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Effectiveness of green bonds on carbon neutrality and clean electricity generation: Comprehensive evidence from the leading emitting country by disaggregated level analysis

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ABSTRACT

Considering increasing public interest in environment-related problems and the carbon-neutrality aims of countries, this study focuses on the effect of green bonds on enabling carbon neutrality and supporting clean electricity in China, which is the leading top carbon-emitting and energy-using country in the world. In this context, the study makes a disaggregated level empirical analysis by considering sectoral emissions and source-based electricity generation by using quantile-based approaches from January 2, 2019, to December 31, 2023. The outcomes show that (i) green bonds decrease mainly emissions in transport and international aviation sectors; (ii) green bonds have mixed effects on the remaining sectoral emissions; (iii) green bonds increase electricity generation from all sources at higher quantiles, whereas they decrease electricity generation at lower quantiles. Thus, the effect of green bonds varies across sectors, electricity generation sources, and quantiles. Accordingly, a set of policy endeavors, such as dealing with firstly such critical sectors as power and industry, supporting the allocated green bond issuance to specified sectors, and focusing on some clean electricity generation sources like solar and wind, are argued for China.

1. Introduction

In recent decades, the negative effects of environment-related issues on humanities have been rapidly increasing [1]. Among all, extreme climate conditions including droughts and floods, decreasing biodiversity, and pollution in air, soil, and water are some important examples that can be evaluated in the context of climate change. Hence, increasing environmental degradation has been causing a stimulus effect on climate change. Due to this fact, the efforts to combat climate change by curbing environmental degradation have been increasing day by day [2].

In searching for ways to combat climate change, various critical drivers, such as energy use and income, have been considered in terms of their effects on environmental degradation in the traditional literature (e.g., Ref. [3,4]). Although these factors are effective on the environment because of the fact that they have directly affected carbon dioxide (CO_2) emissions and energy use, the recent literature has begun to focus on other indicators that are related to financial perspectives. That is why financial capacities and financing opportunities can be influential on the environment by making effect through various channels, such as production and consumption channels as well as increasing the production capacity of sectors and stimulating clean energy use [5–7].

Although various financial indicators, such as credit volume, domestic credits, and financial development index, can be considered, recent literature has begun to highly focus on green bonds (GBs). In the context of the definition, GBs can be specified as *"financial bonds that enable the raising of capital for existing or new investments with environmental benefits and promote a zero-emission economy"* [8]. According to the European Investment Bank, green bonds are a new environmental scheme and offer environmental benefits that are closely connected with the sustainable energy sector [9]. Hence, GBs can take an active role in combating climate change by stimulating clean energy generation and

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curbing CO_2 emissions in this way.

In line with the developing GB concept, various research has explored the effect of GBs on CO_2 emissions and ecological footprint (e.g., Ref. [10,11]) and energy use (e.g., Ref. [12–14]) for various scopes, such as global case, South-East Asia countries, top 10 countries. While different scopes of countries have been examined, among all, China deserves a special interest because of its leading position in GB issuance as well as CO_2 emissions and energy use [15,16]. Fig. 1 presents the CO_2 emissions of China across sectors.

There is relative volatility in China's CO_2 emissions in sectors and total across times between 2019 and 2023. Based on average numbers, among all sectors, the power sector has a leading position (13.51 tons) in terms of causing high CO_2 emissions and the industry sector is the second one (11.52 tons) followed by ground transport (2.43 tons), residential (2.20 tons), domestic aviation (0.15 tons), and international aviation (0.04 tons), in order. Thus, China causes an average of 29.85 tons CO_2 emissions in each day between 2019 and 2023.

Fig. 2 demonstrates the clean electricity generation (EG) of China across generation sources.

On China's clean EG, there is also relative volatility in EG sources and total across times between 2019 and 2023. Based on average numbers, hydro EG has a leading position (3,590 GW-hours) in terms of generating EG and nuclear EG is the second one (1,082 GW-hours) followed by wing EG (1,694 GW-hours) and residential (981 GW-hours), respectively. Thus, China causes an average of 7.347 GW-hours clean EG each day between 2019 and 2023.

Both Figs. 1 and 2 demonstrate some critical points for the Chinese case. First, China has been still emitting an important amount of CO_2 emissions, which makes China the leading country in CO_2 emissions in the world. Second, China has been generating more and more clean EG from various sources. Hence, the share of clean energy in total energy has increased to 18.3% in 2022 from 6.1% in 2000 [16]. Based on these numbers, it is clear that the share of clean energy in total energy has increased in recent years. Although there is an increase in stimulating further clean EG, however, there is a long way for China to go ahead because the remaining big share (i.e., 81.7%) of energy has been generated from fossil sources. For this reason, it is critical to support further clean EG by using possible sources, such as GBs.

Because GBs are relatively new means that generate further cash flows to support the financing of new investments in especially clean energy investment areas [18], they can have the capability to create new capacity to generate clean EG by supporting also eco-friendly technologies and policies [15,19]. In this way, GBs can cause an increase in further clean EG and this progress can displace the use of fossil sources in EG Ref. [20,21]. Thus, GBs can have both an increasing effect on clean EG and a decrease in fossil fuel EG, which demonstrate both positive effects in this area. So, GBs can support combating climate change by curbing CO_2 emissions from EG areas.

By considering the aforementioned information on the recently developing position of GBs as well as the critical role of China in terms of CO_2 emissions and energy use, this study aims to uncover the effectiveness of GBs on carbon neutrality and clean EG. Accordingly, the study searches for the effect of GBs on sectoral CO_2 emissions and disaggregated level clean EG in China. Hence, the study tries to find answers to the following research questions: (i) how are GBs negatively effective (i.e., decreasing effect) on sectoral CO_2 emissions?; (ii) how are GBs positively effective (i.e., increasing effect)?; on clean EG?; (iii) do effect of GBs on both CO_2 emissions and clean EG are linear or do they differ across the levels (quantiles); (iv) are the outcomes collected on these questions robust based on alternative econometric approach? In searching for answers to these research questions, the study focuses on the Chinese case, makes a comprehensive disaggregated analysis for CO_2 emissions at the sectoral level and clean EG at the source-based level, applies quantile-based approaches for the daily data from January 2, 2019, to December 31, 2023. By following up such a comprehensive approach, the study defines that GBs decrease mainly CO_2 emissions in transport and international aviation sectors; GBs have mixed effects on the remaining sectoral emissions; GBs increase clean EG from all sources at higher quantiles. Thus, the study reveals the varying effects of GBs across sectors, EG sources, and quantiles in China. Accordingly, the study discusses various policy endeavors to encourage China further in combating climate change by decreasing CO_2 emissions and increasing clean EG through benefitting from GBs as a recently emerging financing means.

Overall, the study makes the following contributions to the literature. First, the study focuses on mainly the case of China to investigate the effect of GBs on CO_2 emissions and clean EG. While the literature includes various studies regarding GBs (e.g., Ref. [10–14]), based on the best knowledge, no study has mainly focused on Chinese case as well as none of the current studies have examined the effectiveness of GBs on both CO_2 emissions and clean EG simultaneously. Second, the study makes a disaggregated level analysis for CO_2 emissions and clean EG simultaneously in uncovering the effect of GBs. Hence, the study differs from many studies in the literature that prefer to analyze aggregated levels for various countries. Third, the study uses high-frequency daily data from January 2, 2019, to December 31, 2023, and performs quantile-based approaches. In this way, the study differentiates again from current studies in a way that they have mainly used low-frequency

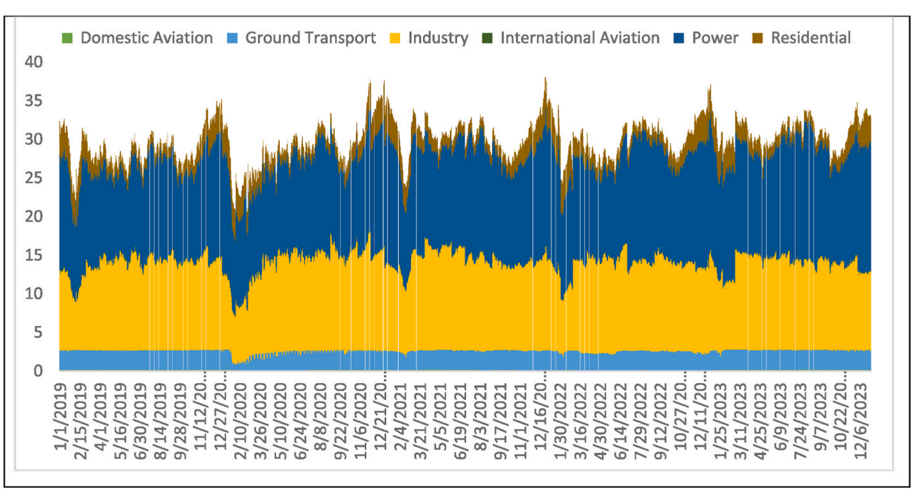

Fig. 1. Progress of disaggregated level CO_2 emissions
Note: The unit is metric tons of CO_2 equivalent/day. The total CO_2 emissions are shown on the right axis.
Source: Carbonmonitor [17].

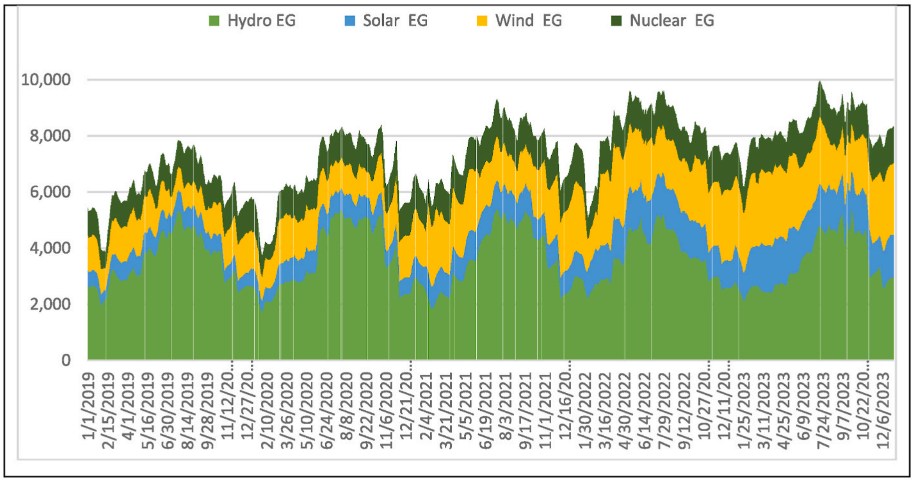

Fig. 2. Progress of disaggregated level clean EG
Note: The unit is Gigawatt-hours/day. The total EG is shown on the right axis.
Source: Carbonmonitor [17].

(e.g., yearly and quarterly) data and performed mean-based (e.g., ARDL and OLS-based) approaches to make an estimation. So, they have missed two important points (i) not considering the time-varying structure of the nexus between the variables, especially in highly volatile times such as energy crisis and geopolitical tension, and (ii) not considering the changing effect between the variables across levels (quantiles). In this way, the study provides three important contributions to the current body of knowledge.

The introduction section is continued by the theoretical framework and literature review in Part II; the methods in Part III; the empirical outcomes in Part IV; the conclusion, policy endeavors, and further research directions in Section 5, in order.

2. Theoretical framework and literature review

2.1. Theoretical framework

Based on the leading studies (i.e., [4,22–24]), the environmental economics area has mainly focused on the nexus between income structure and environmental degradation. Following these seminal studies, a variety of studies have examined the effect of income on the environment across countries (e.g., Ref. [25,26]). While countless studies have considered the role of income in the examination of environmental degradation, in line with the pioneering study of Kraft & Kraft [3], later studies have begun to focus on the effect of energy use (e.g., Ref. [27,28]). Hence, the common literature has been constructed based on mainly income and energy use considerations.

In the literature, some well-known traditional factors, such as income and energy use, have been intensively considered to examine the progress of carbon neutrality and clean EG. Nevertheless, the recent literature has been developing in a way that new research has begun to consider new factors. Among all the factors that have been recently considered by scholars, GB has come into force.

According to their definitions, GBs are recently emerged financing tools that can be used to provide financing for clean EG investments. Accordingly, it can be expected that GBs will be used to finance new clean EG production projects, such as the installation of new nuclear energy plants as well as hydro, solar, and wind energy farms [29]. As countries produce and consume much cleaner EG, it can be expected to see a decrease in CO_2 emissions that result from energy use, especially generated by using clean sources instead of fossil fuel sources [30]. Moreover, GBs can be used to support energy-related R&D activities as well as attract eco-friendly technologies to the country through financing channels. In all these ways, GBs can be effective in supporting sustainable development goals (SDG) 7 and 13 that are related to clean energy and climate action, in order.

2.2. Review of the empirical literature

2.2.1. GBs and carbon neutrality

Since environmental problems have been attracting the interest of societies, research on this aspect has been developing continuously. Also, in line with the progressing literature on GBs, new studies have highly focused on the nexus between GBs and carbon neutrality. For example, Chang et al. [11] analyze 10 green countries and determine the curbing effect of GB on ecological footprint. Meo and Abd Karim [31] handle the top ten selected green economies and report that GBs mitigate CO_2 emissions. Alamgir and Cheng [15] examine selected 67 countries and conclude that GBs have a reducing effect on per capita CO_2 emissions. Sun et al. [32] analyze 25 Chinese provinces and specify the mitigating effect of GBs on CO_2 emissions. Xu and Li [33] explore 355 Chinese cities and define that the outcomes in a generalized approach can be stated that GBs can mitigate city-level CO_2 emissions and the decreasing effect of GBs can be increased by ensuring environmental regulation compliance. Also, Kaewsaeng-on and Mehmood [34] analyze SAARC countries and determine a contributing effect of green finance in curbing environmental risk at higher levels (quantiles).

However, some studies have either mixed or contradictory outcomes. Hammoudeh et al. [35] analyze the United States and state that GBs do not have a causal effect on CO_2 emissions. Fatica and Panzica [10] uncover the global case and conclude that the effect of conventional bonds on CO_2 emissions is defined to be more pronounced, long-lasting, and significant. Adebayo and Kartal [30] examine the United States case and define that GBs have a strong positive (negative) co-movement with industrial CO_2 emissions in the medium-run (long-run). Also, ElBannan and Löffler [36] document that GBs can help firms finance carbon reductions, but a considerable fraction of GB financing does not lead to measurable benefits for the environment. Kartal et al. [29] determine the time and frequency-based varying effect of GBs on global CO_2 emissions.

Based on the aforementioned empirical studies, it can be stated that the effect of GBs on carbon neutrality, which is mainly proxied by CO_2 emissions, is not in a certain way.

2.2.2. GBs and clean electricity

Because the literature on the financial perspective has been increasing, in addition to environmental focus, recent studies have begun to focus on the energy side as well. While previous studies have mainly used financial development (e.g., Anton & Nucu, 2022; [6]) as a financial proxy, new studies have begun to use GBs because both indicators are not the same and their content is different from each other.

Alamgir and Cheng [15] examine selected 67 countries and conclude that GBs have a stimulating effect on renewable energy generation. Alharbi et al. [37] examine selected 44 countries and determine that GBs have a stimulating effect on renewable energy. Dong et al. [14] focus on six developing countries in the Asia region and conclude that GBs support renewable energy consumption. Feng et al. [38] handle the Chinese case and define that GBs increase renewable energy generation by providing an increase in renewable energy investments. Taghizadeh-Hesary et al. [39] focus on the Japanese case and determine that GBs have an increasing effect on renewable (solar & wind) energy. Ye and Rasoulinezhad [40] work on 15 selected countries from the Asia-Pacific region and GBs increase renewable energy efficiency. Zhao et al. [41] handle the Chinese case and define that GBs have an increasing effect on renewable energy investments. Cheng et al. [42] consider selected 12 countries from Asia region and determine that developing the GB market enables resource efficiency.

However, some studies have defined reverse outcomes. Wang and Taghizadeh-Hesary [43] examine 16 OECD countries and define that GBs do not affect solar energy, while green finance stimulates wind and hydropower.

According to the aforementioned empirical studies, it can be concluded that the effect of GBs on clean energy, which is mainly proxied by electricity, is not conclusive.

2.3. Evaluation of the literature

According to the review of the empirical literature, which takes place in the previous sub-section, it can be stated that the literature includes various studies about the effect of GBs on carbon neutrality and clean EG across various scopes. Among all, based on the best knowledge, Taghizadeh-Hesary et al. [39] and Wang and Taghizadeh-Hesary [43] have examined the effect of GBs on renewable energy from a disaggregated perspective. These studies have examined Japan and 16 OECD countries, in order.

The first research gap is that there is no study in the literature that uncovers the effect of GBs on disaggregated level clean EG for China by using quantile-based approaches. Also, another gap is that while some studies have considered sub-sectors in examining GB effect on CO_2 emissions (e.g. Ref. [29]), no study has made a full examination by considering all sub-sectors. Besides, most of the present studies have used low-frequency (e.g., yearly and quarterly) data and performed mean-based (e.g., ARDL and OLS-based) approaches to make an estimation. On the other hand, it is important to use high-frequency (e.g., daily) data to capture the time-varying structure of the nexus between the variables, especially in highly volatile times such as the energy crisis and geopolitical tension and the changing effect between the variables across quantiles. Hence, the literature has also a gap from these points.

By considering the above-specified literature gaps as well as research objectives, this study focuses on the Chinese case for the period from January 2, 2019, to December 31, 2023, by performing quantile-based approaches in uncovering the effect of GBs on sectoral CO_2 emissions and source-based EG. In this way, the study can provide fresh insights into the nexus of GBs with CO_2 emissions and clean EG in China. Thus, the research can make contributions by filling the gaps in the literature.

2.4. Hypotheses

This research investigates the role of GBs on sectoral CO_2 emissions and clean EG at source-based levels in China. In applying comprehensive analyses to do so and realize research objectives, the study takes the literature into account. Accordingly, this investigation searches for the answers to the following hypotheses, which can be proposed based on empirical literature that are examined in the before sub-sections.

H1. GBs have a curbing effect on sectoral CO_2 emissions.

H2. GBs have a stimulating effect on clean EG.

H3. The effect of GBs varies across sectors, clean EG sources, and quantiles.

To test these hypotheses, this research makes a detailed and comprehensive analysis of the Chinese case by benefitting from quantile-based approaches. Hence, the empirical analysis can be applied across various sectors, clean EG sources, and quantiles.

3. Methods

3.1. Data and variables

This analysis aims to comprehensively investigate the effect of GBs on CO_2 emissions and clean EG in China as the leading CO_2-emitter and energy-consumer country by performing a disaggregated level empirical analysis. In this context, the study uses the FTSE Chinese GB Index as the proxy of GBs in China. Also, the study considers sectoral CO_2 emissions as a carbon neutrality indicator and clean EG types as a clean EG indicator.

Data for the FTSE Chinese GB Index is collected from Bloomberg [44]. Also, data for sectoral CO_2 emissions and clean EG are collected from Carbonmonitor [17]. Hence, the study uses daily data between January 2, 2019, and December 31, 2023, which is the most recent available dataset.

Through gathering data from Bloomberg [44] and Carbonmonitor [17] sources, the study includes all sectoral CO_2 emissions and clean EG sources. Table 1 presents the details of the variables.

3.2. Empirical analysis procedure

To investigate the effects of GBs on carbon neutrality and clean EG, the study applies an empirical analysis procedure that includes a total of five steps as demonstrated in Fig. 3.

In the first step, this research examines the fundamental statistics of the variables. In the second step, correlations across variables are analyzed. In the third step, the nonlinearity characteristics of the variables are tested by performing the Broock, Scheinkman, Dechert, and LeBaron (BDS) test [45]. In the fourth step, the study performs the quantile-on-quantile regression (QQR) approach [46] to analyze the effect of GBS on both carbon neutrality and clean EG across different quantiles. In the last step, the study applies the quantile regression (QR) approach [47] to control the robustness of the QQR outcomes.

In the context of empirical analysis, the study relies on quantile-

Table 1
Variables.

Variable Definition	Symbol	Unit	Data Source
Domestic Aviation Sector CO_2 Emissions*	DOM	Metric Tons of CO_2 Equivalent/Day	Carbonmonitor [17]
Ground Transport Sector CO_2 Emissions*	TRA		
Industry Sector CO_2 Emissions*	IND		
International Aviation Sector CO_2 Emissions*	INT		
Power Sector CO_2 Emissions*	POW		
Residential Sector CO_2 Emissions*	RES		
Hydro EG*	HEG	Gigawatt-Hours/Day	
Solar EG*	SEG		
Wind EG*	WEG		
Nuclear EG*	NEG		
FTSE Chinese GB Index**	GBC	Basis Point	Bloomberg [44]

Notes: * and ** show the dependent and independent variables, respectively.

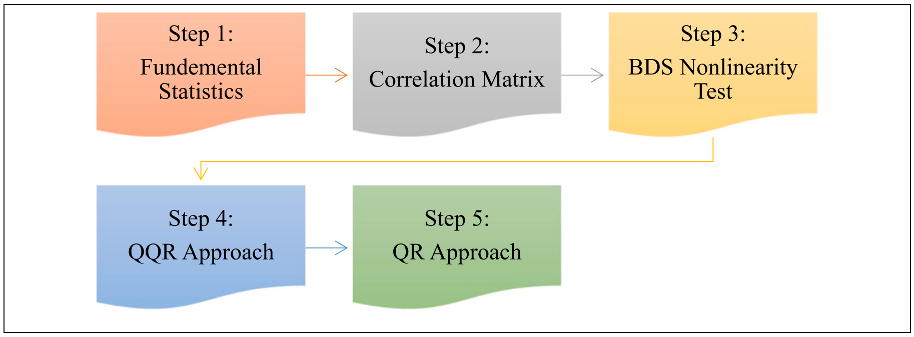

Fig. 3. Empirical analysis procedure.

based approaches since performing linear approaches cannot be the right preference in cases, where variables are nonnormally distributed and nonlinearly structured. Also, the application of such approaches as QQR and QR can provide more efficient empirical outcomes by capturing the nonlinear structure of the variables. Besides, the application of such quantile-based approaches is in line with the recent literature (e.g., Ref. [48,49]). Moreover, in the case of the use of high-frequency daily data, performing such quantile-based approaches can be much more appropriate because there can be high volatility across days and quantiles. By considering all these points, quantile-based approaches (i.e., QQR and QR) are used for empirical analysis.

4. Empirical outcomes

4.1. Preliminary statistics

In the first step, the research analyses the main statistics. In this context, Table 2 demonstrates fundamental statistics.

According to Table 2, clean EG sources have higher mean values than all sectoral CO_2 emissions and GBC. Also, volatility in clean EG sources is much higher than others. Moreover, based on JB values, all variables are not normally distributed, which implies a nonnormal distribution.

Following the examination of fundamental statistics, in the second step, the research examines correlations between the variables that are presented in Table 3.

Based on Table 3, GBC has a negative correlation with DOM, INT, and RES, whereas it has a positive correlation with TRA, IND, and POW in terms of sectoral CO_2 emissions. Also, GBC has a generally positive correlation with clean EG sources except for RES, which has a negative correlation. These correlation coefficients imply that GBC has a decreasing effect on some sectors' CO_2 emissions, whereas it is inefficient in some others. Also, GBC has a stimulating effect on clean EG mainly, but it can be inefficient on RES.

Following the examination of correlations, in the third step, the research tests the nonlinearity characteristics of the variables that are demonstrated in Table 4.

According to Table 4, all variables fail to confirm the null hypothesis, which is that variables have a linear structure, in testing nonlinearities of the variables. Hence, BDS test outcomes show that all variables have a nonlinear structure across various dimensions.

In sum, the outcomes of all preliminary statistics imply some critical properties of the variables. First, variables have significant variations. Second, all variables are not normally distributed. Third, all variables have a nonlinear structure. In line with these determinations, the study performs quantile-based approaches to capture these properties of the variables in empirical investigations.

4.2. GB effect on carbon neutrality

In the fourth step, the study applies the QQR approach to investigating the quantile-based nexus between GBs and sectoral CO_2 emissions. Fig. 4 presents the effect of GBs on carbon neutrality.

GBC has a completely decreasing effect on DOM across all quantiles. It means that GBs are effective in curbing CO_2 emissions in the domestic aviation sector. Similarly, GBC has also a declining effect on INT across all quantiles. This can be related to the greening facilities for the activities that are realized on the ground in both domestic and international aviation sectors. Hence, CO_2 emissions of these sectors can be decreased in this way.

Also, GBC has an almost declining effect on TRA across all quantiles except for the highest one. This finding shows that GBs are quite effective in decreasing CO_2 emissions in the transport sector. This can be attributed to the electrification activities in the transport sector as well as Chinese railway investments that are highly critical to the decline in transport sector CO_2 emissions.

Besides, GBC has a mixed effect on IND and POW across quantiles. While GBs have a declining effect at lower and middle quantiles, however, the effect becomes inefficient at higher quantiles. This determination implies that GBs have an efficient effect on industry and power

Table 2
Fundamental statistics.

Variable	Mean	Maximum	Minimum	Std. Dev.	Skewness	Kurtosis	JB	Prob.
DOM	0.15	0.22	0.02	0.05	−0.89	2.70	169.65	0.0000
TRA	2.45	2.67	0.80	0.24	−4.15	23.51	25,529.76	0.0000
IND	11.53	15.38	6.14	1.46	−1.12	5.01	470.61	0.0000
INT	0.04	0.10	0.02	0.02	1.12	2.78	263.63	0.0000
POW	13.56	17.97	9.62	1.81	0.14	2.22	35.86	0.0000
RES	2.21	5.05	1.31	0.95	0.79	2.26	160.03	0.0000
HEG	3,582.49	5,382.32	1,714.70	996.33	0.23	1.68	102.51	0.0000
SEG	991.52	1,714.05	357.06	346.67	0.34	1.93	84.37	0.0000
WEG	1,712.44	2,648.00	702.51	528.84	0.13	1.84	73.93	0.0000
NEG	1,084.07	1,373.45	538.17	150.50	−1.08	4.57	371.89	0.0000
GBC	122.54	133.91	109.58	6.85	−0.10	1.79	77.75	0.0000

Notes: Std. Dev. and JB imply the standard deviation and Jarque-Bera.

Table 3
Correlation matrix.

Variable	DOM	TRA	IND	INT	POW	RES	HEG	SEG	WEG	NEG	GBC
DOM	1.00										
TRA	0.01	1.00									
IND	0.07	0.11	1.00								
INT	0.31	0.01	0.08	1.00							
POW	0.11	0.10	0.65	0.16	1.00						
RES	0.02	−0.04	0.04	−0.04	0.03	1.00					
HEG	−0.01	0.10	0.14	0.02	0.12	−0.07	1.00				
SEG	0.00	0.06	0.15	0.01	0.06	−0.06	0.35	1.00			
WEG	−0.10	0.12	0.16	0.01	0.03	0.05	0.14	0.33	1.00		
NEG	−0.01	0.14	0.19	0.08	0.14	−0.01	0.37	0.34	0.50	1.00	
GBC	−0.05	0.02	0.02	−0.10	0.00	−0.02	0.00	0.03	0.02	0.00	1.00

Notes: Values denote correlation coefficients.

Table 4
BDS nonlinearity test outcomes.

Variable	DIM2	DIM3	DIM4	DIM5	DIM6	Outcome
DOM	0.0000	0.0000	0.0000	0.0000	0.0000	NL
TRA	0.0000	0.0000	0.0000	0.0000	0.0000	NL
IND	0.0000	0.0000	0.0000	0.0000	0.0000	NL
INT	0.0000	0.0000	0.0000	0.0000	0.0000	NL
POW	0.0000	0.0000	0.0000	0.0000	0.0000	NL
RES	0.0000	0.0000	0.0000	0.0000	0.0000	NL
HEG	0.0000	0.0000	0.0000	0.0000	0.0000	NL
SEG	0.0000	0.0000	0.0000	0.0000	0.0000	NL
WEG	0.0000	0.0000	0.0000	0.0000	0.0000	NL
NEG	0.0000	0.0000	0.0000	0.0000	0.0000	NL
GBC	0.0000	0.0000	0.0000	0.0000	0.0000	NL

Notes: Values show the p-values. DIM and NL denote dimension and nonlinear, respectively.

sector CO_2 emissions in the first place, which reveals the right practices of GBs. However, GBs become ineffective in curbing CO_2 emissions as GBs increase and time passes. This may highlight that GBs, which are issued later, cannot be correctly canalized to efficient areas in these sectors. Hence, they are ineffective at this stage in combating CO_2 emissions in these sectors.

Moreover, GBC has a mixed effect on RES across quantiles. While GBs are ineffective at the beginning across lower quantiles, but, the effect becomes effective and decreasing one at middle and higher quantiles. This finding shows that GBs are efficient on residential sector CO_2 emissions as time passes and GBs increase. This may imply that GBs can be used to support the conversion of houses into much eco-friendlier structures by applying various measures, such as further electrification, insulating, and installing solar panels on houses' roofs. Also, increasing GBs can be correctly used to change the behavior of households to curb CO_2 emissions in the residential sector. Hence, GBs are effective in combating residential sector CO_2 emissions.

In summary, it can be stated that GBs have a mixed effect on sectoral CO_2 emissions in the Chinese case. Whereas they can help curb CO_2 emissions in some sectors at some quantiles, however, they are ineffective in declining CO_2 emissions in some other sectors across various quantiles.

4.3. GB effect on clean EG

Following the examination of the nexus between GBs and sectoral CO_2 emissions, the study also examines the nexus of GBs with clean EG. Fig. 5 demonstrates the effect of GBs on clean EG.

GBC has a mixed effect on HEG and SEG across quantiles. While GBs are ineffective in increasing hydro EG at the lowest and highest quantiles, they can be successful in supporting an increase in hydro EG across lower, middle, and higher quantiles. This is almost the same for SEG except that GBs have an increasing effect at the highest quantile. This determination shows that GBs cannot make a significant effect on HEG and SEG until they become a bit more mature. As they become mature, they can have an increasing effect by financing new investments in these clean EG areas. Hence, they are effective in supporting further hydro and solar EG. However, after GBs reach to a matured level, they become again inefficient in the hydro EG area. This implies that after exceeding a threshold in the issuance of GBs, they cannot successfully be canalized to hydro EG area.

Also, GBC has a mixed effect on WEG and NEG across quantiles. While GBs are effective in increasing wind EG at lower and higher quantiles, they are almost ineffective across middle quantiles. This is almost the same for NEG except that GBs have a decreasing effect at lower quantiles. This determination shows that GBs cannot make a significant effect on WEG and NEG when they follow a stable trend. In other words, GBs are effective in increasing WEG at the beginning (lower quantiles) and ending (higher quantiles) as well as NEG at the ending (higher quantiles). However, GBs do not help provide a stimulating effect when they are in a stable increasing trend that follows almost a horizontal trend. This shows that new GBs are used to finance WEG and a higher increase in GBs are canalized to WEG and NEG. This finding can be related to the requirement of a high installation budget for these types of clean EG, especially for NEG.

Moreover, there is another point for the changing effect of GBs on clean EG sources (i.e., hydro, solar, wind, and nuclear). This changing effect can result from displacement between clean EG sources. That is why the total amount of GBs is stable at a time and these financing sources can be used either one clean EG type or distributed among clean EG types. Hence, whichever clean EG type is selected, this may cause a displacement for the remaining clean EG types. In such a condition, GBs can provide an increase in one clean EG type that is selected to be funded, whereas GBs cannot make a significant increasing effect on the remaining clean EG types although the amount of GBs increases.

To sum up, it can be concluded that GBs have a mixed effect on clean EG in the Chinese case. GBs are beneficial to support the increase in some clean EG sources across some quantiles. On the other hand, GBs are ineffective in stimulating clean EG further in some sources at some quantiles.

4.4. Robustness check

As the last step of empirical analysis, the research performs the QR approach to control the robustness of the outcomes of the QQR approach. The outcomes of the QR approach are detailed in Annexes 1-2 in a comparative way with the QQR approach. Also, a summary of the comparison of QQR and QR approaches is presented in Table 5.

As Table 5 presents, the outcomes of both QQR and QR approaches are highly similar reaching a 99.99% correlation between the two approaches. Based on these outcomes, it can be concluded that outcomes obtained from the QQR approach are consistent with the QR approach,

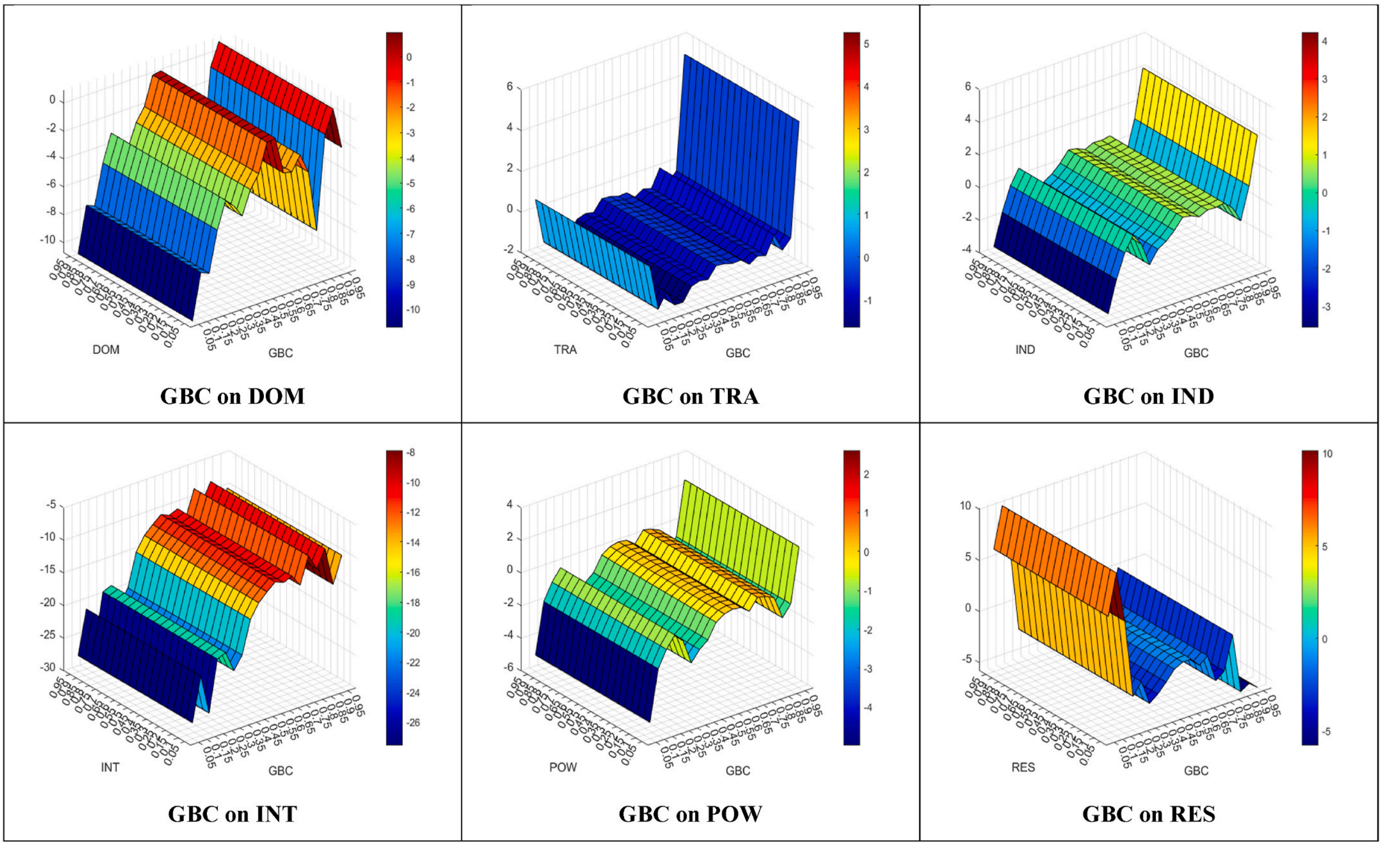

Fig. 4. GB effect on sectoral CO_2 emissions.

which reveals the robustness. Thus, various policy endeavors can be discussed by relying on the outcomes collected.

5. Conclusion, policy endeavors, and further research

5.1. Conclusion and discussion

Climate change-related problems caused by environmental degradation have accelerated in recent decades. These have resulted in mainly anthropogenic activities of humankind, of which it can be argued that such a negative process can be prevented by taking measures in line with SDGs. Among all, SDGs 13 and 7 are highly related to climate actions and clean energy use, in order. Those are important goals for countries because a big share of CO_2 emissions is caused by energy use, especially fossil fuel source-based energy. Based on this fact, in line with the carbon neutrality targets, countries have been focusing on stimulating clean energy much more in combating climate change. In this journey, GBs, which are recently popular financing means, can be a strategic tool for countries to support clean energy generation and curb CO_2 emissions in turn.

This study focuses on the Chinese case, which is the leading country in terms of CO_2 emissions, energy use, and GB issuance, to uncover the effects of GBs on CO_2 emissions and clean EG by making a disaggregated level analysis through using high-frequency daily data and performing quantile-based approaches. In this way, the study searches for the answers to research questions and tests hypotheses. The outcomes of quantile-based approaches present that GBs decrease mainly CO_2 emissions in transport and international aviation sectors, whereas they have mixed effects on the remaining sectoral emissions. Also, GBs increase mainly EG from all clean sources at higher quantiles, whilst they decrease EG at lower quantiles. Overall, the effect of GBs varies across sectors, EG sources, and quantiles.

By benefitting from quantile-based approaches, the study answers the research questions, in order, as follows: (i) GBs have a decreasing effect on some sectors' CO_2 emissions; (ii) GBs stimulate generally clean EG at higher quantiles; (iii) the effect of GBs on sectoral CO_2 emissions and clean EG varies across quantiles by following a nonlinear pattern; and (iv) the outcomes are robust based on alternative economics approach. Thus, the study partially verifies the first hypothesis, almost completely verifies the second hypothesis, and completely verifies the third hypothesis.

The outcomes of this research are mainly consistent with the current literature. For instance, the study determines that GBs have a curbing effect on transport and international aviation sectors' CO_2 emissions that are consistent with the studies of Sun et al. [32] and Xu and Li [33]. However, GBs are a bit inefficient in curbing CO_2 emissions in the remaining sectors as concluded in the studies of Hammoudeh et al. [35] and Fatica and Panzica [10]. Also, the effect of GBs on sectoral CO_2 emission varies across quantiles, this is consistent with Adebayo and Kartal [30] and Kartal et al. [29]. Moreover, the study concludes that GBs increase mainly EG from all clean sources at higher quantiles, which is in line with Alamgir and Cheng [15] and Taghizadeh-Hesary et al. [39]. However, GBs decrease EG at lower quantiles that are similar to Wang and Taghizadeh-Hesary [43]. Overall, the study achieves consistent outcomes with the present literature, but, it extends the current knowledge by providing disaggregated level insights about the differentiating effects of GBs on carbon neutrality and clean EG.

The study makes novel contributions to the current literature by comprehensively focusing on the Chinese case, making a disaggregated level analysis for CO_2 emissions and clean EG simultaneously, and using high-frequency daily and performing quantile-based approaches. In this way, this study has not missed two important points (i) considering the time-varying structure of the nexus of GBs with CO_2 emissions and clean EG; and (ii) considering the changing effect of the nexus of GBs with CO_2

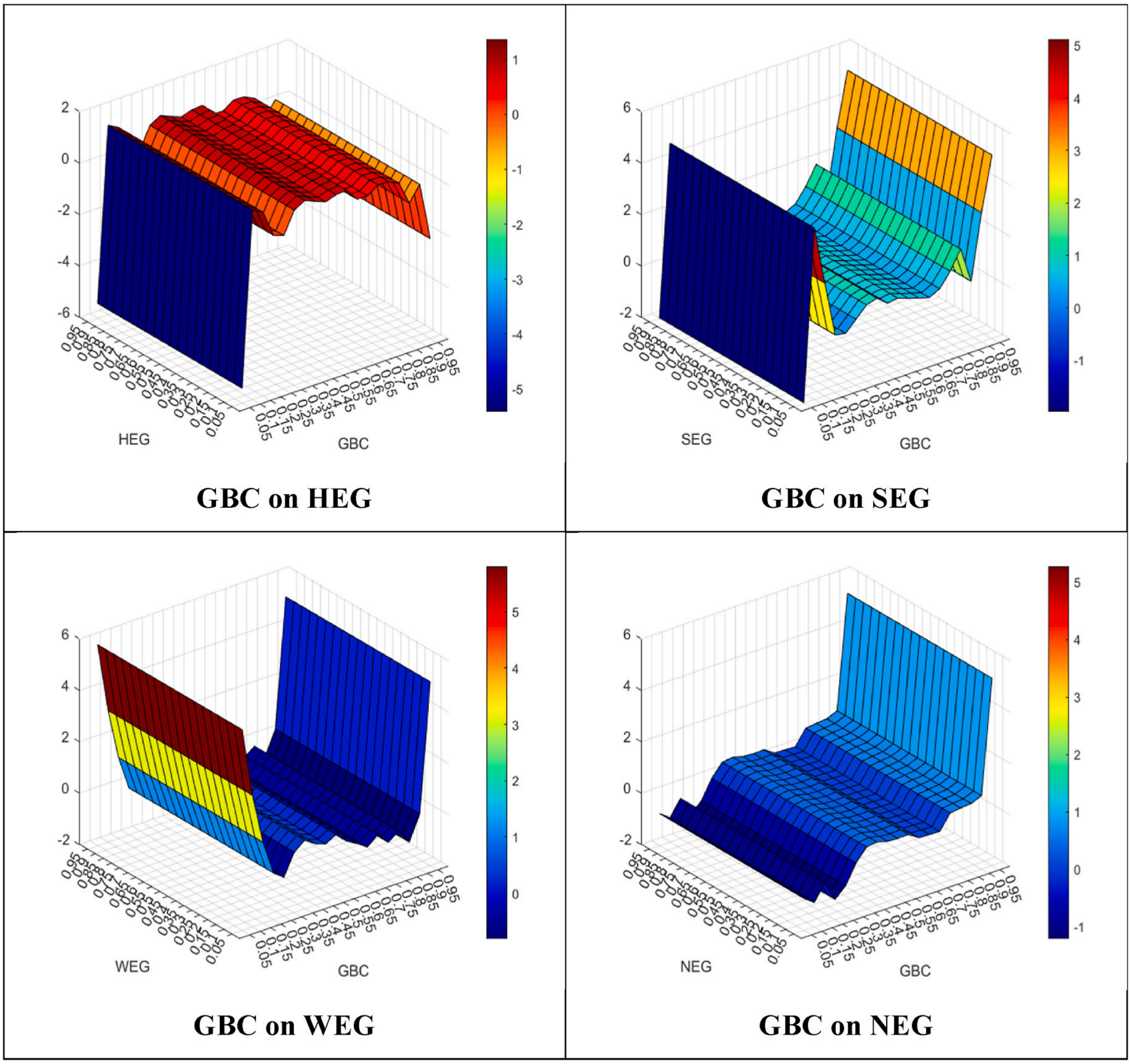

Fig. 5. GB effect on clean EG.

Table 5
Summary of QQR and QR comparison.

Variable Pair	Correlation (%)
GBC on DOM	99.99
GBC on TRA	99.99
GBC on IND	99.99
GBC on INT	99.99
GBC on POW	99.99
GBC on RES	99.99
GBC on HEG	99.99
GBC on SEG	99.99
GBC on WEG	99.99
GBC on NEG	99.99

emissions and clean EG across quantiles.

5.2. Policy endeavors

GBs can be beneficial for various related parties, especially for those, who are GB sellers and governmental agencies, from an environmental and energy perspective. That is why while GBs are issued, countries can benefit from them in financing clean EG projects and GB sellers can benefit also from collecting required financial sources to finance their clean EG project without interacting with any governmental agencies [12,40]. In this way, clean EG projects can be financed independently from governmental agencies, which is an important point for investors, especially for international investors in the clean EG area.

It can be stated that GBs can take a critical role in Chinese environmental and energy policies while supporting the combating of climate change and ensuring carbon neutrality targets by curbing environmental degradation. So, by performing quantile-based approaches, this study presents fresh insights into how GBs are effective in carbon neutrality and clean electricity generation in the Chinese case. In line with these outcomes, this research discusses a set of policy endeavors.

From the perspective of GB and carbon neutrality nexus, the study reveals the declining effect of GBs on transport and international aviation sectors' CO_2 emissions. Accordingly, China can continue to rely on GBs to curb CO_2 emissions in these sectors, especially to finance the installation of high-speed railways, which are an important component of the Chinese policy framework [50]. Hence, China can continue to manage CO_2 emissions in these sectors with the support of GBs.

On the other hand, a big share of Chinese CO_2 emissions has been resulting from the power and industry sectors. According to outcomes, while GBs have a curbing effect on these sectors at the beginning, they become inefficient later. This determination requires Chinese policymakers to focus on these sectors due to their high share in total CO_2 emissions and support GB issuance, which is directed to these sectors, that increases especially energy efficiency, eco-friendly technologies, and clean EG investments. Also, electrification of critical sectors, such as industry, can be an option to deal with CO_2 emissions in total and such sectors as long as additional electricity power requirements resulting from electrification can be met by using clean EG sources [51].

Moreover, in the case of domestic aviation and residential sectors, there are mixed effects of GBs on CO_2 emissions. At higher quantiles, which present the higher issuance of GBs and higher CO_2 emissions, GBs have an inefficient effect on CO_2 emissions of domestic aviation and a decreasing effect on CO_2 emissions of the residential sector. This determination implies that Chinese policymakers should follow continuously the progress of both GB issuance and sectoral emissions and make some arrangements in the issuance of GBs to make them helpful to sectors (e.g., residential) and prevent their inefficient effect on some sectors (e.g., domestic aviation). In the way of supporting the allocated GB issuance to specified sectors, China can benefit from GBs further in ensuring carbon neutrality in these sectors by providing additional helpful shocks to these sectors as well as preventing displacement among clean EG sources.

From the perspective of GB and clean EG nexus by considering also the leading role of power sector CO_2 emissions in total CO_2 emissions of China, the study defines the increasing effect of GBs on almost all types of clean EG at higher quantiles, whilst they have a decreasing effect on hydro, solar, and nuclear EG at lower quantiles. This finding implies some facts. At the initial step, the issuance of GBs cannot be enough to make an efficient increasing effect on clean EG. However, as the amount of GBs increases, the effect of GBs on clean EG becomes effective and makes a significant increasing effect, while this effect is seen as highly stimulating at higher quantiles across all clean EG sources except for hydro EG. Hence, a high volume of GB issuance is needed to make an efficient stimulating contribution to clean EG. Also, some production companies, such as those dealing with industrial production of solar panels and wind turbines, can be encouraged to issue GBs and support with governmental support from various perspectives, such as financial advisory, tax-exempt, investment subsidies, credits with lowering interest rates, to increase clean EG from these sources. In this way, while China can be much more resistant to external shocks in energy generation areas, such as energy crisis and geopolitical tensions, they can also benefit from much cleaner EG sources, which decreases external dependency to import fossil fuel sources.

Also, Chinese policymakers can encourage the financial sector to use GBs as a financial asset much more. In this way, the issuance of GBs can be increased, which will result in further sources to finance new clean EG projects. Besides, because issued GBs are purchased by investors, public awareness of clean EG can be extended in this way and GB buyers can be much more interested in the use of clean EG instead of fossil fuel-based ones.

In summary, while various policy endeavors have been discussed, it can be mainly suggested that Chinese policymakers should deal with firstly such critical sectors as power and industry to curb CO_2 emissions, support the allocated GB issuance to specified sectors to make them efficient in decreasing CO_2 emissions in these sectors, and focus on some clean EG such as solar and wind to stimulate clean EG further and combat climate change in this way. Also, making a follow-up for carbon neutrality and clean electricity generation at disaggregated levels (i.e., sectoral CO_2 emissions and clean EG based on sources) as well as across various quantiles is important in line with the outcomes of this research because they reveal that GBs have a varying effect across sectors, EG sources, and quantiles.

5.3. Limitations and further research

In this study, a detailed analysis of the nexus of GBs with carbon neutrality and clean EG for the Chinese case is applied. Although this study aims to make a comprehensive empirical investigation of China, nevertheless, it is not free from drawbacks.

The first limitation is related to the scope of the study because this research focuses on mainly the Chinese case. However, there are some other countries that have a significant role in carbon neutrality, clean EG, and GB issuances, such as France, Germany, and Sweden. Therefore, future studies can think about this point and may include either these countries or many more countries in new analyses.

The second limitation is related to the scope of the study. In fact, based on high-frequency available daily data, this study includes all possible sectors and clean EG sources. However, there are some other sectors based on different classifications by various data reporters. So, new studies can consider such different classifications on sectors and clean EG and may prefer to use these in empirical investigations as well. Also, because this study makes a country-level analysis, new studies analyze provinces and cities of China.

The third limitation is related to the empirical approach used in the study. To consider the varying effects of GBs on carbon neutrality and clean EG, the study applies quantile-based approaches. Although these approaches consider tail-dependence and make analysis across various levels, however, they do not take into account structural breaks as well as time and frequency structure. Therefore, new studies can consider applying other econometric approaches that consider such points in empirical investigations.

Disclosure statement

The authors certify that they have NO affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

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Availability of data and materials

Data will be made available on request.

Ethics approval and consent to participate

Not applicable.

Consent for publication

The authors are willing to permit the Journal to publish the article.

Informed consent

No personal or identifiable data was gathered in this article. The informed consent is not relevant.

CRediT authorship contribution statement

Mustafa Tevfik Kartal: Supervision, Conceptualization, Methodology, Software, Data curation, Writing – original draft, Writing – review & editing. **Ugur Korkut Pata:** Supervision, Conceptualization, Writing – original draft, Writing – review & editing. **Cosimo Magazzino:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

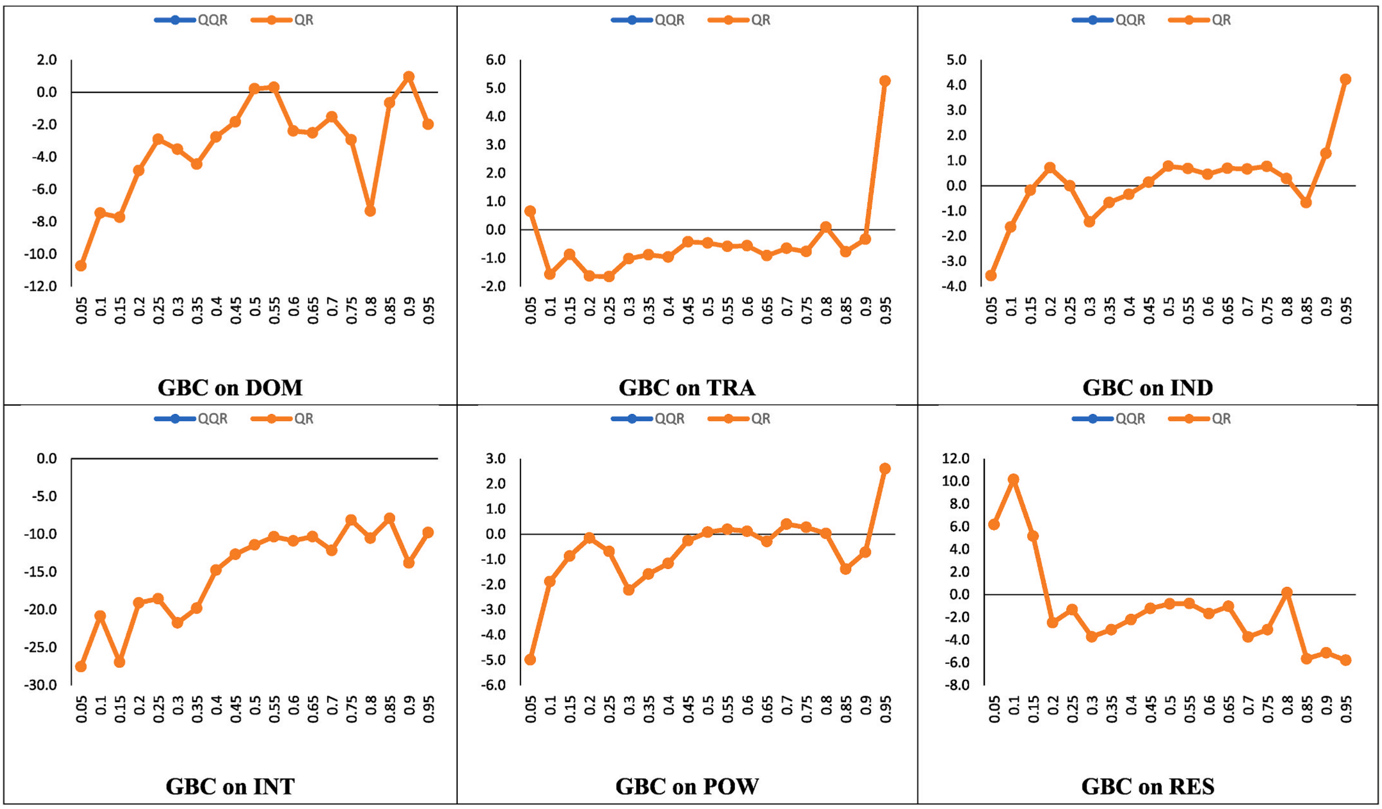
Data availability

Data will be made available on request.

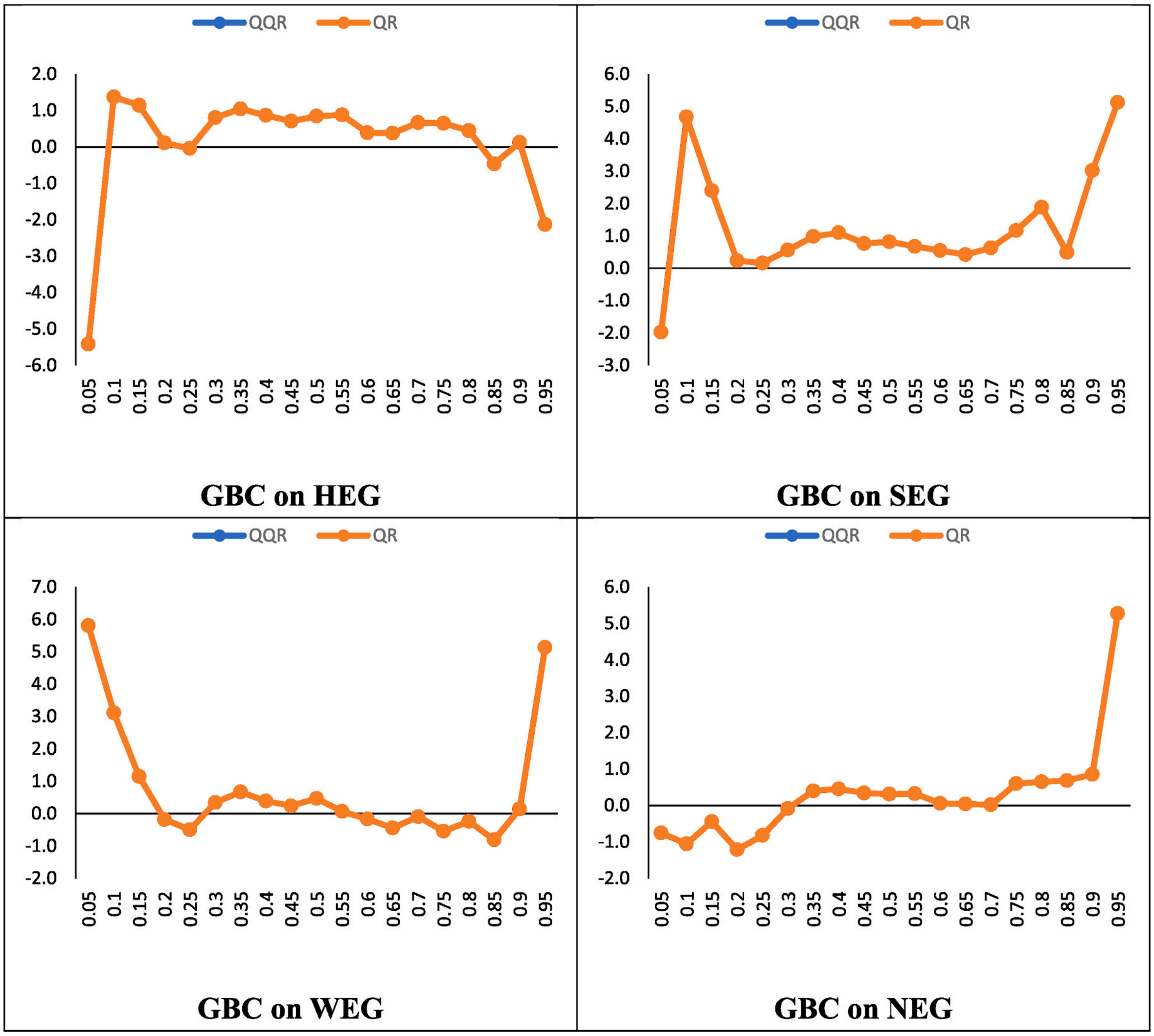
Acknowledgments

Not applicable.

Annex-1. QQR and QR comparison for GB effect on sectoral CO_2 emissions



Annex-2. QQR and QR comparison for GB effect on clean EG



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