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Routledge
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Zongke Bao[a], Diogo Ferraz[b,c,d] and Daisy Aparecida do Nascimento Rebelatto[e]

[a]School of Accounting, Zhejiang University of Finance & Economics, Hangzhou, China; [b]Department of Economics (DEECO), Federal University of Ouro Preto (UFOP), Rua do Catete, Mariana, Brazil; [c]Department of Production Engineering, São Paulo State University (UNESP), São Paulo, Brazil; [d]University of Hohenheim, Stuttgart, Germany; [e]Department of Production Engineering, University of São Paulo, Avenida Trabalhador São Carlense, São Carlos, Brazil

ABSTRACT

Since the last few decades, scholars and policy-makers have been struggling to find ways to achieve carbon neutrality target or a low carbon economy. To contribute to the existing literature regarding the said issue, this study aims to investigate whether energy efficiency could lead to achieving carbon neutrality target in the case of China. Also, this study analyses the association of economic growth to energy-related greenhouse gas emissions while using quarterly data over the period from 1990Q1 to 2014Q2. Empirical findings of the study suggest the mixed order of integration and Cointegration between economic growth, energy efficiency, and energy-related greenhouse gas emissions. This study employed a Quantile-on-Quantile regression approach to examine the long-run association at various quantiles. The estimated results asserted that energy efficiency holds a weaker relationship in the lower and medium quantiles, while relatively higher association to energy-related emission in the upper quantiles. On the other hand, economic growth and its squared are found significantly and highly associated with enhancing energy-related emissions in the country. Besides, the frequency domain causality indicates a causal association running from energy efficiency and economic growth to energy-related greenhouse gas emissions. This study recommends revised policies for energy efficiency and suggests that economic growth could be used as a remedial measure for environmental recovery by enhancing investment in the renewable energy sector, energy efficiency, and structural transformation of the industrial sector.

List of abbreviations: CO2: Carbon Dioxide; GHG: Greenhouse Gas; GDP: Gross Domestic Product; GDPS: Square of GDP; EGM: Energy related Greenhouse Gas emissions; $ENEF_1$: Energy Efficiency; $ENEF_2$: Square of $ENEF_1$; EKC: Environmental Kuznets Curve; SREB: Silk Road Economic Belt; ARDL: Autoregressive Distributed Lag; QQ: Quantile-on-Quantile

CONTACT Zongke Bao 154486901@163.com; 294244417@qq.com

1. Introduction

Energy has a critical influence on a country's economic performance. It is, nonetheless, a major contributor to global warming (Shahzad et al., 2020). Global energy consumption has grown by 50% in the previous two decades compared to levels of 1995. China alone makes a significant contribution to production and consumption of energy because of its high gross domestic product (GDP) and population expansion (Shahzad et al., 2022). Because of its negative effects on environmental quality, increased energy use is a major challenge to environmental sustainability (Danish et al., 2019). Additionally, several structural reasons such as population trends, the increasing economic growth of emerging nations, and the expanding industrialisation, transportation and electrification systems are expected to boost energy demand (Espa & Holzer, 2018). The energy industry is the primary source of greenhouse gas (GHG) emissions, accounting for around two-thirds of global GHG emissions (IEA, 2013). The fact that fossil fuels meet 80% of world energy consumption is the primary driver.

Energy efficiency has risen as a critical policy instrument for achieving decarbonised economic development and mitigating climate change. Energy efficiency could be described as producing the same amount of output while utilising less energy (Bashir et al., 2020). Energy efficiency in developing nations is critical for attaining sustainable economic growth and resolving environmental issues, as per the United Nations (Fatima et al., 2021). Investing in energy efficiency has several advantages. For example, energy efficiency programs may help avoid depletion of natural resources, improve the quality of the environment by lowering GHG emissions, minimise countries' reliance on fossil fuels, enhance energy security, minimise energy shortages, and boost productivity and competitiveness by limiting operational expenses (European Commission, 2016). According to the United Nations, developing countries account for 65 percent of all real return energy efficiency investment potential (United Nations, 2011). Energy efficiency has become an essential aspect of developing nations' green development programs, aiming to reduce CO_2 emissions by optimising energy consumption and satisfying sustainability requirements (Guo et al., 2021). Improved energy efficiency could also aid developing nations in achieving their long-term growth targets (Cui et al., 2022). However, lowering energy consumption by means other than technical advancements may negatively influence a country's economic growth. As a result, any strategy promoting fuel substitution and energy efficiency should be prioritised to minimise CO_2 emissions (Shahzad et al., 2021a). In developing, nations such as China, energy efficiency and renewable energy programs play a key role in narrowing emissions disparities. Consequently, combining energy efficiency with renewable energy can assist developing countries in meeting overall national development goals (United Nations, 2017).

Concerning China, a substantial improvement has been observed in the energy efficiency programs adaptation and implementation. As can be seen from Figures 1 and 2, China has become the world's largest energy efficiency heavyweight because of its efforts to adopt obligatory energy efficiency laws over the last ten years. China has achieved significant progress in terms of technological energy efficiency. It would have consumed 25% more energy in 2018 if energy efficiency advances had
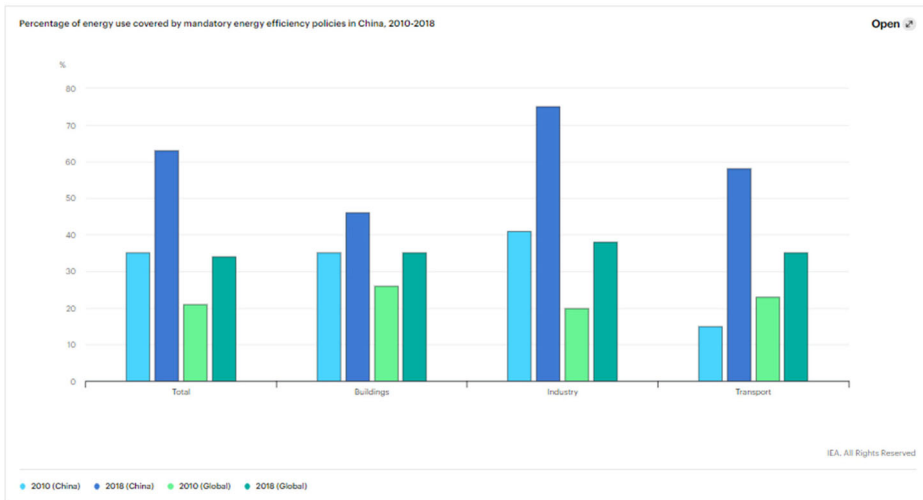
Source: International Energy Agency (IEA)[1]

Figure 1. EGM and ENEF$_1$.
Note. The *z*-axis indicates the coefficient values, the *x*-axis indicates ENEF$_1$, and the *y*-axis represents EGM.
Source: International Energy Agency (IEA) https://www.iea.org/
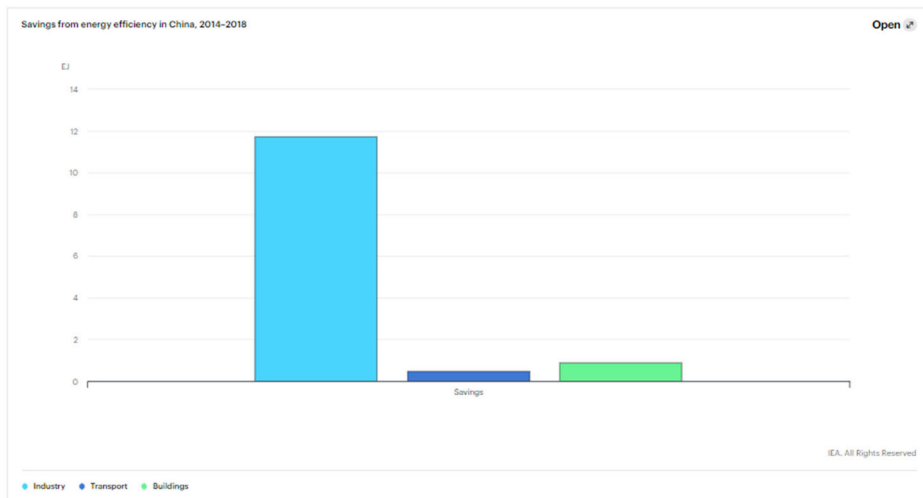
Source: International Energy Agency (IEA)

Figure 2. EGM and ENEF$_2$.
Note. The *z*-axis indicates the coefficient values, the *x*-axis indicates ENEF2, and the *y*-axis represents EGM.
Source: International Energy Agency (IEA) https://www.iea.org/

not been implemented since 2010. Since then, China's economy evolved from energy-intensive sectors, mostly heavy industries, to the service sector, resulting in structural reforms that helped lower demand for energy. On the other hand, the industrial sector accounted for the majority of efficiency increases. Innovative energy efficiency initiatives, such as digital energy labelling and strengthening the

required TOP 10000 system in the industrial sector, have now been praised by the world community for achieving significant increases in technological energy efficiency. These important initiatives put China's energy efficiency primary focuses far ahead of the world average.

The primary objective of this study is to investigate whether energy efficiency leads to carbon neutrality target achievement or not? Albeit, many empirical studies provide evidence regarding the low carbon economy. Yet the energy efficiency attracts the attention of scholars and policy-makers due to its essential role in minimising the energy use required for production or offering services. Also, China holds significant importance from an economic and environmental perspective since it is one of the largest energy importing economies across the world. Also, this country stood among the leading carbon and GHG emitter in the world. Therefore, empirical investigation of such variables for the said country could be imperative for the rest of the developed and developing nations. Another study's objective is to analyse the association between economic growth and energy-related greenhouse gas emissions. Nonetheless, many studies provide empirical evidence of the association between economic growth and CO_2 emissions (for instance, Ozturk & Acaravci,2010; Wen et al., 2021; Yang et al., 2021a; Zhang, 2021). However, empirical investigation on energy-related greenhouse gas is hardly investigated in association with economic growth. Moreover, this study aims to analyse the nexus of increased economic growth – captured by squared economic growth. This will further instigate the question of whether the EKC paradox is valid in case of China.

This study is novel and contributes to the existing literature in three-fold. Firstly, this study is unique as it provides empirical evidence regarding the association of energy efficiency and energy-related greenhouse gas emissions, which is relatively less explored. Unlike previous studies that examined CO_2 emissions and GHG emissions, this study specifically analyses energy-related greenhouse gas emissions, which is produced as a biproduct as a result of the industrial manufacturing. Since China is an emerging economy and concentrated on the development and expansion of industrial sector. Therefore, the empirical findings of this study could be a pathway for China's lower emission economy. Secondly, this study contributes to the existing literature by reinvestigating the association of economic growth and emissions. Although the existing literature empirically analysed the nexus in particular to the CO_2 emissions. Still, the literature remained silent in energy-related greenhouse gas emissions. Therefore, the results of this study will provide a pathway for the scholars and policy insights for the environmental recovery of the country. Lastly, China remained an important and rapidly growing economy as the largest energy importer and emission producer; however, various domestic and international organisations force China to limit the level of pollution and emissions for a sustainable environment. In this sense, current study provides important findings that could help governors and policy-makers for constructing appropriate policies to tackle the burning issue of environmental degradation and global warming.

The remaining parts of the paper are organised into four sections: Sections 2 provides literature review; Section 3 covers data and the methodological setup for empirical investigations; Section 4 represents empirical results and discussion; Section 2 provides conclusion and policy implications.

2. Literature review

Industrial production and expansion are counted as essential factors for economic growth. However, to maintain industrial production and economic growth to run rapidly, energy consumption is the most substantial factor in this regard (Aqeel & Butt, 2001; Belke et al., 2011; Hondroyiannis et al., 2002; Ozturk & Acaravci, 2010). Specifically, these studies suggest the long-run equilibrium relationship and reveal that energy consumption in electricity, petroleum, natural gas, and coal has no side effects on economic growth; instead, it leads to economic development. Interestingly, Ozturk and Acaravci (2010) argued that fossil energy consumption contributes to economic growth and enhances the pollution level of the country via carbon dioxide (CO_2) emissions. On the other hand, Hu et al. (2021) demonstrate that consumption of renewable energy sources and technological innovation significantly reduces CO_2 emissions in the region and promotes environmental sustainability.

In order to analyse the association of economic growth and environmental quality degradation, scholars and policy-makers have made efforts by examining CO_2 emissions and greenhouse gas (GHG) emissions in relation to economic growth for various countries and regions. Specifically, the recent study of Wen et al. (2021) examined South Asian economies over the period 1985–2018 by adopting the fully modified ordinary least square (FMOLS) approach. The empirical results indicate the validity of the region's environmental Kuznets curve (EKC). An increase of CO_2 emissions occurs in the earlier stages of economic development, and consequently, the emissions are reduced after availing the threshold income level. In addition, Yang et al. (2021a) investigated 24 Silk Road Economic Belt (SREB) economies between 1995 and 2014 by using the autoregressive distributed lags (ARDL) model. The empirical results asserted the presence of EKC hypothesis in the region, that is, inverted U-shaped association. However, the authors argued that renewable energy promotes the capital formation and reduced CO_2 emissions. In case of BRICS economies, the recent study of Zhang (2021) investigated the nexus of economic growth, technological innovation and CO_2 emissions in carbon neutrality's context. The empirical results unveil that the EKC exists for each country, that is, inverted U-shaped association for Russia and South Africa. In contrast, U-shaped association is diagnosed in Brazil, China and India. However, the whole region does not hold the property of EKC. On the other hand, technological innovation is considered a significant factor for carbon neutrality. The study also claims that a unidirectional causal nexus exists running from economic growth and technological innovation to CO_2 emissions.

Albeit the fact that economic growth and CO_2/GHG emissions have mixed results. Yet there are a number of empirical evidence that analyses factors for decoupling economic growth from emissions. In this regard, the recent study of Wang and Zhang (2021) analysed the role of trade openness in the decoupling process of 182 economies over the period 1990–2015. Empirical findings of the study asserted that trade openness significantly contributes to the decoupling process only in the rich economies while promoting emissions in the poor nations. Besides, the authors claimed that renewable energy and high oil prices could encourage the decoupling process. Additionally, Yang et al. (2021b) analysed a panel of 78 economies from 2000 to

2017 and revealed that per capita economic growth and population contribute to environmental degradation. However, production efficiency and energy-saving-related technological progress significantly promote the decoupling process in the global carbon economy. However, the earlier evidence reveals that economic growth enhances CO_2 emissions due to non-renewable energy consumption. However, in case of 30 Chinese provinces, Song (2021) argued that economic growth having a sustained technological investment substantially helped reduce emissions in the region during 2001–2016. Using the novel method of moment quantile regression, Razzaq et al. (2021a) examined the top 10 GDP economies over the period 1998–2018. Empirical results asserted that economic growth asymmetrically enhances CO_2 emissions level, where its impact is greater for less-developed economies. Besides, the authors claimed that technological innovation is a significant factor in decarbonising developed and polluted countries. That is, it accelerates not only economic growth, but also reduces CO_2 emissions in the region.

Besides various measures channelised for decoupling economic growth from emissions, energy efficiency is also considered an essential factor for environmental quality. For instance, Akram et al. (2020a, 2020b) investigated BRICS and developing economies, respectively. Using panel cointegration and nonlinear ARDL methods, the empirical findings suggest that energy efficiency and renewable energy are asymmetric, yet negative. This indicates that both the variables significantly reduces CO_2 emissions in the region. However, the rising disparity which the study of Khan and Pinter (2016) measured by the population density exhibits adverse effect on energy consumption efficiency and CO_2 emission and encourages carbon footprints in the urban areas. In case of the food and beverages sectors of sic European economies, Meyers et al. (2016) demonstrates that companies having small and coal burning installation have the great potential for reducing CO_2 emissions. However, in order to achieve 30%–40% emissions reduction, energy efficiency and consumption of renewables could be a statistically significant factor for the bakery and meat industry. In the same line, Gutowski et al. (2013) analysed five major subsectors including iron and steel, cement, plastics, paper, and aluminium. The study found that a rising demand of these sectors indeed brings economic prosperity, but also enhances global pollution level. Ion the other hand, energy efficiency and technological improvement are the remedial measures to meet demand for such sectors and improved environmental quality.

Concerning emissions reduction and pollution control, there are number of recent studies examining different countries and regions. In case of China, Shahbaz et al. (2022) argued that pollution and CO_2 emissions could be reduced via financial inclusion. That is, financial inclusion encourages technologies, investment in new energy industry and green development, that further promotes renewable energy and consequently reduces pollutions and carbon emissions (Cai et al., 2022; Luan et al., 2022; Qin et al., 2021a; 2021b; Shahzad et al., 2021b). In addition, Dong et al. (2022) asserted that China can achieve lower level of pollution via levying pollution fees. Although these studies mentioned that financial development and financial inclusion is a prominent factor of environmental sustainability. Yet the study of Shahbaz et al. (2021) claimed the M-shaped and N-shaped influence of financial development on

CO_2 emissions. However, the risk (financial risk) is persisting, which along with the technological innovation asymmetrically and heterogeneously affects global carbon emissions (Zhao et al., 2021). However, the study of Dong et al. (2021) empirically asserted that energy resilience is a harmful for environmental sustainability since it enhances the emissions level at the global level.

The recent study of Razzaq et al. (2021b) investigated the United States over the period 1990–2017 by employing the novel bootstrapping ARDL model. The empirical results suggest that recycling of municipal solid waste significantly enhances economic growth and reduces CO_2 emissions in the country. Also, improved energy efficiency not only promote economic growth, but also encourages environmental quality by curbing CO_2 emissions in long and short run. Moreover, the authors validate bidirectional causality between energy efficiency and CO_2 emissions, energy efficiency and economic growth. López-Peña et al. (2012) provides a comparative analysis of renewable energy and energy efficiency in terms of cost-savings in Spain. The study argued that the demand side management is dominated by renewable energy while targeting CO_2 emissions reduction. However, energy efficiency could provide a savings of €5 billion yearly while adopting energy efficiency strategy for emissions reduction. Stern (2010) modelled trends in energy efficiency and CO_2 emissions in case of 85 economies over the period of 37 years. The study demonstrates that general total factor productivity enhances energy efficiency, which is found higher in economies with undervalued currencies. Besides, the study also identified that economies with larger reserves of fossil fuel have lower energy efficiency.

In addition, the recent studies of Khan et al. (2021) and Hassan et al. (2022) investigated 16 high income economies via employing various panel data approaches. The estimated results asserted that economic growth accelerates the use of fossil fuels, that contributes to environmental degradation, but renewable energy, technological innovation, and energy efficiency are the possible factors of environmental sustainability via reducing harmful emissions. On the other hand, technical improvement is found substantial in for lowering the CO_2 emissions without affecting economic growth. Besides, there are many studies including Schumacher (1999), Worrell et al. (2001), Li and Colombier (2009), Clark (2013), Wang and Wei (2014), and Fernando and Hor (2017) also provides empirical evidence regarding the negative association of energy efficiency with the emissions, its role in improved productivity of industries, cost minimisation of environmental quality improvement, and reducing dependency of CO_2 emissions in various countries and regions.

3. Methodology

3.1. Variables and data

Based on the objectives and literature provided in Section 2, this study used a total of three variables. Where, the dependent variable represents environmental quality/degradation captured by energy related greenhouse gas emissions (EGM). On the other hand, two variables representing energy efficiency and economic growth (GDP) are the explanatory variables. However, in order to examine the association of energy efficiency more extensively, this study adopted two energy efficiency variables with a

different units. Firstly, $ENEF_1$ – which is measured as constant 2017 PPP \$per kg of oil equivalent. Secondly, $ENEF_2$ – which is measured as PPP \$per kg of oil equivalent. Besides, this study used GDP as indicator of economic growth since it reflects an economy's health by considering consumption, investment, government expenditure, among others. Therefore, this study adopts the said variable and is measured as constant US 2015 prices. Additionally, this study used the squared term of GDP (GDPS), that demonstrates that will help analyse the influence of increased income on the EGM. Data for all the variables are obtained from two sources: where data for EGM is extracted from Organisation of Economic Cooperation and Development (OECD) database,[1] and data for the rest of the variables are obtained from the World Development Indicators (WDI) databank.[2] Data for all the variables are collected on quarterly basis, covering the period from 1990Q1-2014Q2 for China.

3.2. Estimation strategy

3.2.1. Descriptive statistics, data normality and unit root test

We developed descriptive statistics for all of the variables under study prior to conducting empirical analysis. The descriptive statistics, which include mean, median, standard deviation (a basic measure of volatility in a time series variable), and range values, help describe the data in summarised form. Furthermore, in order to comprehensively assess the data's normality, this study used the Jarque and Bera (1987) normality test, which accounts for both skewness and excess Kurtosis. The null hypothesis of normally distributed time series data is supported by this test. Jarque-statistical Bera's values might be calculated as using the following standard equation:

$$JB = \frac{N}{6} \left(S^2 + \frac{(K-3)^2}{4} \right) \tag{1}$$

This study looks for the presence of unit root after evaluating the descriptive statistics and normality of the data. In order to analyse the stationarity properties between the variables under examination, the current study used the non-linear based quantile unit root test.

3.2.2. Bayer-Hanck combined cointegration test

This study looked at the cointegration relationship among variables after checking for the unit root presence or stationarity of the data. To examine the cointegration relationship between these variables, we used the Bayer-Hanck combined cointegration test, which combines the cointegration tests of Engle and Granger (1987), Johansen (1991), Banerjee et al. (1998), and Boswijk (1994). However, if the mentioned tests are used independently, the cointegration test's explanatory power qualities may produce ambiguous findings (Shahbaz et al., 2018). As a result, we used Bayer and Hanck's (2009) combined cointegration test technique to improve the power of cointegration analysis and overcome doubtful or ambiguous estimations. This test uses Fisher F-statistics to integrate all of the previously described cointegration tests and offer conclusive and trustworthy findings (Shahbaz et al., 2018). Furthermore, this test involves a distinct order of integration, that is, I(1). As a null hypothesis, it

assumes no cointegration between the study variables. However, if the projected values are significant at any level of significance, such as 10%, 5%, or 1%, this might be rejected. The Fisher's formula for Bayer-Hanck cointegration may be summarised as follows:

$$EG - J = -2\big[\ln(P_{EG}) + \ln(P_J)\big] \tag{2}$$

$$EG - J - Ba - Bo = -2\big[\ln(P_{EG}) + \ln(P_J) + \ln(P_{Ba}) + \ln(P_{Bo})\big] \tag{3}$$

The probability values for Engle and Granger (1987), Johansen (1991), Banerjee et al. (1998), and Boswijk (1994) cointegration tests are P_{EG}, P_j, P_{Ba}, and P_{Bo}, respectively, in Eq. (3). These versions of Fisher's statistics, on the other hand, show whether the variables under discussion are cointegrated.

3.2.3. Quantile-on-quantile regression
The current study employs the Quantile-on-Quantile (QQ) technique, as explained and suggested by Sim and Zhou (2015). This strategy, also referred as the generalisation of the traditional and standard quantile regression model, permits the assessment of the effects of quantiles of one variable on the quantiles of other variable. It also incorporates two strategies: firstly, quantile regression, which looks at the impact of indicators on dependent variable quantiles, and secondly, non-parametric approximation. The more sophisticated form of standard ordinary least square (OLS) based regression analysis, where the variable's average is matched to the average of another variable and was initially suggested by Koenker and Bassett (1978). Quantile regression, on the other hand, may explain greater variance in quantiles, allowing economists to forecast with fewer mistakes. Additionally, as discussed and shown by Stone (1977) and Cleveland (1979), classical regression reduces dimensionality to accommodate a linear function, leading to a loss in prediction ability. On the other hand, the ability to predict enhances when the quantiles of independent factors are compared to the quantiles of dependent variables, as allowed by the QQ method, because more variation between the components is described (Shahzad et al., 2017). An equation for a non-parametric QQ regression model is as follows:

$$EGM_t = \beta^\theta(X_t) + \mu_t^\theta \tag{4}$$

From Eq. (4) it is mentioned that the said equation describes a framework wherein the EGM_t represents energy related greenhouse gas emissions in a given period of time t. Whereas, X_t is a vector that represent each explanatory variable employed in this study, that is, $ENEF_1$, $ENEF_2$, GDP, and GDP^2 throughout the selected time period. Besides, θ is the θth quantile, selected on the basis of standard conditional distribution, and the symbol μ_t^θ indicates error term of the quantile where the conditional θ th is considered as equal to 0. Moreover, $\beta^\theta(.)$ Indicates a function which is unidentified due to limited information on the association between the given dependent and independent variable, that is, EGM_t and X_t.

The QQ technique is concerned with the overall behaviour of the concepts while examining the correlation between multiple factors. To put it another way, all the shocks in X_t, whether negative or positive, would have the same effect on EGM_t. The types of instabilities in X_t, for example, may be negative or positive, and the EGM_t might react symmetrically or asymmetrically.

In order to analyse the effects of the θth quantile EGM on X's τth quantile – represented as X_t, the Eq. (4) could be assessed along with the X_t while adopting a linear regression approach. Since the function of $\beta^\theta(.)$ is unidentified, the first order Taylor expansion function could be estimated and expressed as follows:

$$\beta^\theta(X_t) \approx \beta^\theta(X^\tau) + \beta^{\acute{\theta}}(X^\tau)(X_t - X^\tau), \qquad (5)$$

Where in the Eq. (5), $\beta^{\acute{\theta}}$ denotes the partial derivative of $\beta^\theta(X_t)$ in terms of each specific independent variable – referred as marginal or response effect, which can be estimated in the similar way as of the standard linear regression model. Additionally, the parameters are twice indexed, which can be clearly seen from Eq. (5), that is, $\beta^{\acute{\theta}}(X^\tau)$ and $\beta^\theta(X^\tau)$ in terms of θ and τ. Further, X^τ are the functions indicating $\beta^{\acute{\theta}}(X^\tau)$ and $\beta^\theta(X^\tau)$, where X^τ is the function of τ demonstrating $\beta^\theta(X^\tau)$ and $\beta^{\acute{\theta}}(X^\tau)$ are the functions of θ and τ. Moreover, $\beta^\theta(X^\tau)$ and $\beta^{\acute{\theta}}(X^\tau)$ can be structured as $\beta_1(\theta, \tau)$ and $\beta_2(\theta, \tau)$ accordingly. Thus, Eq. (5) is presented in the transformed form as follows:

$$\beta^\theta(X^\tau) = \beta_1(\theta, \tau) + \beta_2(\theta, \tau)(X_t - X^\tau) \qquad (6)$$

While Eq. (6) can further be structured, and the transformed form is given as Eq. (7) below:

$$GDP_t = \beta_1(\theta, \tau) + \beta_2(\theta, \tau)(X_t - X^\tau) + \mu_t^\theta \qquad (7)$$

$$(*)$$

The (*) in Eq. (7) represents the θth conditional quantile of energy-related greenhouse gas emissions captured by EGM. The parameters of the aforesaid conditional quantile are twice indexed, β_1 and β_2 in terms of θ and τ, respectively, and it represents the θth quantile of EGM with the τth quantile of X. There might be a variation between the parameters of θth quantiles of the EGM and the τth quantile of the X. Additionally, there is no expectation of a linear connection between the two variables at any point in time. As a consequence, Eq. (7) examines the model's total interconnectedness depending on the distribution-based dependence of the variables under consideration. Furthermore, in Eq. (7), the estimated analogues $\widehat{X_t}$ and $\hat{X}^\tau$ should be replaced for X_t and X^τ, respectively. Hence, the coefficients β_1 and β_2, which are projected by b_1 and b_2, are estimated using local linear regression and may be obtained using the minimisation problem presented below:

$$\min_{b_1, b_2} \sum_{i=1}^n \rho_\theta \left[GDP_t - b_1 - b_2(\widehat{X_t} - \hat{X}^\tau) \right] \times K\left(\frac{F_n(X_t) - \tau}{h} \right), \qquad (8)$$

where $\rho_\theta(u)$ in the above function, indicates the quantile loss, which is explained as $\rho_\theta(u) = u.(\theta - I(u > 0))$. In addition, function for unusual indicator is presented by I. While the kernel function is denoted by K (*) and h is the kernel bandwidth parameter.

The Gaussian kernel is applied in this study to determine the weighting of the neighbourhood observations of X^τ. The Gaussian kernel is one of the most frequently used, studied, and renowned kernel functions in economics and finance, having the advantage of being simple to use and evaluate. This kernel has the benefit of being symmetric as it approaches 0, with low weights allocated to subsequent data. The above-mentioned weightage and distances between the distribution function of $\widehat{X}_t$ are inversely related in the current study and are represented as $F_n(\widehat{X}_t) = \frac{1}{n}\sum_{k=1}^{n} I(\widehat{X}_k > \widehat{X}_t)$, where the result of the distribution function that might deal with the quantile $\hat{X}^\tau$ is indicated by τ.

3.2.4. Frequency domain causality test

This research study also aims to analyse the causal impacts of $ENEF_1$, $ENEF_2$ and GDP on EGM_t to explore the carbon neutrality situation of China at various frequencies. In this sense, we used the frequency domain causality test of Breitung and Candelon (2006). The said test comes from the work of Geweke (1982) and Hosoya (1991). The primary difference between the time-domain and frequency-domain strategies is that the time-domain specifies if a certain variance exists inside a time series, meanwhile the frequency-domain method to ensure the strength of a given time series variability (Gokmenoglu et al., 2019). As per Breitung and Candelon (2006) (B.C. from now), the frequency domain reduces seasonality-based variations in the small sample. Importantly, at both upper and lower frequencies, the B.C. frequency domain analysis may detect nonlinearities and causality cycles, along with the causalities across temporal variables (Guan et al., 2020). In other words, the B.C. frequency domain causality analysis clearly distinguishes between long-run (permanent) and short-run (temporal) causal correlation across time variables.

The econometric representation of the B.C. frequency causality test could be constructed as follows: let $X_t = (H_t, C_t, D_t)$, where X_t denotes three-dimensional vector of stationary and endogenous variables in a time ($t = 1, 2, ..., T$), while assuming a finite order VAR representation of X_t, given as:

$$\theta(L)X_t = \varepsilon_t. \tag{9}$$

Where Eq. (9) demonstrates that $\theta(L)$ is a 3×3 p-ordered lagged polynomial and could be represented as $\theta(L) = I - \theta_1 L^1 - ... - \theta_p L^p$, While $L^k X_t = X_{t-k}$. On the other hand, ε_t indicates the residual term based on the white noise process expected as zero, and $\varepsilon_t \acute{\varepsilon}_t = \sum$. Interestingly there is a positive and symmetrical representation of $\sum$. Adopting the study of Breitung and Candelon (2006), the said equation does not hold any deterministic term for simplicity.

Since it is reported that $\sum$ is positive as well as symmetric, yet the Cholesky decomposition occurs $\acute{G}G = \sum^{-1}$. From this equation, G indicates lower triangular matrix and $\acute{G}$ reveals upper triangular matrix. In this case, $E(\eta_t \acute{\eta}_t) = I$, whereas

$\eta_t = G\varepsilon_t$. Thus, by following Cholesky decomposition, the MA of the system could be represented as follows:

$$X_t = \begin{bmatrix} H_t \\ C_t \\ D_t \end{bmatrix} = \theta(L)\varepsilon_t = \begin{bmatrix} \theta_{11}(L) & \theta_{12}(L) \\ \theta_{21}(L) & \theta_{22}(L) \\ \theta_{31}(L) & \theta_{32}(L) \end{bmatrix} \begin{bmatrix} \varepsilon_{1t} \\ \varepsilon_{2t} \\ \varepsilon_{3t} \end{bmatrix} \tag{10}$$

$$X_t = \begin{bmatrix} H_t \\ C_t \\ D_t \end{bmatrix} = \Psi(L)\eta_t = \begin{bmatrix} \Psi_{11}(L) & \Psi_{12}(L) \\ \Psi_{21}(L) & \Psi_{22}(L) \\ \Psi_{31}(L) & \Psi_{32}(L) \end{bmatrix} \begin{bmatrix} \eta_{1t} \\ \eta_{2t} \\ \eta_{3t} \end{bmatrix} \tag{11}$$

where $\phi(L) = \theta(L)^{-1}$, and $\Psi(L) = \phi(L)G^{-1}$. Following this representation, the spectral density of H_t could be presented as Eq. (12) below:

$$f_H(\omega) = \frac{1}{2\pi}\{|\Psi_{11}(e^{-i\omega})|^2 + |\Psi_{12}(e^{-i\omega})|^2 \tag{12}$$

As illustrated in Eqs. (10) and (11), H_t may be defined as the sum of two uncorrelated MA operations, the intrinsic component generated by the prior simulation of H_t and the component carrying the prediction power of C_t and D_t parameters. The predictive capacity of both C_t and D_t parameters can only be determined in relation to the predicting component of the spectrum with fundamental component at each frequency. The null hypothesis of no Granger causality is addressed in this series. That is, C_t does not Granger cause H_t at frequency ω if the predictive element of the H_t spectrum at frequency ω is zero. This extends Geweke's (1982) and Hosoya's (1991) causation testing for the 'x' and 'y' variables, expressed as follows:

$$M_{x \to y}(\omega) = ln\left[\frac{2\pi f_y(\omega)}{|\Psi_{11}(e^{-i\omega})|^2}\right] \tag{13}$$

$$= ln\left[1 + \frac{|\Psi_{12}(e^{-i\omega})|^2}{|\Psi_{11}(e^{-i\omega})|^2}\right] \tag{14}$$

When $|\Psi_{12}(e^{-i\omega})|^2 = 0$, the Geweke's measured equations mentioned above will be zero.

4. Results and discussion

This study begins the empirical estimation by evaluating variables' descriptive statistics and normality results for the selected variables. The estimated results of descriptive statistics and normality results are provided in Table 1. Specifically, the mean and median values of these variables have a slight difference yet found positive. Which indicates the enhancement of energy related emissions in the concerned country. Nonetheless, China is rapidly increasing its economic growth, yet primarily

Table 1. Descriptive statistics.

	EGM	ENEF$_1$	ENEF$_2$	GDP
Mean	41.34698	3.694787	3.411065	4.28E + 12
Median	42.01040	3.860224	3.497232	3.27E + 12
Maximum	52.56115	5.454631	5.702433	1.06E + 13
Minimum	29.65162	1.769772	1.200830	1.01E + 12
Std. Dev.	8.610882	0.931925	1.260458	2.83E + 12
Skewness	−0.092901	−0.323377	0.027563	0.742515
Kurtosis	1.403872	2.223433	1.939282	2.279593
Jarque-Bera	10.75894	4.255612	4.700674	11.35125
Probability	0.004610	0.119098	0.095337	0.003429

Source: Authors' own estimations from the given data sources.

depending upon the industrial growth. While in the case of China, consumption of fossil is regarded as the backbone of industrial growth, which significantly promote environmental degradation. Alongside such emissions, the country also positively contributes to energy efficiency that are aimed to reduce environmental degradation. Besides, the range values reports a significant difference, which demonstrates that emissions level, energy efficiency, and economic growth values are fluctuating throughout the time, which could be better represented via standard deviation. The fluctuations captured by the standard deviation demonstrates that the GDP reports the highest value of standard deviation (2.83E + 12), followed by EGM (8.610882) and energy efficiency. Concerning the normality of the time series, the Jarque and Bera (1987) reveals that only ENEF$_1$ failed to reject the null hypothesis and asserted that the variable is normally distributed. On the other hand, EGM, ENEF$_2$, and GDP provides significant estimates of the Jarque-Bera normality test – indicating the rejection of normal distribution. Hence it is concluded that the latter three variables follows irregular path or abnormal distribution, which need an appropriate empirical estimator, and QQ regression is a prominent estimator to deal such issues of data.

In order to test for the stationarity properties, current research study utilised non-linear based quantile unit root Augmented Dickey-Fuller (ADF) test. The estimated result for the said test is provided in Table 2, indicating the persistence parameter coefficients and t-statistics. The empirical results of quantile unit root ADF reveals that *EGM*, *ENEF$_1$*, and *ENEF$_2$* are stationary at level. All these variables at levelled stationary are found significant at 1% level. On the other hand, *GDP* is found insignificant at level as reporting the value of −1.6214, which is less than the critical values at 1%, 5%, and 10% levels.

After testing for the stationarity, this study found the mixed order of integrations, which allows to analyse the long-run relationship between the variables. Therefore, current study used the Bayer-Hanck (2009) cointegration test, that combinedly assess the Engle and Granger (1987) (EG), Johansen (1991) (j), Banerjee et al. (1998) (Ba), and Boswijk (1994) (Bo) cointegration tests and the results are displayed in Table 3. Besides, the Bayer-Hanck (2009) cointegration test offers the combined estimates for Engle and Granger (1987) and Johansen's (1991) cointegrations tests. In order to extensively analyse the cointegration between the variables, this study examines the association of *EGM* with each explanatory variable. Concerning *EGM* and *ENEF$_1$*, the results reveal that EG-J-Ba-Bo provides significant results at 5% level, which is clear evidence of cointegration association between these variables. Also, the empirical

Table 2. Quantile unit root ADF test.

Break in level and trend	EGM	$ENEF_1$	$ENEF_2$	GDP
$\rho_{quantile}$	1.0034	1.0014	0.9981	–
ρ_{OLS}	0.9962	1.0000	1.0005	1.0002
δ	0.0068	0.0016	0.0014	0.0000
$ADF_{quantile}$	2255.8573	344.1991	−279.5748	−1.6214
$CV_{[1\%, 5\%, 10\%]}$	[−2.966, −2.308, −1.952]	[−2.966, −2.308, −1.952]	[−2.966, −2.308, −1.952]	[−2.966, −2.308, −1.952]

Note. Significance is indicated by 10, 5, and 1% through *, **, and ***.
Source: Authors' own estimations from the given data sources.

Table 3. Bayer-Hanck cointegration (2009) analysis.

Cointegration between EGM and $ENEF_1$					
Engle-Granger (EG)	Johansen (J)	Banerjee (Ba)	Boswijk (Bo)	EG-J	EG-J-Ba-Bo
−2.4727	17.1786**	−3.3943**	16.7538***	10.1790	27.3521**
Cointegration between EGM and $ENEF_2$					
Engle-Granger (EG)	Johansen (J)	Banerjee (Ba)	Boswijk (Bo)	EG-J	EG-J-Ba-Bo
−2.3266	23.2016***	−3.1371*	21.9051***	14.4954**	34.6779**
Cointegration between EGM and GDP					
Engle-Granger (EG)	Johansen (J)	Banerjee (Ba)	Boswijk (Bo)	EG-J	EG-J-Ba-Bo
−3.4200**	22.1560***	−4.5787***	21.4006***	18.0309**	46.8943**

Note. Significance is indicated by 10, 5, and 1% through *, **, and ***.
Source: Authors' own estimations from the given data sources.

results of EG-J and EG-J-Ba-Bo for EGM and $ENEF_2$, EGM and GDP are also statistically significant at 5% level. These significant results rejected the null hypothesis of the test and concludes that all the explanatory variables are in the long-run relationship to EGM. Thus, any policy regarding economic growth and energy efficiency could influence energy related greenhouse gas emissions in China.

The irregular or non-normal distribution of data allows us to use QQ regression, which is considered as efficient in dealing with the irregular data distribution of a time series. Figure 3 presents the graphical representation for the impact of $ENEF_1$ on EGM. Since the study of Xu et al. (2021) illustrates that the darker blue colour of the graphical representation indicates the lowest value of coefficient, and the darker red colour indicates the higher value of the coefficients. This study found that the lower quantile (0–0.4) of $ENEF_1$ is weakly associated to the greenhouse gas emissions that are associated to energy. However, the higher quantile (0.4–0.8) indicates that there is relatively a higher coefficient values between the variables. Nonetheless, most of the existing studies have demonstrated that there is a negative association between energy efficiency and CO_2 emissions (Akram et al., 2020a, 2020b; Khan & Pinter, 2016). In the current times, China is an emerging economy and the energy efficiency is not up to the mark level that could negatively affect pollution emissions. Therefore, it is noted that the influence of $ENEF_1$ is weaker, still positive, which should be a great policy concerns regarding the emission curbing policies and regulations. The combustion of fossil fuels such as coal and oil contribute to air pollution, which includes mercury, nitrogen oxides, soot, CO_2 sulphur dioxide, and lead. A large amount of money is spent by power plants, manufacturers, and automobile manufacturers on technology that is designed to absorb pollution before it is discharged into
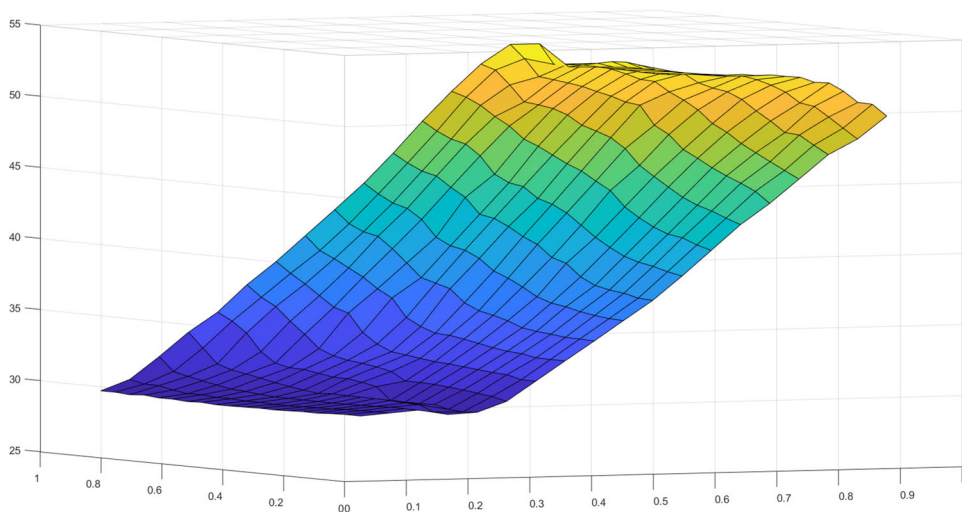
Figure 3. Savings from energy efficiency in China, 2014–2018.
Source: International Energy Agency (IEA).[3]

the atmosphere. Energy efficiency decreases the need to burn fuels in the first place, so lowering pollution levels while simultaneously saving money. With reference to Figure 4, where the graphical depiction indicates the association of $ENEF_2$ and EGM, the findings follow the same track. That is, the graph reports that at the lower and medium quantiles (0–0.7), there is a weaker but positive association between these variables. While at the higher quantiles (0.7–1), the magnitude of the $ENEF_2$ increases demonstrating higher positive impact on EGM. Which is consistent to the findings of Figure 3. The rapid industrialisation of China is noticed with the prime moto of higher economic growth, where the industrialisation is increasing at a higher phase than that of energy efficiency implementation due to the excessive use of fossil fuel energy resources. However, industries with smaller and coal burning installations have a great potential for emissions reduction (Meyers et al., 2016). Also, iron and steel, cement, plastics, paper, and aluminium are the most demanded sectors of the recent times, which although brings economic prosperity, but also enhances emissions level with the lower level of energy efficiency. Environmental pollutants such as GHGs are the most significant contributors to climate change and global warming. Such gases are able to absorb infra-red radiation, which results in the atmosphere being able to trap and store the heat it generates. It would follow that the amount of heat emitted by the Earth's surface will keep rising. The combustion of fossil fuels, which results in the generation of energy, may also cause global warming. The burning of fossil fuels would result in the emission of GHG and CO_2 into the environment. Such CO_2 and GHG may operate as an insulating shell, allowing solar energy to pass through while preventing it from bouncing back onto the Earth's surface. When the heat from solar radiation is retained on the Earth's surface, hence causes global warming and climate change, which are both harmful.

With reference to Figure 5, the QQ regression presents the graphical estimates of the association between EGM and GDP at different quantiles. The estimated results revealed that from lower to medium quantiles (0–0.5), there is a positive but weaker
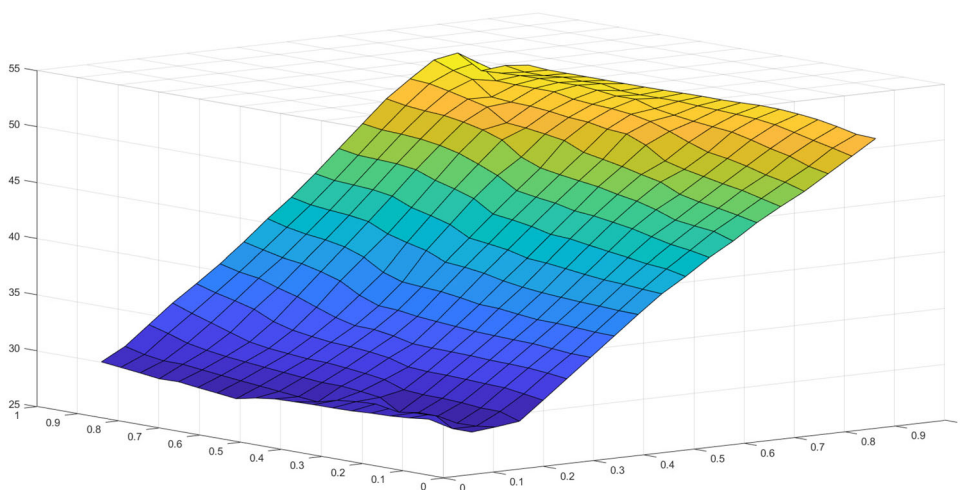
Figure 4. Percentage of energy use covered by mandatory energy efficiency policies in China, 2010–2018.
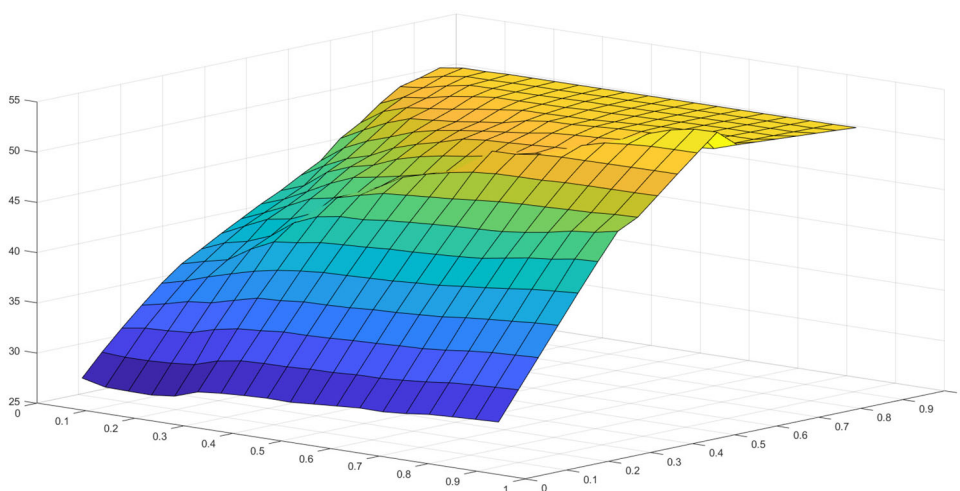*Source:* International Energy Agency (IEA).

Figure 5. EGM and GDP.
Note: The *z*-axis indicates the coefficient values, the *x*-axis indicates GDP, and the *y*-axis represents EGM.
Source: Authors' own estimations from the given data sources.

association between these variables. While moving from medium to upper quantiles (0.5–1), a considerable enhancement in the energy related greenhouse gas emissions in response to the increased level of economic growth. Consistent findings are provided by Wen et al. (2021) and Yang et al. (2021b), which indicates that increased economic growth significantly enhances economic growth. The primary reason for the positive association of economic growth and emissions is that the enhancement in the income level further increase the demand for goods and services, which increased the production level as well as expansion of the manufacturing sector. However, to fulfil energy demand for the production and consumption, China utilised
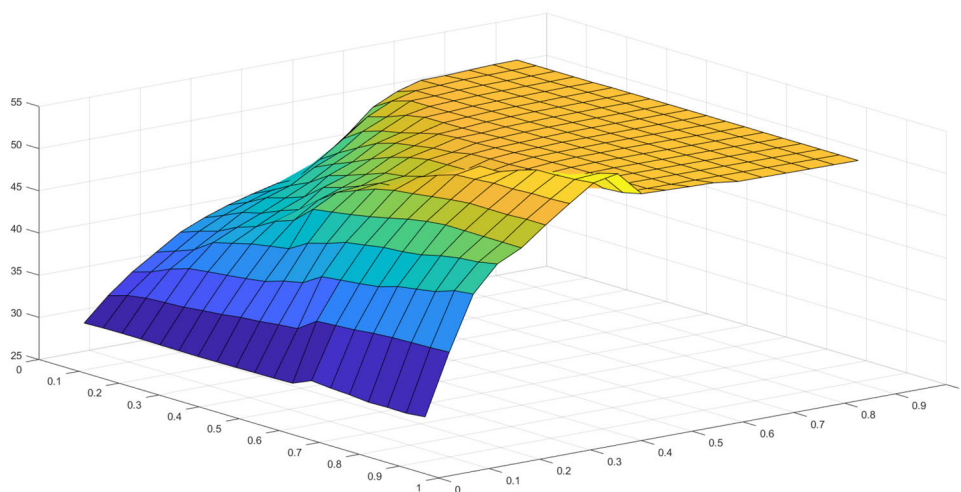
Figure 6. EGM and GDPS.
Note: The *z*-axis indicates the coefficient values, the *x*-axis indicates GDPS, and the *y*-axis represents EGM.
Source: Authors' own estimations from the given data sources.

fossil fuels, which are harmful for environmental sustainability due to emissions of various greenhouse gases. Based on this fact, China is one of the leading energies importing and emissions producing economy across the world. Since many studies have provided empirical evidence regarding the EKC hypothesis, where the emissions level start declining after achieving an optimum level of economic growth (Wen et al., 2021; Zhang, 2021). Therefore, this study used the squared term of GDP (GDPS), and the empirical outcomes are shown in the Figure 6. Interestingly, the findings revealed that the magnitude level of the EGM increases throughout the medium and upper quantiles (0.3–1). The positive coefficient values demonstrates that the EKC does not holds for China, which contradicts the findings of (Wen et al., 2021; Zhang, 2021). Instead, these findings are consistent to the empirical findings of Razzaq et al. (2021a), which indicates that economic growth asymmetrically enhances the emissions level, and its impact is greater in the developing economy such as China. The empirical findings asserted that in China, the increased level of income is also providing a supportive role for energy related emissions. This indicates that with the increasing level of income, the industrial production and industrial expansion further promote the use of non-renewable and traditional energy resources that nonetheless leads to economic development. But on the other hand, degrades environmental sustainability, which is alarming. Based on these findings, it could be concluded that with the increased level of economic growth, China expands their fossil fuel energy consumption, which enhances the level of energy related greenhouse gas emissions.

After analysing the long-run association between EGM and explanatory variables, that is, $ENEF_1$, $ENEF_2$, GDP, and GDPS, this study examined the causal association between EGM and the explanatory variable ($ENEF_1$, $ENEF_2$, GDP). In this regard, current study employed the frequency domain causality test presented by Breitung and Candelon (2006) and the estimated results are reported in Table 4. The results revealed that $ENEF_1$, $ENEF_2$, and GDP rejects the null hypothesis of no granger

Table 4. Frequency domain causality test (2006).

Causality	$(\omega = 0.05)$	$(p - value)$
$ENEF_1 \rightarrow EGM$	8.776**	0.0124
$ENEF_2 \rightarrow EGM$	7.572**	0.0227
$GDP \rightarrow EGM$	13.424***	0.0000

Note. *, ** and *** indicates 10%, 5%, and 1% significance level.
Source: Authors' own estimations from the given data sources.

causality from these explanatory variables to EGM. Instead, the highly significant (at 5% and 1% levels) estimates reveal that these variables cause greenhouse gas emissions that are associated to energy. Consistent findings are provided by the studies of Yang et al. (2021b) and Razzaq et al. (2021a). As mentioned earlier, these variables significantly promote and causes emissions in China. Therefore, any policy change in each of the study variables could significantly affect the energy related emissions in the country. Therefore, appropriate policies are needed to tackle emissions in order to achieve carbon neutrality target.

5. Conclusion and policy implications

Economic growth and environmental degradation are the research interest areas of scholars since a while. However, various international environmental protection agencies have warned nations to reduce CO_2 and GHG emissions and achieve a low carbon economy. Yet, policy makers are concerned about energy efficiency as a tool for environmental recovery and carbon neutrality target achievement. This study investigates the association of energy efficiency and economic growth on the energy related GHG emissions in case of China while using quarterly data from 1990Q1 to 2014Q2. This study analysed this association by using QQ regression and the empirical estimates asserted that the lower quantiles indicate weaker, and the upper quantile indicates relatively greater and positive association energy efficiency and energy related emissions. On the other hand, economic growth and its squared term is found to have a greater association with the energy related emissions in the country. Albeit the fact that China is a developing economy, where the primary objective of the country is achieving higher economic growth. Yet, China has initiated various environmental recovery plans to achieve low carbon economy, that include energy efficiency. Still, the energy efficiency is not at the optimal level, that could help reduce energy related emissions. On the other hand, enhancement in the level of income further encourages the investors, industrialists, and households to consume more traditional energy products and services, which is alarming with respect to environmental sustainability. Therefore, some serious policies and steps must be taken to prevent energy related emissions.

Based on the empirical results, this study recommends that energy efficiency could be a healthy tool for environmental recovery and carbon neutrality target achievement. Therefore, policies regarding energy efficiency must be reinforced by further investing in the energy efficiency initiatives and projects. Consequently, this will reduce the use of non-renewable energy both at household and industrial levels, which can help reduce energy related emissions and enhances environmental quality. Additionally, the findings suggest that higher economic growth is a factor of energy

related emissions. In this regard, it is suggested to use the higher income level as tool for carbon neutrality target achievement. Particularly, policies could be designed that could reduce funding and promotion of fossil fuel energy sector. Instead, China could use the increased income as an investment in the renewable energy sector, technological advancement, renewable energy research and development. Also, the increased income level helps the industrial structural transformation from pollution intensive industry to environmentally friendly energy resources sources. Specifically, with the increased level of income, economies invest in renewable energy-based and energy efficient equipment. In turn, these renewables and energy efficient resources utilisation not only enhances economic growth, but also reduces environmentally hazardous emissions that are associated to energy combustion. Moreover, with the increased level of income, economies are more open to invest in the environmental related technologies and low carbon production, which encourages the culture of renewable and energy efficient resources utilisation. As a result, the use of energy intensive resources dropped, and the economy moves towards sustainable development.

Notes

1. For data and information, visit: https://stats.oecd.org/
2. For data and information, visit: https://databank.worldbank.org/source/world-development-indicators#
3. Visit IEA: https://www.iea.org/articles/e4-country-profile-energy-efficiency-in-china

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

ORCID

Daisy Aparecida do Nascimento Rebelatto 🄳 http://orcid.org/0000-0002-9732-7223

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