=1}^{n_6} \beta_{k6} \Delta FDI_{t-k} + \epsilon_t \]  

(3)

\[ \Delta CEC_t = \beta_0 + \sum_{k=1}^{n_1} \beta_{k1} \Delta CEC_{t-k} + \sum_{k=1}^{n_2} \beta_{k2} \Delta ER_{t-k} + \sum_{k=1}^{n_3} \beta_{k3} \Delta EM_{t-k} + \sum_{k=1}^{n_4} \beta_{k4} \Delta ET_{t-k} + \sum_{k=1}^{n_5} \beta_{k5} \Delta GDP_{t-k} + \sum_{k=1}^{n_6} \beta_{k6} \Delta FDI_{t-k} + \epsilon_t \]  

(4)

Specifications (3 and 4) have occupied the form of the linear ARDL of Pesaran et al. (2001). Once we estimate Eqs. (3 and 4), we get both long-run with short-run estimates simultaneously. The estimates connected to the first-difference indicators (\(\Delta\)) represent the short-run estimates; whereas, the estimates connected to \(\rho_2 = \rho_0\) normalized on \(\rho_1\) are long run. Moreover, this method is efficient in a small sample size. Another advantage is that pre-unit root testing is not a prerequisite for ARDL. This method provides robust estimates even as the variables are incorporated by distinct orders such as \(I(0)\) otherwise \(I(1)\). But we cannot include any variable, which is \(I(2)\). The main assumption behind Eqs. (3 and 4) is that environmental regulation has symmetric effects on clean energy consumption and CO2 emissions. Following Shin et al. (2014) approach, we can also examine the possibility of asymmetries, which contain positive changes in environmental regulation as well as negative changes. The NARDL method captures anticipated asymmetry in environmental regulation. The NARDL method has some advantages over other time series methods. Also, unlike nonlinear switching models, the NARDL method jointly contains complex and asymmetry cointegration dynamics between the variables (Bahmani-Oskooee et al. 2020). Zhou et al. (2019) reported that the NARDL is better suited to modeling the nonlinear effect of environmental regulation. NARDL method separates between long- and short-run asymmetries. The mathematical form of the partial sum procedure is presented below:

\[ ER^+ = \sum_{n=1}^{t} \Delta ER^+ \]  

(5)

In Eq. (5), \(ER^+\) represents the positive changes in the series, whereas Eq. (6) \(ER^-\) represents the negative changes in the selected series. Next, we incorporate partial sum variables in the original models as shown below:

\[ ER^- = \sum_{n=1}^{t} \Delta ER^- \]  

(6)

After entering the partial sum variables in place of original variables, the new Eqs. (7 and 8) are known as the NARDL of Shin et al. (2014), which is a new form of the ARDL model. This method is subject to the same cointegration test and critical values as Pesaran et al. (2001) proposed for the linear ARDL model. However, few asymmetric tests are to be applied to confirm the presence of asymmetry in the impacts of positive and negative components of ER. First, we see if the size of the estimate attached to \(\Delta ER^+\) at a particular lag is different from the size of the estimate attached to \(\Delta ER^-\) or not, and if they are different, this is a sign of short asymmetry. Then, to confirm the short-run asymmetries, we nullified the null hypothesis of Wald-SR, i.e., \(\sum \beta_{2k} = \sum \beta_{3k}\). Finally, the long asymmetries will confirm if we nullified the null hypothesis of Wald-LR, i.e., \(\frac{\beta_2}{\beta_3} = \frac{\beta_3}{\beta_2}\).

The data are attained from the IMF, OECD, and World Bank by covering the period 1993–2019. Environmental regulation promotes clean energy consumption and significantly mitigates CO2 emissions (Wang and Zhang 2022), where eco-innovation, economic development, and financial development have been considered the crucial driver to clean energy consumption and CO2 emissions (Ullah et al. 2021; Li et al. 2022a, b). However, this study examines the impact of environmental regulation on clean energy consumption and CO2 emissions by controlling potential influences including eco-innovation, GDP, and financial development. Annual data of China is employed for analysis, and we used the consumption of clean energy and CO2 emissions as dependent variables. We used the electric power consumption (KWh per capita) and carbon dioxide emissions (kilotons) as proxies of clean energy demand and environmental quality (Usman et al. 2020). The remaining details of independent and control variables are also given in Table 1. We transformed CO2, clean energy consumption, environmental technology, and GDP per capita into logarithmic form. In
Table 2, the mean of CO$_2$, CEC, ER, EM, ET, GDP, and FDI are 15.59 kt, 7.463 kWh per capita, 3.225%, 4.024, 9.795, 8.018, and 0.723, respectively. The Jarque–Bera test outcomes shown in Table 2 are insignificant for all variables. It shows that data is normally distributed. Hence, the use of the quantile ARDL method is not suitable for this study.

**Results and discussion**

The first is used without and with structural breaks unit root tests to observe the order of integration of all nominated variables. The results are provided in Table 3 and the turn out depicts mixed order of integration, but none of the variables is integrated I (2). This section also reports the empirical results and their discussion. The long- and short-run results are obtained using the ARDL method employing time series data for China. Two models are estimated where the first model provided the estimates for clean energy, and the second model provided the outcomes for the CO$_2$ emission model. Table 4 presents the empirical outcomes using linear ARDL model specification whereas Table 5 shows results based on nonlinear ARDL model specification. As discussed earlier, the main objective of the present study is to explore the dynamic linear and nonlinear effects of environmental regulation on clean energy and CO$_2$ emissions.

In Table 4, the parameter estimate of ER has a positive and statistically significant effect on clean energy consumption at a 10% level of significance in the short run, implying that ER helps to mitigate carbon emissions in the short run. Particularly, the numerical estimate suggests that a 1% increase in environmental regulation will increase demand

### Table 1 Definitions and sources

| Variables                      | Abbreviations | Definitions                                      | Sources  |
|--------------------------------|---------------|--------------------------------------------------|----------|
| Carbon dioxide emissions       | CO$_2$        | Carbon dioxide emissions (kilotons)              | World Bank|
| Clean energy consumption       | CEC           | Electric power consumption (kWh per capita)      | World Bank|
| Environmental regulation       | ER            | Environment-related taxes, % total tax revenue   | OECD     |
| Environmental monitoring       | EM            | Total number of environmental monitoring         | OECD     |
| Environmental technology       | ET            | Environment-related technologies                  | OECD     |
| GDP per capita                 | GDP           | GDP per capita (constant 2010)                    | World Bank|
| Financial development index    | FDI           | An index that captures financial markets development | IMF      |

### Table 2 Descriptive statistics

| Variables | Mean  | Median | Maximum | Minimum | Std. Dev | Skewness | Kurtosis | Jarque–Bera | Probability |
|-----------|-------|--------|---------|---------|----------|----------|----------|-------------|-------------|
| CO$_2$    | 15.59 | 15.69  | 16.27   | 14.87   | 0.505    | -0.078   | 1.360    | 3.052       | 0.217       |
| CEC       | 7.463 | 7.620  | 8.276   | 6.496   | 0.595    | -0.245   | 1.504    | 2.787       | 0.248       |
| ER        | 3.225 | 2.980  | 6.360   | 0.200   | 1.763    | 0.189    | 2.053    | 1.170       | 0.557       |
| EM        | 4.024 | 4.575  | 6.510   | -0.511  | 2.119    | -0.786   | 2.546    | 3.011       | 0.222       |
| ET        | 9.795 | 9.847  | 11.99   | 7.387   | 1.508    | -0.059   | 1.676    | 1.987       | 0.370       |
| GDP       | 8.018 | 8.027  | 9.018   | 6.906   | 0.669    | -0.059   | 1.653    | 2.058       | 0.357       |
| FDI       | 0.723 | 0.740  | 0.797   | 0.580   | 0.057    | -1.151   | 3.511    | 4.256       | 0.144       |

### Table 3 Without and with structural breaks unit root test

| Variables | Without structural breaks unit root test | With structural breaks unit root test |
|-----------|------------------------------------------|--------------------------------------|
|           | I(0) | I(1) | Decision | I(0) | Break period | I(0) | Break period | Decision |
| CO$_2$    | -0.535 | -3.090** | I(1) | -4.562** | 2002 | I(0) | 2002 | 2002 | I(1) |
| CEC       | -1.595 | -3.712*** | I(1) | -3.212 | 2002 | I(1) | 2002 | 2002 | I(1) |
| ER        | -1.632 | -3.861** | I(1) | -2.012 | 2010 | I(1) | 2010 | 2010 | I(1) |
| EM        | -3.431 | I(0) | 2009 | I(0) | 2009 | I(0) | 2009 | 2009 | I(0) |
| ET        | -2.762* | I(1) | -2.032 | 2003 | I(1) | 2003 | 2003 | I(1) |
| GDP       | -2.268* | I(0) | -6.565*** | 2004 | I(0) | 2004 | 2004 | I(0) |
| FDI       | -2.732* | I(0) | -3.012 | 2003 | I(1) | 2003 | 2003 | I(1) |

*p < 0.1; **p < 0.05; ***p < 0.01
for clean energy consumption by 0.042% in the short run. The estimates for EM and ET suggest that no significant relationship is turned out between EM/ET and clean energy consumption suggesting that it is environmental regulation that mainly regulates the demand for clean energy in the short run. Similarly, FDI did not show any significant effect on clean energy in the short run. The effect of GDP, however, is positive in the short run suggesting that a 1% increase in economic growth will escalate the demand for clean energy in China by 2.396%.

Panel B of Table 4 presents the long-term result based on the linear model. The parameter estimate of ER has a positive significant influence on energy consumption in the long run as well. Particularly, a 1% increase in ER will mitigate carbon emissions by 0.117%. Thus, the effect of ER is not only consistent, but the magnitude of effect also increases by almost three times implying that environmental regulation has more impact in the long run. The effect of EM and ET turn out to be positive and significant in the long run revealing that EM and ET have more power to influence clean energy in the long run. The coefficient of EM (ET) reveals that a 1% increase in EM (ET) will increase the demand for clean energy by 0.088% (0.376%) in the long run. The impact of GDP, however, turns out to be insignificant in the long run. The role of FDI also remains insignificant in the long run.

The third and bottom panel of Table 4 presents the results of numerous diagnostic tests. The estimates of “the Lagrange multiplier (LM) test” are statistically insignificant signifying that the residuals are free from autocorrelation problem. Some other diagnostic tests including “Ramsey RESET test, Heteroskedasticity test, and CUSUM test” are also applied. The numerical values of the RESET test are insignificant implying that functional forms are not misspecified, and our selected models are suitable. In addition, the numerical value of the BP test is also insignificant showing that the heteroskedasticity problem does not influence the outcomes. Finally, to test for the stability of linear ARDL models, “CUSUM and CUSUM-squared tests” are applied where “S” shows the stable model and the “US” denotes the unstable model. Both models are shown to be stable in the estimation linear ARDL. Besides, the test for goodness of fit also

| Variable | Clean energy | Coefficient | S.E | t-Stat | Prob | Coefficient | S.E | t-Stat | Prob |
|----------|--------------|-------------|-----|--------|------|-------------|-----|--------|------|
| Short run |              |             |     |        |      |             |     |        |      |
| D(ER)    | 0.042***     | 0.009       | 4.585| 0.003  |      | -0.033**  | 0.014| 2.339 | 0.048|
| D(ER(-1))| -0.151***    | 0.012       | 12.94| 0.000  |      |             |     |        |      |
| D(EM)    | 0.021        | 0.027       | 0.789| 0.456  | 0.032| 0.041      | 0.777| 0.459  |
| D(EM(-1))| 0.031        | 0.032       | 0.960| 0.369  | 0.115*| 0.067      | 1.726| 0.123  |
| D(ET)    | -0.016       | 0.089       | 0.181| 0.861  | 0.148| 0.125      | 1.183| 0.271  |
| D(ET(-1))| -0.146       | 0.118       | 1.237| 0.256  | -0.793***| 0.258| 3.070 | 0.015 |
| D(GDP)   | 2.396***     | 0.464       | 5.167| 0.001  | 0.144| 0.828      | 0.137| 0.894  |
| D(GDP(-1))| 0.667 | 0.488       | 1.366| 0.214  | 1.992***| 0.708| 2.814 | 0.023 |
| D(FDI)   | 0.451        | 0.373       | 1.211| 0.265  | -0.972*| 0.508| 1.912 | 0.092 |
| D(FDI(-1))| -0.271 | 0.227       | 1.192| 0.272  | 0.469| 0.329      | 1.423| 0.192  |
| Long run |              |             |     |        |      |             |     |        |      |
| ER       | 0.117***     | 0.008       | 14.36| 0.000  |      | -0.142*** | 0.044| 3.211 | 0.012|
| EM       | 0.088**      | 0.041       | 2.162| 0.067  |      | -0.019     | 0.078| 0.247 | 0.811|
| ET       | 0.376***     | 0.129       | 2.915| 0.023  |      | -2.085***  | 0.800| 2.607 | 0.031|
| GDP      | -0.061       | 0.265       | 0.229| 0.825  |      | -3.687**   | 1.769| 2.084 | 0.071|
| FDI      | 1.223        | 0.859       | 1.424| 0.197  |      | -4.651**   | 1.965| 2.367 | 0.046|
| C        | 3.173***     | 0.897       | 3.538| 0.010  | 27.69***| 7.217| 3.837 | 0.005|
| Diagnostic |          |             |     |        |      |             |     |        |      |
| F test   | 8.023***     | 0.055       | 15.71| 0.000  |      | -0.469     | 0.148| 3.161 | 0.013|
| ECM(-1)  | -0.872***    | 0.922       | 0.508| 0.508  |      | 1.577      |     |        |      |
| LM       | 2.465        | 0.189       | 1.464| 0.189  |      | 0.010      | 0.010| 1.464 | 0.189|
| BP       | 0.454        | 2.465       | 1.577| 1.577  |      | 0.010      | 0.010| 1.464 | 0.189|
| RESET    | S            | S           | S    | S      |      |            |     |        |      |
| CUSUM    | S            | S           | S    | S      |      |            |     |        |      |

*p < 0.1; **p < 0.05; ***p < 0.01
shows a high level of goodness of fit. Thus, with these tests’ outcomes, we can safely conclude that our empirical results based on the linear ARDL are efficient and stable.

The results for the CO$_2$ model suggest that the effect of EM on CO$_2$ emissions is negative and significant in the short run. Particularly, a 1% increase in EM will mitigate CO$_2$ emissions by 0.033% in the short run. The effects of EM and ET do not show any significant impact on CO$_2$ emissions in the short run. Similarly, GDP is not significantly associated with CO$_2$ emissions in the short run. The effect of FDI, however, is positive and significant at a 1% level of significance in the short run. The numerical value of FDI suggests that a 1% increase in FDI will control emissions by 0.972% in the short run. Thus, financial development helps to improve environmental quality in the short run.

Panel B of Table 4 presents the long-run result based on the linear model. The parameter estimate of ER has a negative and significant influence on CO$_2$ emissions in the long run as well. Particularly, a 1% increase in ER will mitigate carbon emissions by 0.142%. Thus, the effect of ER is not only consistent, but the magnitude of the effect also increases by almost four times in the long run. This result is backed by prior studies (Porter and Van der Linde 1995; Laplante and Rilstone 1996; Marconi 2012; Cairns 2014). The effect of EM remains insignificant in the long run as well; however, the effect of ET turns out to be negative and significant in the long run revealing ET has more power to influence CO$_2$ emissions in the long run. The coefficient of ET reveals that a 1% increase in ET will decrease CO$_2$ emissions by 2.085% in the long run. The impact of GDP,

| Variable | Clean energy | CO$_2$ |
|----------|--------------|--------|
| **Short run** | | |
| D(ER_POS) | 0.173*** | 0.063 | 2.767 | 0.070 | 0.025 | 0.066 | 0.380 | 0.713 |
| D(ER_POS(-1)) | -0.281** | 0.110 | 2.545 | 0.084 |
| D(ER_NEG) | -0.081*** | 0.014 | 5.912 | 0.010 | 0.005 | 0.010 | 0.467 | 0.652 |
| D(ER_NEG(-1)) | -0.131*** | 0.011 | 12.10 | 0.001 |
| D(EM) | -0.045 | 0.036 | 1.248 | 0.301 | 0.034 | 0.024 | 1.433 | 0.186 |
| D(EM(-1)) | 0.091*** | 0.031 | 2.937 | 0.061 | 0.132*** | 0.042 | 3.126 | 0.012 |
| D(ET) | -0.029 | 0.083 | 0.354 | 0.746 | -0.389* | 0.203 | -1.915 | 0.069 |
| D(ET(-1)) | -0.309*** | 0.067 | 4.649 | 0.019 | -0.733*** | 0.154 | 4.758 | 0.001 |
| D(GDP) | 1.822*** | 0.235 | 7.766 | 0.004 | -0.324 | 0.489 | 0.664 | 0.523 |
| D(GDP(-1)) | 1.633*** | 0.349 | 4.673 | 0.019 | 1.761*** | 0.422 | 4.178 | 0.002 |
| D(FDI) | 0.260 | 0.334 | 0.777 | 0.494 | -0.186 | 0.308 | 0.603 | 0.562 |
| D(FDI(-1)) | -0.262 | 0.164 | 1.594 | 0.209 |
| **Long run** | | |
| ER_POS | 0.309*** | 0.071 | 4.376 | 0.022 | -0.418*** | 0.067 | 6.269 | 0.000 |
| ER_NEG | 0.028 | 0.031 | 0.888 | 0.440 | 0.009 | 0.019 | 0.458 | 0.658 |
| EM | 0.158*** | 0.043 | 3.676 | 0.035 | -0.233*** | 0.051 | 4.594 | 0.001 |
| ET | 0.370*** | 0.068 | 5.420 | 0.012 | -2.095*** | 0.431 | 4.859 | 0.001 |
| GDP | 0.580*** | 0.205 | 2.825 | 0.067 | -4.532*** | 1.052 | 4.308 | 0.002 |
| FDI | 0.947 | 0.587 | 1.615 | 0.205 | -0.355 | 0.567 | 0.626 | 0.547 |
| C | 7.056*** | 1.165 | 6.054 | 0.009 | 30.97*** | 4.166 | 7.436 | 0.000 |
| **Diagnostic** | | |
| F-test | 4.264*** | | | 6.280*** | |
| ECM(-1) | -0.307 | 0.211 | 1.454 | 0.114 | -0.523*** | 0.088 | 5.939 | 0.000 |
| LM | 1.534 | | | 2.010 | |
| Hetro | 0.709 | | | 0.642 | |
| RESET | 0.226 | | | 0.369 | |
| CUSUM | S | | | S | |
| CUSUM-2 | S | | | S | |
| Wald-SR | 2.012 | | | 1.023 | |
| WALD-LR | 4.302*** | | | 5.325*** | |

*p<0.1; **p<0.05; ***p<0.01
surprisingly, turns out to be significant with a negative sign in the long run. The numerical value suggests that a 1% increase in GDP will decrease emissions by 3.687% in the long run. This finding suggests that in the long run, economic growth can help to lower emissions owing to the reasons for replacement of fossil fuels with clean energy and promoting environmental care in the long run. The role of FDI also remains significant with a negative sign suggesting that FDI can play a key role in the mitigation of CO₂ emissions in the long run. Furthermore, the magnitude of the effect is also increased in the long run.

The ongoing analysis revolves around a question: “How do the results change if we apply the nonlinear ARDL model?” To check whether or not the effect of environmental regulation, environmental monitoring, and environmental technology on clean energy consumption, and CO₂ emission is nonlinear or not, Table 5 presents short-run and long-run findings of the asymmetric ARDL approach along with diagnostic tests. The short-run outcomes show that the positive (negative) component of ER increases (decreases) clean energy consumption. As the estimated coefficient of ER is +0.173 (−0.081), infer that a 1% increase (decrease) in ER enhances (reduce) clean energy consumption by +0.173 (−0.081%). These estimates are significant at a 10% level of significance. Thus, a positive shock in ER is positively linked with clean energy, and a negative shock is negatively associated with clean energy consumption. The effects of EM and ET are, however, insignificant. The coefficient of GDP has a positive effect while the coefficient of FDI suggests an insignificant impact.

The long-run outcomes show that the positive (negative) component of ER increases (decreases) clean energy consumption. The estimated positive coefficient suggests that a 1% increase in ER enhances clean energy consumption by +0.309%. However, the negative shock in ER does not have any significant impact on clean energy consumption. Interestingly, EM (ET) is positively connected with clean energy consumption. The numerical values show that a 1% increase in EM (ET) will fall CO₂ emissions by 0.233% (2.095%). This result is backed by Zhao et al. (2015) and Wang and Zhang (2022), who reported that environmental regulation effectively mitigates CO₂ emissions by forcing industrial structure upgrades and technological progress. This result is consistent with Zhang et al. (2021), who reasoned that environmental regulations have a negative impact on CO₂ emissions, while regional heterogeneity also exists in China. The results are also inconsistent with Zhao et al. (2015), Chen et al. (2018), and Wang and Zhang (2022), who noted that CO₂ emissions respond symmetrically to environmental regulations. Our findings are in line with the findings of Li et al. (2019), who argued that environmental regulation improves environmental performance via economic incentives that escalate the polluters’ economic costs. Additionally, environmental regulation enhances and mobilizes the awareness about environmental protection that develops an active eco-friendly atmosphere. It is argued that carbon taxes on industrial enterprises can raise their costs of production, thus reducing energy demand that is conducive to reducing carbon emissions. The GDP is reducing CO₂ emissions by 4.532%. The effect of FDI is, however, not significant.

Table 5 also presents short-run and long-run asymmetric associations of ER with clean energy tested using the Wald test. The numerical value of the Wald test for short-run analysis does not reject the hypothesis of the short-run asymmetry while the numerical Wald test for long-run analysis rejects this hypothesis. Thus, ER has nonlinear impacts on clean energy only in the long run. Similarly, the Wald test outcome confirms a long-run asymmetry for our second model of CO₂ emissions. Thus, ER has an asymmetric association with CO₂ emissions only in the long run. Moreover, the F-statistics of nonlinear ARDL is statistically significant for both models of clean energy and carbon emission. Thus, we can infer that cointegration exists among
selected variables in both models. The “error correction term (ECT)” for both models is negative significant, confirming the presence of cointegration among the selected variables. Particularly, the coefficients of ECT show that clean energy (CO₂ emission) readjust their long-run equilibrium, with a rate of 31% (52%) each year. Besides, the nonlinear ARDL also qualifies the main diagnostic tests comprising “Ramsey RESET, Heteroskedasticity, R², and LM test.”

Conclusions and policy

There is growing empirical evidence that the effect of environmental regulation on clean energy consumption and CO₂ emissions may not be linear. To this end, a plethora of empirical literature has examined the possibility of a nonlinear nexus between environmental regulations on CO₂ in China and well documented by Wang et al. (2019). The previous linear model faced problems in empirical estimates, signifying the essential of nonlinear estimation techniques in the energy and environmental production model (Ullah et al. 2021).

By relaxing the linearity hypothesis, this study examined the nonlinear influence of environmental regulation on clean energy consumption and carbon emissions in China. The linear ARDL results show that environmental regulation has a promotional effect on clean energy consumption; however, environmental regulations in China lead to a reduction in CO₂ emissions in the short run and long run. The linear findings also show that environmental monitoring and environmental technology have a better long-term effect on clean energy consumption and environmental quality, but environmental-related technological improvements inspired by consumption of clean energy in return improve the quality of the environment in long-term incentives. Thus, linear findings show that environmental regulation, environmental monitoring, and environmental technology are reasonable sources of the green economy. The nonlinear estimates show that the positive shock of environmental regulation has positively influenced clean energy consumption in the short and long term, while the negative shock of environmental regulation has decreased clean energy in the only short run. Accordingly, a positive shock has reduced CO₂ emissions, and ultimately, induced environmental quality in the only long run. Our findings show that the environmental regulation shocks have different magnitude and similar signs in clean energy consumption, while it has different magnitude and opposite signs in CO₂ emissions. The results show that nonlinear estimates of focused variables deviate from the linear models.

Based on these findings, market-based environmental regulations can encourage economic as well as energy efficiency. There is also a necessity to set a possible level of environmental regulation, and authority should reinforce the environmental regulation in the economy. The government should increase smart technology to reduce fossil fuel energy intensity and follow the route of green growth. Developing clean energy and upgrading the digitization structure of the economy is a forward-thinking policy. China should impose a carbon tax on pollutant industries. China should increase regulatory efficiency by attaining the goals of carbon emissions reductions. Carbon pricing might be an effective policy tool to improve environmental quality, but authorities should also reconsider the institutions in environmental quality. China can correct the environment by using regulations for green growth purposes.

Although this study assessed the asymmetric impact of environmental regulation on clean energy and carbon emissions using a nonlinear model, the study is still introductory. The empirical study did not include a provincial analysis and so sub-national level analysis that provides targeted policies by using the nonlinear ARDL. In future studies, an updated quantile ARDL regression approach should be used that provides more accurate evidence regarding the asymmetric impact of environmental regulation on CO₂ emissions and renewable energy consumption. Our research work does not explore asymmetric determinants of green growth. There is much space for further expansion of the model. The proposed empirical approach can also be applied to examine the clean energy and environmental efficiency of sector-wise in China at micro-level data. Furthermore, the influence of carbon taxes on various sectors of the economy, such as industry, agriculture, transport, automobile, can also be considered in the forthcoming studies.

Author contribution This idea was given by Chuan Zhang. Chuan Zhang, Ruoxi Cao, and Muhammad Tariq Majeed analyzed the data and wrote the complete paper. While Ahmed Usman read and approved the final version.

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

Declarations

Ethics 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 for publication Not applicable

Competing interests The authors declare no competing interests.
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