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Relationship between green bonds and carbon neutrality: evidence from top five emitting countries' sectoral CO_2 emissions

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Abstract

This study analyzes the influence of green bonds on carbon neutrality. It examines the daily data of sectoral CO_2 emissions of the top five CO_2-emitting nations from January 2, 2019 to December 30, 2022 using wavelet transform coherence, quantile-on-quantile regression, Granger causality in quantiles, and quantile regression approaches. The results revealed that (i) green bonds are strongly related to sectoral CO_2 emissions; (ii) green bonds reduce transport sector CO_2 emissions in China, the US, and Japan while causing an upsurge in India and Russia; (iii) green bonds reduce industrial sector CO_2 emissions only in the US; (iv) green bonds have a declining influence in energy sector CO_2 emissions at lower quantiles in India, China, and the US, whereas the impact increases at higher quantiles; and (v) green bonds decrease residential sector CO_2 emissions in the US, Russia, and Japan. The study revealed that green bonds help reduce CO_2 emissions in the residential sector in various quantiles. Therefore, the US, Russia, and Japan should raise household awareness of green energy utilization by promoting them with green bonds. In addition, green bonds can effectively reduce transportation sector CO_2 emissions in China and the US. Therefore, the policymakers of the two global powers should contribute to global CO_2 reduction by promoting green transportation and clean energy transition in the transportation sector through green bonds. Thus, green bonds can play an effective role in the fight against global warming.

Keywords: Green bonds , Sectoral CO_2 emissions , Nonlinear approaches , Top emitting countries

JEL Classification: C32, N50, O13

Introduction

Global policymakers expressed their concern about rising emissions at the COP27 Summit. The unsustainable usage of fossil fuel energy sources is the major reason behind the global predicament. The incessant heating of these hydrocarbon-based energy sources results in CO_2 emissions into the ambient atmosphere. Utilizing energy sources helps to expand the range of economic activity in a country but affects the sanitary conditions of the workforce and causes global warming through the emissions produced as a byproduct.

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The International Energy Agency (IEA 2022) has stressed the need for a realignment of global energy consumption and identified ways to finance this realignment. Upon realizing the role of green and climate finance in rapid climate mitigation, policymakers have unilaterally agreed to pay attention to it (Bolton et al. 2022). Achieving the objective of net zero emissions by 2050 requires appropriately allocating green funding. The need for green finance (GF) is a gap identified in the COP27 discussions. This study aims to develop a baseline framework for scaling up financial activities for carbon neutrality targets.

A carbon peak indicates the point at which carbon emissions stop growing and their reduction begins, while carbon neutrality refers to anthropogenic carbon emissions balanced by anthropogenic removals over a certain period (Wei et al. 2022). Carbon neutrality is the state of achieving net zero emissions by balancing carbon emissions released as a result of a country's activities with carbon removal incentives (Chen et al. 2022). Thus, carbon neutrality is when the amount of carbon released by society as a result of activities is equal to the amount absorbed, which can be achieved through tree planting, energy saving, and clean energy promotion (Zhao et al. 2022).

To be carbon neutral, policymakers need to ensure an upsurge in the share of non-fossil energy, technological progress, carbon sequestration, and the promotion of green markets (Liu et al. 2022). In this context, green bonds can play an effective role in achieving carbon neutrality goals through green markets as they can provide incentives for various sectors to reduce emissions (Kartal et al. 2024a). Using clean energy sources is a tool for carbon reduction in the transportation sector. Supporting energy efficiency technologies, disseminating energy conservation, and promoting renewable energy sources for carbon reduction in the energy sector are important policy options. In the industrial sector, carbon taxes and mandates to filter smokestacks can be part of green practices. In the residential sector, training programs promote conscious and green consumption, while energy conservation incentives can support carbon reduction.

GF, which is proxied by green bonds, can be an approach to reduce emissions, which cause a high amount of pollution (Kartal et al. 2024b). Hence, this study explores the impacts of green bonds on CO_2 in the top five CO_2-emitting nations. These countries have achieved higher per capita GDP growth rates, electricity consumption, and CO_2 emissions than the global average (World Bank 2023). Figure 1 depicts the sectoral CO_2 emissions of these countries. CO_2 emissions are concentrated in different sectors. For example, in the US, CO_2 emissions from the transportation sector are the highest after the power sector, while in China, the industrial sector is the second highest emitting sector. Thus, green bonds can have different impacts in different sectors.

Discussions at COP27 focused on criticizing the emissions levels of the top five CO_2-emitting countries. US climate envoy John Kerry criticized climate pressures exerted by China and Russia (Milman 2022). Although Russia promised at the COP26 summit to take action to mitigate climate change, emissions have not declined as expected (Rapoza 2021).

Japan has also repeatedly been criticized at the COP25 and COP26 summits for its continued reliance on coal (Siripala 2021). Despite this criticism, Japan's lack of ministerial presence at the COP27 summit and its greenwashing behavior have received further criticism (Mesmer 2022).

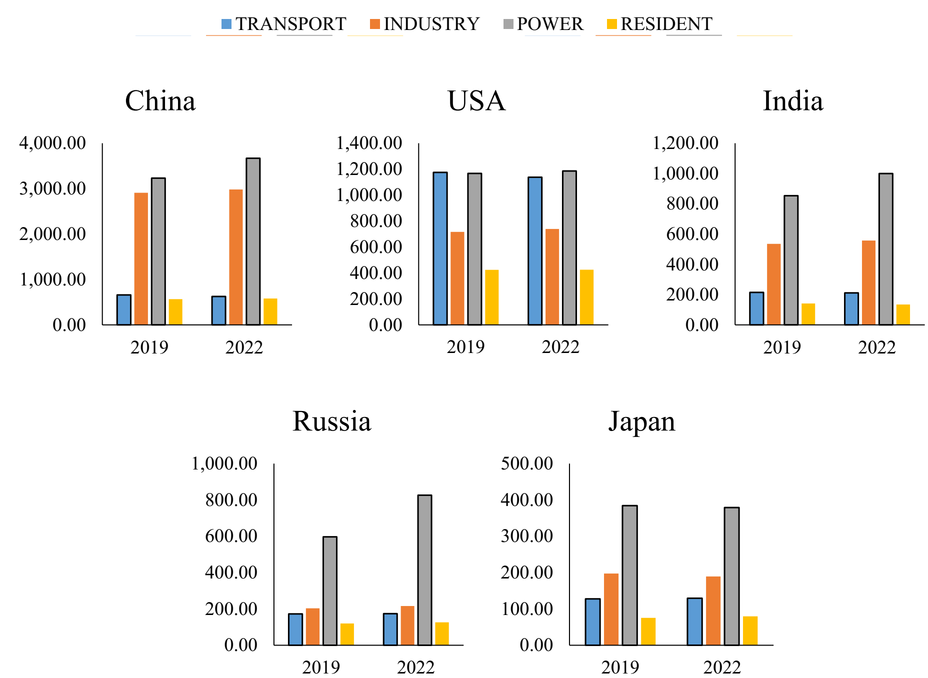

Fig. 1 Sectoral CO_2 emissions of top five emitting countries *Source*: Carbonmonitor 2023

India has demonstrated a consistent performance commitment to address CO_2 emissions. At the COP27 summit, India presented a strategic roadmap to achieve low emissions in the long term (Ministry of Environment Forest and Climate Change 2022). However, even after reducing emission intensity, overall emissions have not decreased as expected (Friedlingstein et al. 2022).

The US has been criticized for arguing that its lack of bilateral climate cooperation with China harms global climate cooperation (Blaine 2022). The ongoing ideological division in the US Parliament over Joe Biden's climate policies has weakened the US position on global climate policy (Kennedy et al. 2022).

The overall policy void in the top five CO_2-emitting countries calls for a review of their existing energy and climate finance policies and the development of a revised policy framework for reorienting their growth with lower emissions, which is the focus of this study. The IPCC's Sixth Assessment Report (2023) highlighted the "lack of finance as a barrier to climate action." This report points out two things—(a) identifying a proper financialization channel to reduce emissions and (b) avoiding misallocation issues. Addressing these two issues requires financing low-emission development through GF that simultaneously targets sectoral CO_2 emissions.

Adopting a sectoral approach to GF-based carbon reduction can solve the problem by avoiding potential misallocations. This argument brings forth the research question of the study as follows: "How can GF help achieve carbon neutrality by reducing sectoral CO_2 emissions?".

The treatment of CO_2 emissions at the sectoral level can be influenced by considering the impact of green bonds at different levels. The impact of green bonds on sectoral emissions may be nonlinear. Moreover, each sector may require different green financing practices to achieve carbon neutrality. For example, the energy sector has a higher capacity from this perspective as renewable energy generation can be supported with green financing. Green financing for energy use in the transportation sector can be more challenging. This is because it is difficult to cut off the link between some modes of transport and coal and oil. The conversion of the industrial sector is also somewhat difficult compared to the other sectors because continuity is important, requiring the use of a certain amount of fossil fuels. Thus, achieving carbon neutrality in different sectors is a difficult issue due to the nature of these sectors (Rehman Khan et al. 2023).

Developing a climate change policy focused on sectoral CO_2 emissions can help identify different opportunities for climate finance at different levels (Kou et al. 2023). Thus, this study aims to uncover the impact of green bonds on sectoral CO_2 emissions. It utilizes tail-dependent policy simulation by applying wavelet transform coherence (WTC), quantile-on-quantile regression (QQR), and Granger causality in quantiles (GCQ) approaches. The wavelet and quantile approaches used in this study will not only capture the implicit nonlinearity of the impacts but also reveal the tail dependence through advanced modeling. Thus, the CO_2 mitigation impact of green bonds can be effectively analyzed for different quantiles in different sectors. The results of the study can be utilized to develop a tiered policy framework that aligns with the SDGs, which will enable these countries to make progress toward achieving SDG 13 targets.

The rest of the paper is organized as follows: Sect. "Literature Review" presents the literature review; Sect. "Methods" reports the empirical scheme; Sect. "Results" reveals the nuances of the outcomes; and Sect. "Conclusion and Policy Implications" concludes.

Literature review

CO_2 reduction has become one of the greatest challenges to improving global environmental quality (Kartal 2022; Kou et al. 2022). The Paris Agreement calls for immediate action to decrease global temperature rise and achieve carbon neutrality (Fareed and Pata 2022). Hence, scholars have scrutinized the role of various factors that can contribute to achieving carbon neutrality. Among these factors, GF has emerged as a new instrument to stimulate progress toward the climate goals set in the famous Paris Agreement; thus, regulations on financial instruments have been gradually enacted to stimulate environmental sustainability in various countries (Tolliver et al. 2020).

To finance environmentally friendly activities, GF offers low interest rates for companies that produce fewer carbon emissions (Aizawa and Yang 2010). Thus, green financing diverts financial resources from polluting industries and firms to more technologically efficient industries and firms (Ren et al. 2020). Due to the importance of GF, some studies have assessed its pro-environmental impacts.

Studying a panel of 66 countries, Tolliver et al. (2020) revealed that green bond proceeds are invested in green energy. This implies that GF plays a positive role in energy transition, which can curb emissions. Similarly, Chang et al. (2022) used the QQR and revealed asymmetries in the influence of GF on EF in the top 10 countries in green bond investment. They found that GF enhances ecological quality in eight nations but not in the remaining two. Using a generalized least squares test for data on Chinese provinces, Zhou et al. (2020) illustrated the favorable impacts of GF. Umar and Safi (2023) investigated the Organization for Economic Co-operation and Development (OECD) countries and found that GF and environmental innovation curb emissions (adjusted emissions).

Khan et al. (2022) employed regression methods and revealed that GF impacts EF mitigation in 26 Asian countries. Focusing on a panel of 46 countries, Al Mamun et al. (2022) found that GF is negatively related to CO_2 mainly due to the favorable impacts of green bonds on energy efficiency, pollution, and waste control. In addition, countries with higher levels of innovation and well-established credit markets tend to have a stronger influence of GF on emissions reductions. Through cross-sectionally augmented autoregressive distributed lag analysis, Sharif et al. (2022) revealed that GF and green innovation limit the spread of emissions in G7 countries. Similarly, Ren et al. (2020) found a correlation between GF and a reduction in China's carbon intensity.

Wang et al. (2022) scrutinized the GF and ecological efficiency of regions using the data envelopment analysis method for China. The estimates concluded that there are some variations at the regional level. For example, GF and regional efficiency had a U-shaped relationship in western and central regions but not in eastern regions. Nevertheless, GF and eco-efficiency exhibit a U-shaped relationship at the national level. Guo et al. (2022) revealed that GF has a direct impact on carbon reduction in the Yangtze River but no spillover impact in nearby regions.

Chen and Chen (2021) focused on China to explore the GF–CO_2 emissions relationship. The spatial panel models unveiled that GF is influential in reducing CO_2 emissions and has certain spillover impacts in nearby areas, which also reduce emissions in such areas. In addition, GF encourages environmental innovation and limits financial constraints. Adebayo and Kartal (2023) also determined the reducing impact of green bonds on CO_2 emissions in the US by using the WLMC method.

Hammoudeh et al. (2020) found that green bonds do not Granger cause environmental and financial variables. However, there are causal impacts from financial variables and emission allowance prices to green bonds. Li et al. (2021) used Chinese data from 1990 to 2020 and found no causality from GF to green energy investments, but green energy investments were found to Granger cause GF. Wang et al. (2021) assessed the impacts of GF and pollution on high-quality growth in various areas around the Yangtze River. Based on the spatial Dubin model, they found considerable heterogeneity in the direct impacts of GF on development. However, the spillover impacts of GF were not found in any region.

Overall, the current literature contains several studies on GF and environmental variables. However, most of these studies focused heavily on national and regional data, and the impact of GF on sectoral emissions has been overlooked. It is impossible to achieve environmental sustainability and limit global temperature rise if countries that emit the most CO_2 do not reduce their emissions. These studies have mainly examined OECD countries as a whole, Chinese data, or leading countries in terms of green bonds. However, in examining the relationship between GF and CO_2 emissions, the studies have not simultaneously focused on high CO_2 emitting countries and sectoral differences. Therefore, this study evaluates this point as a literature gap and future research direction. Accordingly, the study investigates the relationship between GF and CO_2 emissions at the sectoral level to contribute to the literature by filling the defined gap. In doing so, the study uses the S&P Green Bond Index (GBI) and applies novel approaches, which allow researchers to account for heterogeneous and asymmetric impacts, as well as to incorporate time-, frequency-, and quantile-based varying impact of variables. Thus, this study adopts a comprehensive approach to examine the impacts of green bonds and CO_2 emissions in leading CO_2-emitting countries at the sectoral level by applying novel approaches to daily high-frequency data. By following such an approach, the study provides policy insights by considering the sectoral impacts of green bonds across different time points, frequencies, and quantiles, which will help countries become carbon neutral by curbing sectoral CO_2 emissions.

Methods

Data

This study investigates the impacts of green bonds on sectoral emissions. The study considers CO_2 emissions as an environmental indicator at the sectoral level. In this way, a high frequency (i.e., daily) dataset can be used in the empirical analysis to identify the most up-to-date developments by applying an econometric approach across various times, frequencies, and quantiles. This approach is compatible with recent literature (e.g., Kartal et al. 2024c).

The study uses daily data for both CO_2 emissions and green bonds from January 2, 2019 to December 30, 2022. Data for sectoral CO_2 emissions are obtained from Carbonmonitor (2023), and data for the S&P GBI are gathered from Bloomberg (2023). Log difference series are used for the empirical investigation (Kartal and Depren 2023). Table 1 summarizes information on the variables.

Methods

The first step is to collect data on the sectoral CO_2 emissions of the top five CO_2-emitting countries and the S&P GBI. Second, the preliminary statistics are examined. Further, the linearity properties are examined using the BDS test (Broock et al. 1996). Third, the WTC approach is applied to investigate the impact of green bonds on sectoral CO_2 emissions (Goupillaud et al. 1984). Fourth, the QQR approach is used to examine the impact of green bonds on sectoral CO_2 emissions (Sim and Zhou 2015). Fifth, the GCQ approach is used to investigate the causal impacts of green bonds on sectoral CO_2 emissions based on the quantiles of the variables (Troster 2018). Lastly, the quantile regression (QR) approach is used for a robustness test (Koenker and Bassett 1978).

Comprehensive details on the aforementioned empirical approaches can be found in the studies by Broock et al. (1996), Goupillaud et al. (1984), Sim and Zhou (2015),

Table 1 Description of the variables

Variable	Explanation	Unit	Data source
TRA	Transport sector CO_2 emissions	Tons	Carbonmonitor (2023)
IND	Industry sector CO_2 emissions	Tons	
POW	Power sector CO_2 emissions	Tons	
RES	Residential sector CO_2 emissions	Tons	
GBI	S&P green bond index	Basis Point	Bloomberg (2023)

Troster (2018), and Koenker and Bassett (1978) for the BDS test and the WTC, QQR, GCQ, and QR approaches.

WTC approach

A WTC approach is used to determine the correlation between a series and the direction of the relationship, allowing the simultaneous acquisition of the time and frequency dimensions in the series. WTC removes noise from raw data and reveal correlation and causality links by splitting different frequencies into time scales (Kassouri et al. 2022). Goupillaud et al. (1984) suggested that WTC can accurately represent the covariance between variables (Torrence and Webster 1999). The squared WTC coefficient can be calculated as follows:

$$R^2(m,n) = \frac{\left|C(f^{-1}W_{xy}(m,n))\right|^2}{C(f^{-1}|W_x(m,n)|^2)N(f^{-1}|W_y(m,n)|^2)} \tag{1}$$

where R^2 is the WTC coefficient ($0 \leq R^2(m,n) \leq 1$); m denotes the location; n represents frequency; and C is the period and the smoothing process, with values ranging from $0 \leq R^2(m,n) \leq 1$. If $R^2(m,n)$ approaches 1, it indicates the presence of a strong correlation with the area bounded by a black circle in red. Conversely, if $R^2(m,n)$ converges to 0, the blue-colored area means that there is no relationship between the series (Abban et al. 2022).

After measuring $R^2(m,n)$, the positive or negative interactions of the two-time series can be described by the WTC phase approximation specified as follows:

$$\pi_{xy}(m,n) = tan^{-1}\left(\frac{L\left\{S(f^{-1}W_{pj}(m,n))\right\}}{O\left\{S(f^{-1}W_{pj}(m,n))\right\}}\right) \tag{2}$$

where O denotes the actual part function. If the calculated value of x is 0, the straight arrow to the right indicates a positive relationship between the variables, whereas a straight arrow to the left indicates a negative relationship. If the arrow points to the upper right, there is a positive relationship between the two variables and X causes Y.

QQR approach

This study applies the QQR approach of Sim and Zhou (2015). The QQR approach is an extension of the traditional QR approach. Koenker and Bassett (1978) developed the QR approach by converting linear regression analysis into a median-based estimator. The QR approach captures the time-varying levels of the dependent variable for different quantiles, and compared with linear regression, quantile functions more accurately depict the impacts of independent variables (Koenker and Bassett 1978). The QR approach can provide information that goes beyond the median by recovering information in the upper and lower tails. Unlike a standard regression, the QR approach accounts for the impact of a variable on another through the different quantiles. However, the QR approach is incomplete because it cannot fully capture the influences of the independent variable (Gupta et al. 2018).

The QQR approach makes it possible to measure the quantile impact of a single independent variable on the different quantiles of another dependent variable. Thus, the

QQR approach tests the impacts of the 0.05 quantile of the GBI on 19 different CO_2 quantiles ranging from 0.05 to 0.95. These procedures are repeated individually for all quantiles of the GBI from 0.5 to 0.95. The QQR approach is defined as a combination of QR and nonparametric estimation. Through this combination, the QQR approach allows for a deeper and more detailed examination of the relationships between variables. A QQR approach used to test the impact of green bonds on sectoral CO_2 emissions can be expressed as follows:

$$CO_{2_t} = \beta^{\sigma}(\mathrm{GBI}_t) + \mu_t^{\sigma} \tag{3}$$

where CO_2 includes sectoral CO_2 emissions in t period; *GBI* is the GBI; σ denotes σ^{th} quantile; μ_t^{σ} is the quantile residual term; and β^{σ} indicates an undefined function. For the sectoral calculations, the QQR approach is applied, replacing the CO_2 series with TRA, IND, POW, and RES.

GCQ approach

For quantile causality analysis, the following equation illustrates the null of no causality from X to Y within τ-quantile:

$$H_0^{X \nrightarrow Y} : Q_\tau^{Y,X}\left(Y_t, I_t^Y, I_t^X\right) = Q_\tau^Y\left(Y_t, I_t^Y\right), \forall \tau \epsilon \partial 0 < \tau < 1 \tag{4}$$

where $Q_\tau^{Y,X}\left(Y_t, I_t^Y, I_t^X\right)$ is the τ-quantile of $F_y\left(.\backslash I_t^Y, I_t^X\right)$, which defines a conditional distribution function of Y_t. In addition, $\left(I_t^Y, I_t^X\right) \in R^d$ denotes the explanatory vector; ∀ means "for all"; and ∂ represents a compact set.

The null and alternative hypotheses can be modified to define $Q_\tau^{Y,X}\left(Y_t I_t^Y\right)$ with a parametric quantile model $(m(I_t^Y, \theta_0(\tau))$ as follows:

$$H_0^{X \nrightarrow Y} : E\left\{1\left[Y_t \leq m\left(I_t^Y, \theta_0(\tau)\right)\right] | I_t^Y, I_t^X\right\} = \tau \quad \textit{for all } \tau \epsilon T \tag{5}$$

$$H_{alternative}^{X \nrightarrow Y} : E\left\{1\left[Y_t \leq m\left(I_t^Y, \theta_0(\tau)\right)\right] | I_t^Y, I_t^X\right\} \neq \tau \quad \textit{for some } \tau \epsilon T \tag{6}$$

The ST statistic recommended by Troster (2018) can be employed to investigate the null of no causality as follows:

$$S_T = \frac{1}{Tn} \sum_{j=1}^{n} \left| \varphi_j' W_{\varphi j} \right| \tag{7}$$

where T is the time; n is the number of observations; W illustrates the TxT matrix; and $\varphi_{j'}$ represents the j-th column of the Txn matrix with the elements $\varphi_{j'} = \psi_{\tau j}\left(Y_i - m\left(\partial_{i-1}^Y, \theta_T\left(\tau_j\right)\right)\right)$. If the measured S_t statistic is higher than the critical values provided by Troster (2018), it implies that there is a causality running from X to Y in a certain quantile.

Results

Preliminary statistics

Table 2 presents the descriptive statistics of the variables. As presented, China has the highest sectoral emissions. The standard deviation is also quite high for green bonds,

Table 2 Descriptive statistics

Country	Variable	Mean	Median	Max	Min	SD	Skewness	Kurtosis	JB	JB Prob
China	TRA	2.43	2.52	2.67	0.80	0.25	− 3.91	20.78	16,383.85	0.0000
	IND	11.60	11.82	15.18	6.19	1.50	-1.28	5.39	530.75	0.0000
	POW	13.34	13.10	19.09	8.80	2.08	0.50	2.82	44.00	0.0000
	RES	2.21	1.83	5.05	1.32	0.94	0.79	2.21	135.45	0.0000
USA	TRA	4.36	4.41	5.65	1.68	0.41	− 1.31	7.43	1,150.18	0.0000
	IND	2.74	2.73	3.56	2.12	0.22	0.29	3.51	25.88	0.0000
	POW	4.36	4.18	6.65	2.56	0.86	0.39	2.24	51.20	0.0000
	RES	1.58	1.29	4.67	0.59	0.92	0.77	2.48	114.92	0.0000
India	TRA	0.78	0.82	0.87	0.13	0.13	− 3.06	11.86	5,032.60	0.0000
	IND	2.02	2.08	2.49	0.63	0.29	− 2.65	12.16	4,861.01	0.0000
	POW	3.45	3.44	4.44	2.31	0.43	− 0.03	2.69	4.43	0.1092
	RES	0.53	0.32	3.26	0.26	0.48	2.32	7.99	2,017.38	0.0000
Russia	TRA	0.67	0.68	0.70	0.33	0.05	− 3.59	17.91	11,886.99	0.0000
	IND	0.81	0.81	1.17	0.57	0.10	0.53	3.64	65.89	0.0000
	POW	2.86	2.81	4.54	1.57	0.66	0.24	2.49	21.36	0.0000
	RES	0.48	0.45	1.23	0.10	0.29	0.29	1.81	76.29	0.0000
Japan	TRA	0.49	0.49	0.53	0.20	0.03	− 4.72	37.17	54,549.56	0.0000
	IND	0.73	0.73	0.98	0.41	0.09	− 0.35	3.88	55.25	0.0000
	POW	1.46	1.43	2.22	0.72	0.25	0.13	2.72	6.12	0.0469
	RES	0.30	0.22	0.80	0.11	0.19	0.63	1.96	116.62	0.0000
	GBI	141.68	142.08	158.99	109.80	11.88	− 0.77	2.90	103.56	0.0000

Min, Minimum; Max, Maximum; SD, Standard Deviation; JB, Jarque–Bera

while the sectoral CO_2 emissions have a relatively low standard deviation. All variables except for energy sector CO_2 emissions in India have a non-normal distribution.

Table 3 reports the linearity test results for the variables. As reported, except for industrial CO_2 emissions in Russia, all variables have a nonlinear structure.

Overall, the variables have a non-normal and nonlinear properties. Therefore, nonlinear approaches are the best econometric approach when these properties of the variables are considered.

WTC results

After reviewing the descriptive statistics of the dataset, the WTC approach is first implemented to examine the time and frequency impacts of green bonds on sectoral CO_2 emissions. This allows the changes in the impact of green bonds on CO_2 over different periods and frequencies to be examined in detail.

In the WTC graphs, the influence area is depicted as a black cone, where a much darker color presents a higher degree of dependence; short term ranges from 0 to 8; medium term is from 9 to 32; long term is from 33 to 128 scale; very long term is from 129 to 256; low frequency ranges from 0 to 0.4; medium frequency is from 0.4 to 0.6; and high frequency is from 0.6 to 1.0. In the WTC graphs, a positive correlation between variables is depicted by right arrows, and a negative correlation is depicted by left arrows. The causation of the first variable to the second is depicted by right-down and left-up arrows. The causation of the second variable to the first variable is depicted by right-up and left-down arrows. In all WTC graphs, the horizontal and vertical axes denote

Table 3 Linearity test results

Country	Variable	Dimensions				Decision
		2	3	4	5	
China	TRA	0.0000	0.0000	0.0000	0.0000	Nonlinear
	IND	0.0000	0.0000	0.0001	0.0001	Nonlinear
	POW	0.0000	0.0000	0.0000	0.0000	Nonlinear
	RES	0.0000	0.0000	0.0000	0.0000	Nonlinear
USA	TRA	0.0000	0.0000	0.0000	0.0000	Nonlinear
	IND	0.0000	0.0000	0.0000	0.0000	Nonlinear
	POW	0.0005	0.0017	0.0055	0.0019	Nonlinear
	RES	0.0000	0.0000	0.0000	0.0000	Nonlinear
India	TRA	0.0000	0.0000	0.0000	0.0000	Nonlinear
	IND	0.0000	0.0000	0.0000	0.0000	Nonlinear
	POW	0.0000	0.0000	0.0000	0.0000	Nonlinear
	RES	0.0000	0.0000	0.0000	0.0000	Nonlinear
Russia	TRA	0.0000	0.0000	0.0000	0.0000	Nonlinear
	IND	0.9148	0.8900	0.8736	0.8490	Linear
	POW	0.0000	0.0000	0.0000	0.0000	Nonlinear
	RES	0.0000	0.0000	0.0000	0.0000	Nonlinear
Japan	TRA	0.0000	0.0000	0.0000	0.0000	Nonlinear
	IND	0.0080	0.0036	0.0037	0.0069	Nonlinear
	POW	0.0000	0.0000	0.0000	0.0000	Nonlinear
	RES	0.0000	0.0000	0.0000	0.0000	Nonlinear
	GBI	0.0000	0.0000	0.0000	0.0000	Nonlinear

Values indicate *p*-values

times and frequencies, respectively, and the first and second variables denote sectoral CO_2 emissions and an index of green bonds, respectively. Figure 2 presents the impact of green bonds on CO_2 emissions from the transport sector.

In China, green bonds reduced transportation CO_2 emissions at medium and high frequencies from 2019/1 to 2020/12. In the US, green bonds had an increasing impact on transportation CO_2 emissions at medium frequencies from 2019/9 to 2020/5. In India, increasing transportation CO_2 emissions Granger caused green bonds at high frequencies. Green bonds also had an increasing impact on transportation CO_2 emissions at medium frequencies, while they had a decreasing impact around 2021/8 in India. In Russia, green bonds mitigated transportation CO_2 at medium and higher frequencies from 2019/9 to 2020/5. In Japan, green bonds had a decreasing impact on transportation CO_2 emissions at medium frequencies around 2021/8. The WTC results revealed that green bonds had a decreasing impact on transportation CO_2 emissions in China, the US, and Japan, while they had an increasing impact in India and Russia. Figure 3 illustrates the influence of green bonds on industrial CO_2 emissions.

Green bonds had a stimulative impact on industrial CO_2 at high frequencies in China from 2019/1 to 2021/8. In the US, green bonds had an accelerating impact on industrial CO_2 from 2019/9 to 2020/5. However, from 2022/4 to 2022/12, green bonds had a declining impact on industrial CO_2 emissions at low and medium frequencies. In India, a positive relationship was found between green bonds and industrial CO_2 emissions from 2019/1 to 2020/5, while there was a negative relationship around 2021/10, 2021/12,

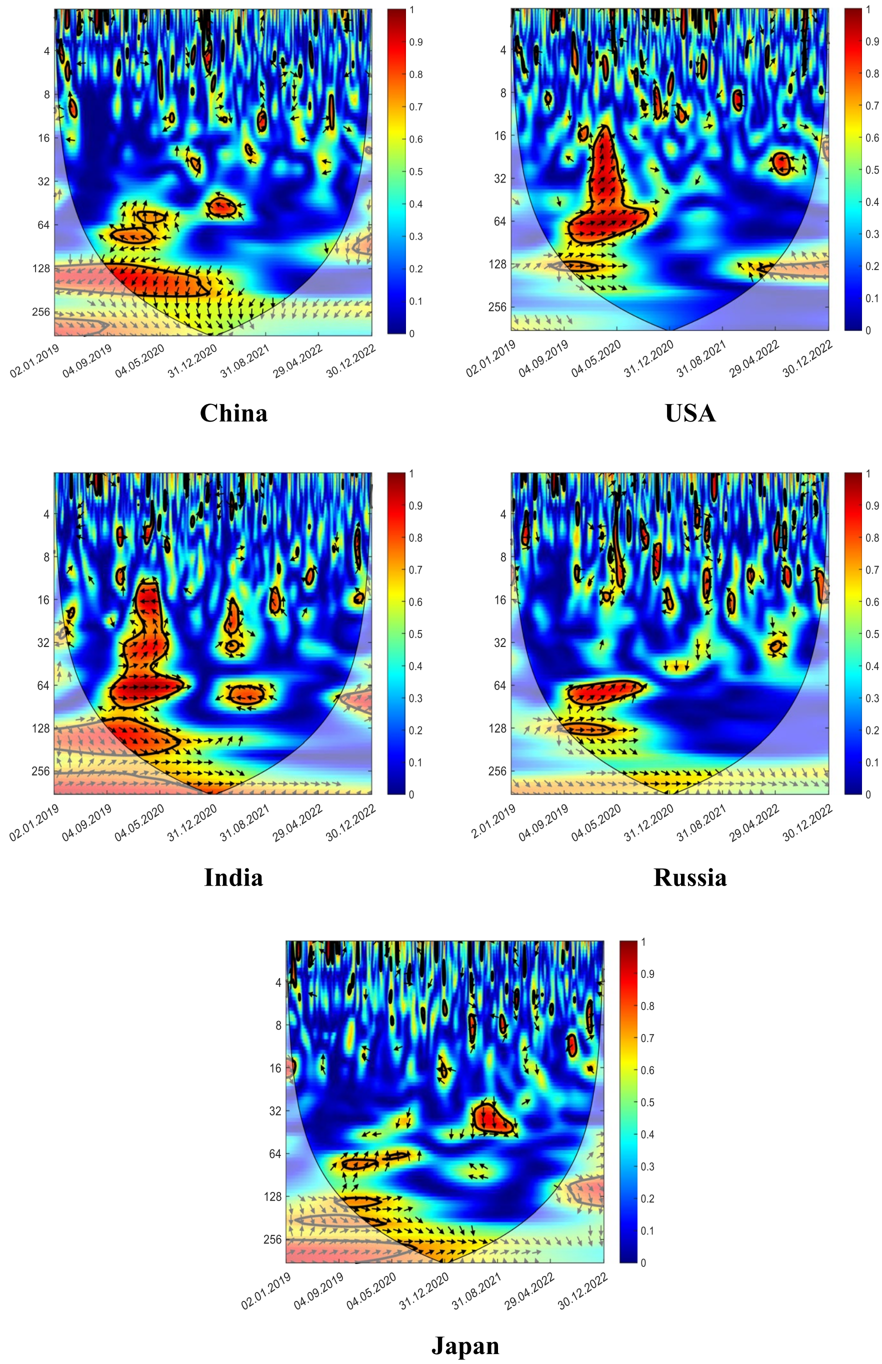

Fig. 2 WTC Results for GBI impact on transport sector CO_2 emissions

and 2022/12. In the case of Russia, there was almost no significant relationship between green bonds and industrial CO_2 emissions. In Japan, green bonds also had no impact on industrial CO_2 emissions. In summary, green bonds had a declining impact on industrial CO_2 emissions in the US and India at certain periods and frequencies, while they had a stimulating impact in China and no impact in Russia and Japan. Figure 4 displays the impact of green bonds on power sector CO_2 emissions.

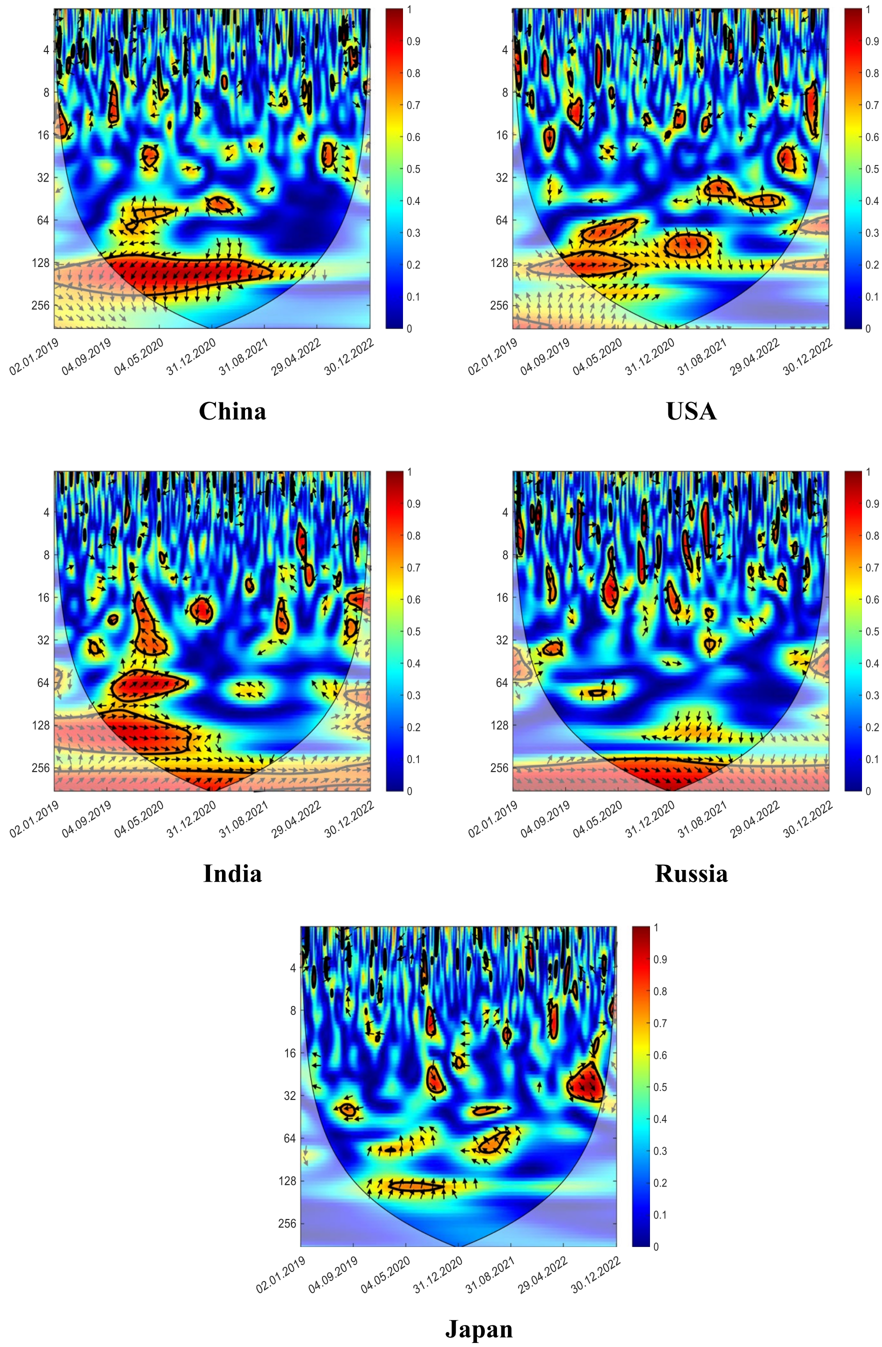

Fig. 3 WTC Results for GBI impact on industry sector CO_2 emissions

In China, at higher frequencies, green bonds were positively related to power sector CO_2 emissions from 2019/1 to 2022/12, while at low frequencies, there was a negative relationship from 2020/2 to 2022/1. The condition at high frequencies was also similar in the US and Japan. In India, there was a negative relationship between green bonds and the power sector's CO_2 emissions at low and middle frequencies around 2020/5, 2020/12, 2022/1, and 2022/12. The condition at middle frequencies was similar in Russia.

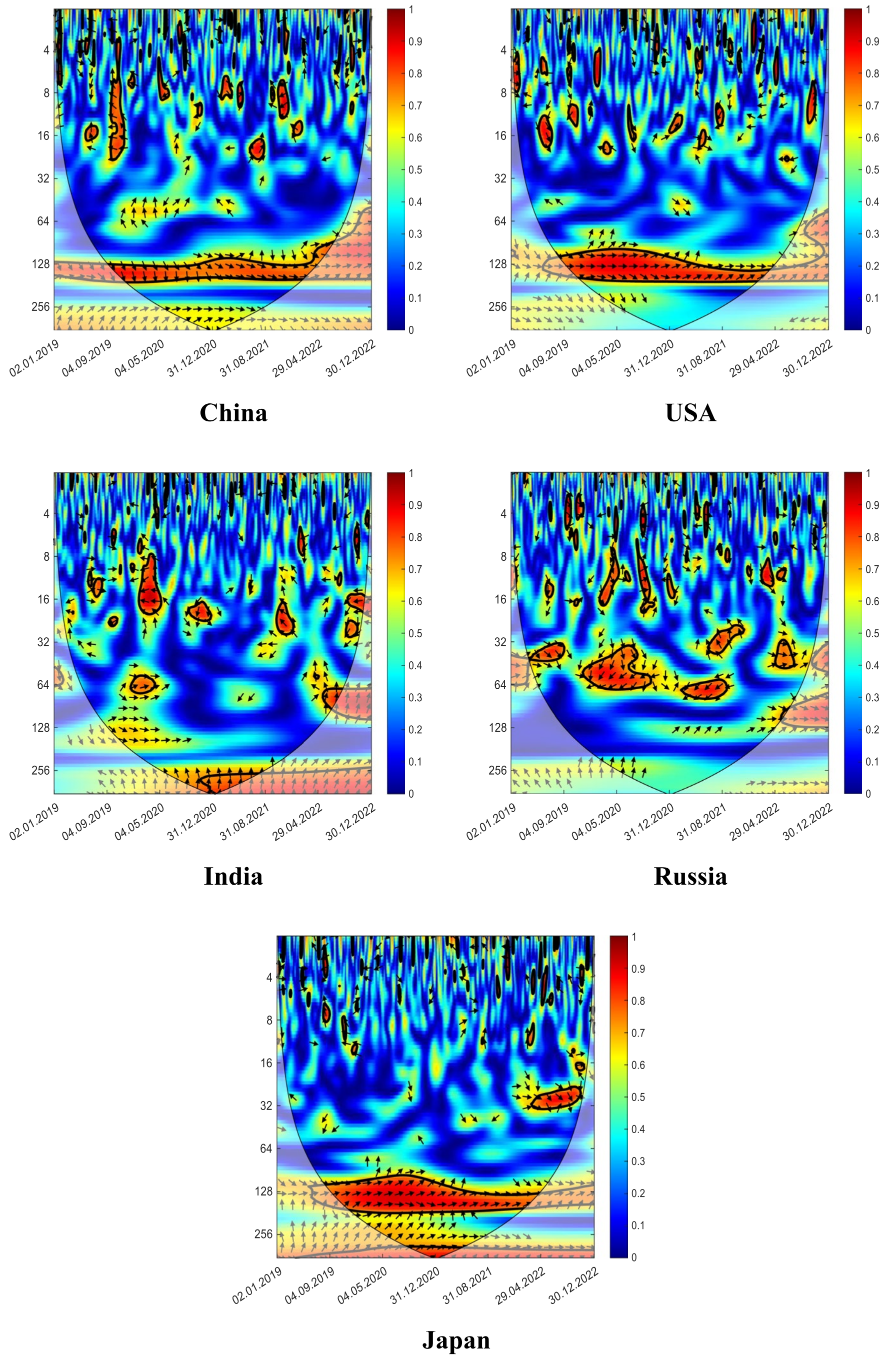

Fig. 4 WTC Results for power sector CO_2 Emissions

The WTC results imply that green bonds did not contribute to the reduction of power sector CO_2 emissions in all countries. Finally, Fig. 5 depicts the impact of green bonds on residential sector CO_2 emissions.

Green bonds have a significant impact on residential CO_2 emissions. In particular, residential CO_2 emissions positively lead to green bonds in China. The case of India is also similar to China. Green bonds have a reducing impact on residential CO_2

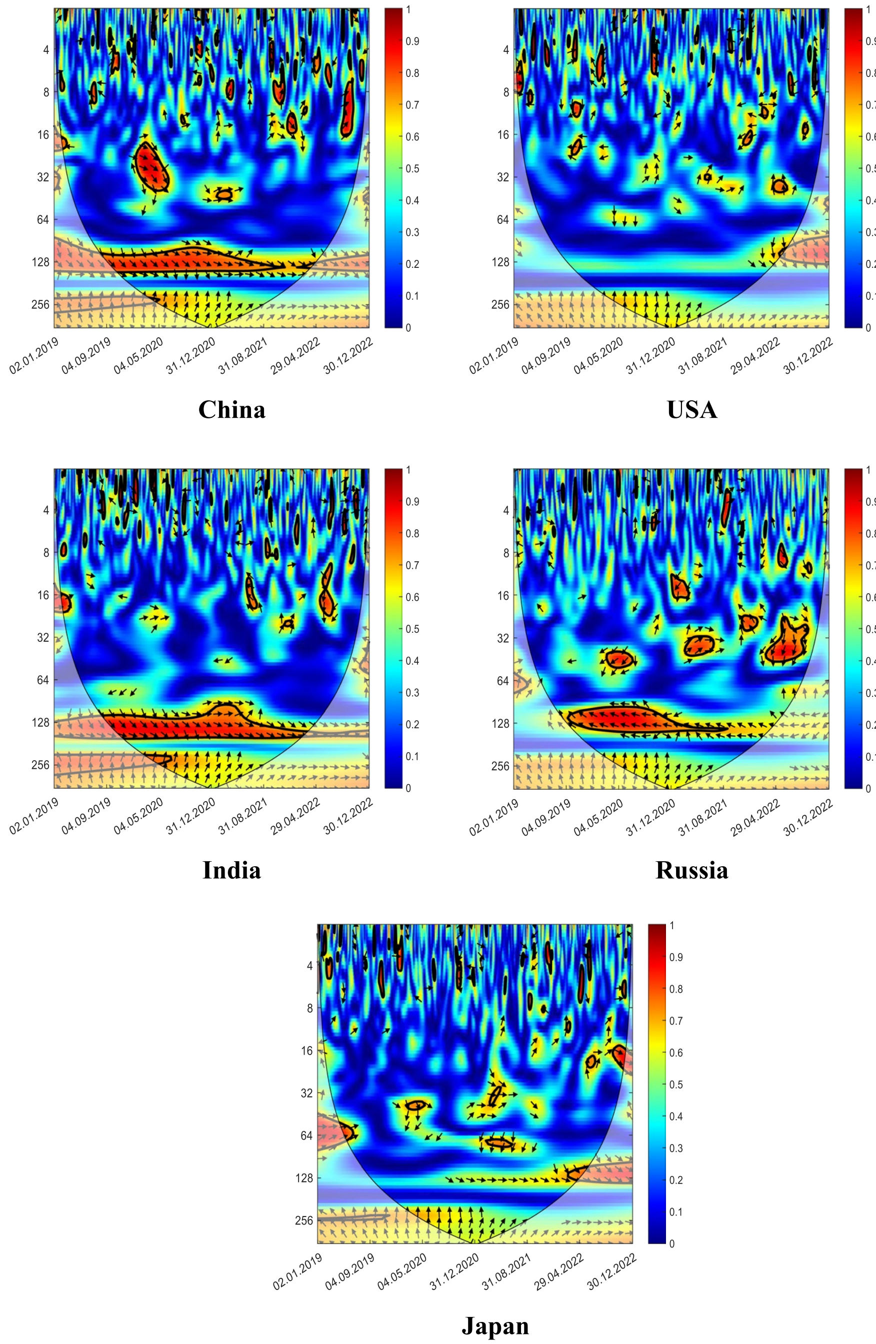

Fig. 5 WTC Results for GBI impact on residential sector CO_2 emissions

emissions at different time points with low and medium frequencies in the US. This condition also holds for Russia around 2022/7 at medium frequencies and 2019/9–2021/8 at high frequencies. In Japan, green bonds have a declining impact on residential CO_2 emissions at low frequencies at different points in time. The WTC results imply that green bonds contribute well to limiting residential CO_2 emissions in the US, Russia, and Japan.

QQR results

Following the time- and frequency-based impact of green bonds on sectoral CO_2 emissions using the WTC approach, the QQR approach is used to examine the impacts of green bonds on sectoral CO_2 emissions at various quantiles. In the QQR graphs, the x-axis denotes the independent variable (i.e., GBI) and the y-axis denotes the dependent variables (i.e., sectoral CO_2 emissions). Each QQR graph depicts the impact of the independent variable on the dependent variables at each quantile for both variables. Figure 6 depicts the effect of green bonds on transportation sector CO_2 emissions.

Regarding transportation CO_2 emissions, in China, green bonds have a decreasing impact at higher quantiles (i.e., levels). Green bonds also have a dampening impact in the US and Japan. Although green bonds are making progress, they have a stimulative impact in both India and Russia. In summary, green bonds' role in reducing transportation CO_2 emissions is beneficial to China, the US, and Japan, with the strongest restraining impact in the US, followed by Japan and China. The influence of green bonds on industrial CO_2 is depicted in Fig. 7.

Regarding industrial CO_2 emissions, green bonds have an increasing impact in China, Russia, and Japan, while they have almost no impact in India. In the US, green bonds have a reducing impact at higher levels. Green bonds are beneficial for the US in limiting industrial CO_2 emissions. The impact of green bonds on power sector CO_2 emissions is depicted in Fig. 8.

Unlike other sectoral CO_2 emissions, green bonds have an increasing impact on power sector CO_2 emissions in all countries. Therefore, green bonds do not have a significant impact on limiting CO_2 emissions in the power sector. The impact of green bonds on residential CO_2 emissions is depicted in Fig. 9.

Regarding residential CO_2 emissions, in China and India, green bonds have an increasing impact at higher quantiles (i.e., levels). However, green bonds have a negative impact on residential CO_2 emissions in the US, Russia, and Japan. Thus, green bonds are helpful for the US, Russia, and Japan, and they have the highest decreasing impact on residential CO_2 emissions in the US, followed by Russia and Japan.

GCQ results

After analyzing the impact of green bonds on sectoral CO_2 emissions, the GCQ approach is performed to examine whether the impacts are at the causality level. In the GCQ results, the causality impacts are investigated at each quantile of the variables. The results of the causal impact of green bonds on sectoral CO_2 emissions are presented in Table 4.

Green bonds cause transportation CO_2 in all countries at all quantiles, except at some low quantiles (0.05) in Japan and middle quantiles (0.50–0.55) in China, the US, and India. Green bonds cause industrial CO_2 emissions in all countries at all quantiles, except for some lower quantiles (0.05) in India and Japan, middle quantiles (0.45–0.60) in all countries, and higher quantiles (0.95) in the US. In addition, green bonds cause power sector CO_2 emissions in all countries at all quantiles except for some lower quantiles (0.05) in China and the US; middle quantiles (0.40–0.70) in the US, India, Russia, and Japan; and higher quantiles (0.90–0.95) in the US and Japan.

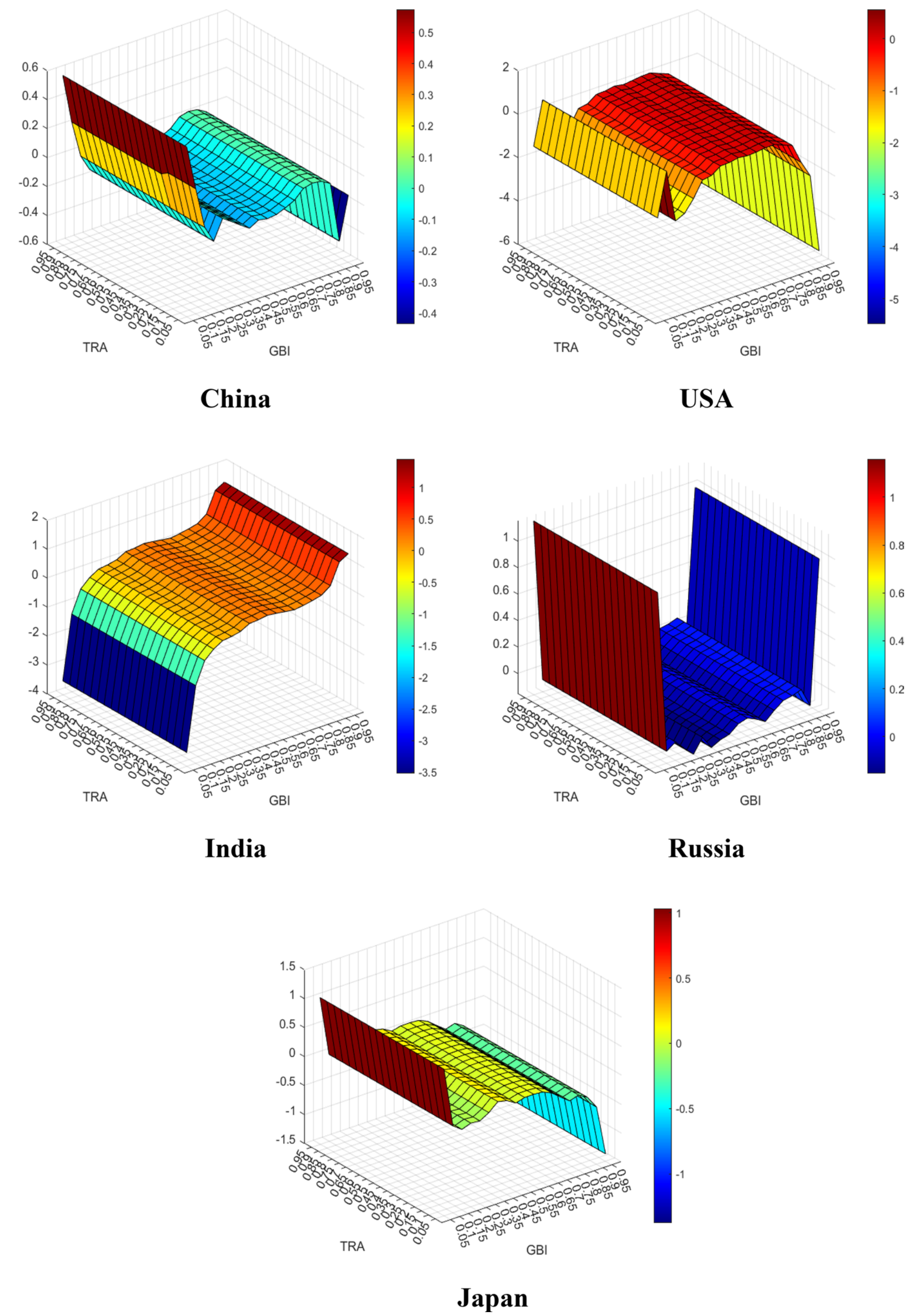

Fig. 6 QQR Results for GBI impact on transport sector CO_2 emissions

Green bonds also have a significant impact at the causal level on residential sector CO_2 emissions in all countries at all quantiles, except some low quantiles (0.05) in the US, India, and Japan; middle quantiles (0.45–0.50) in all countries; and higher quantiles (0.95) in China, US, Russia, and Japan. Overall, green bonds have a significant and causal impact on sectoral CO_2 emissions, with results varying by sector, country, and quantile.

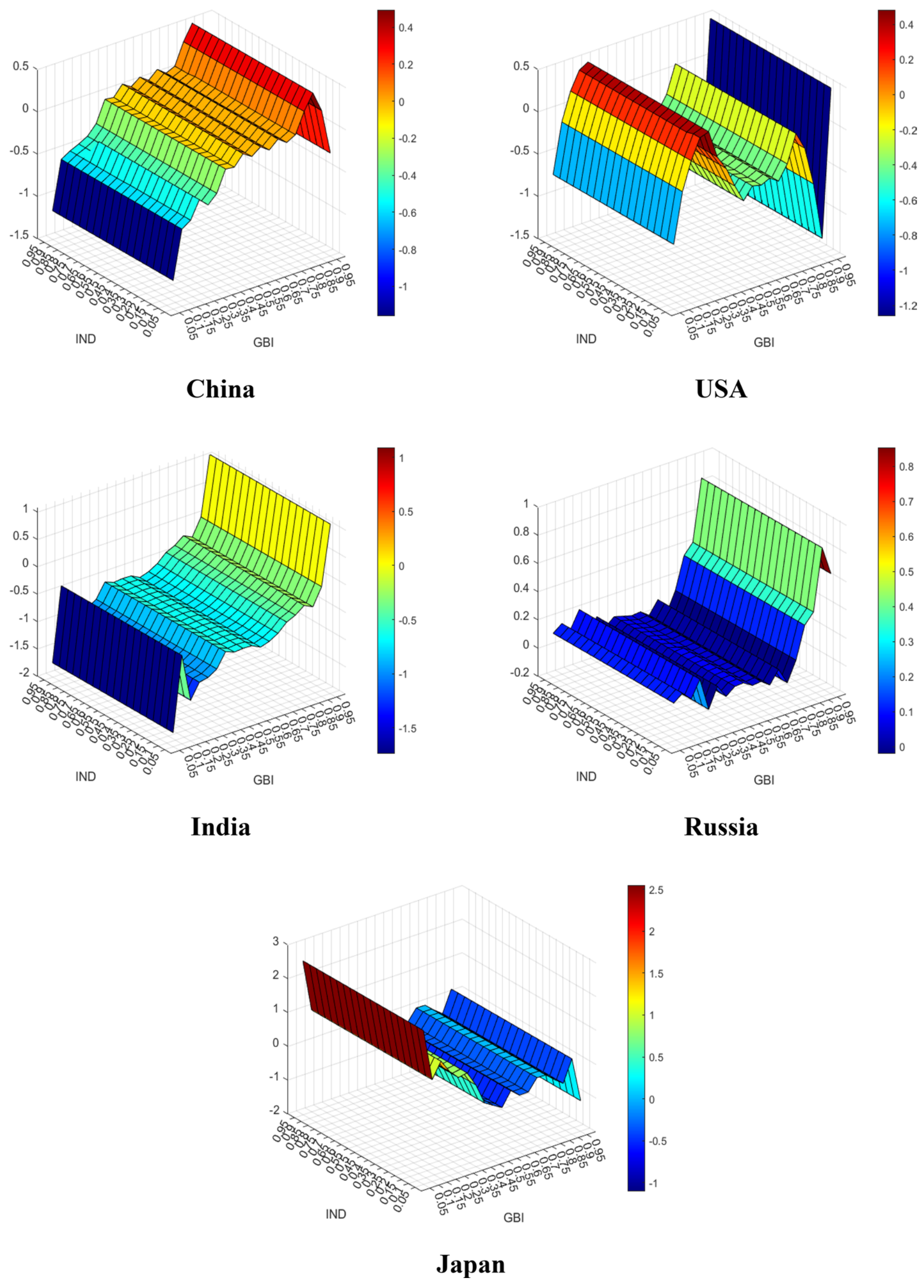

Fig. 7 QQR Results for GBI impact on industry sector CO_2 emissions

Robustness check

The QR approach is performed to control the robustness of the QQR results. The detailed comparison of these approaches is depicted in Figs. 10, 11, 12 and 13.

Therein, the x-axis denotes the quantiles, and the y-axis denotes the power of the impact of the independent variable (i.e., GBI) on the dependent variables (i.e., sectoral CO_2 emissions) for both the QQR and QR approaches. A summary of the robustness check results is also presented in Table 5.

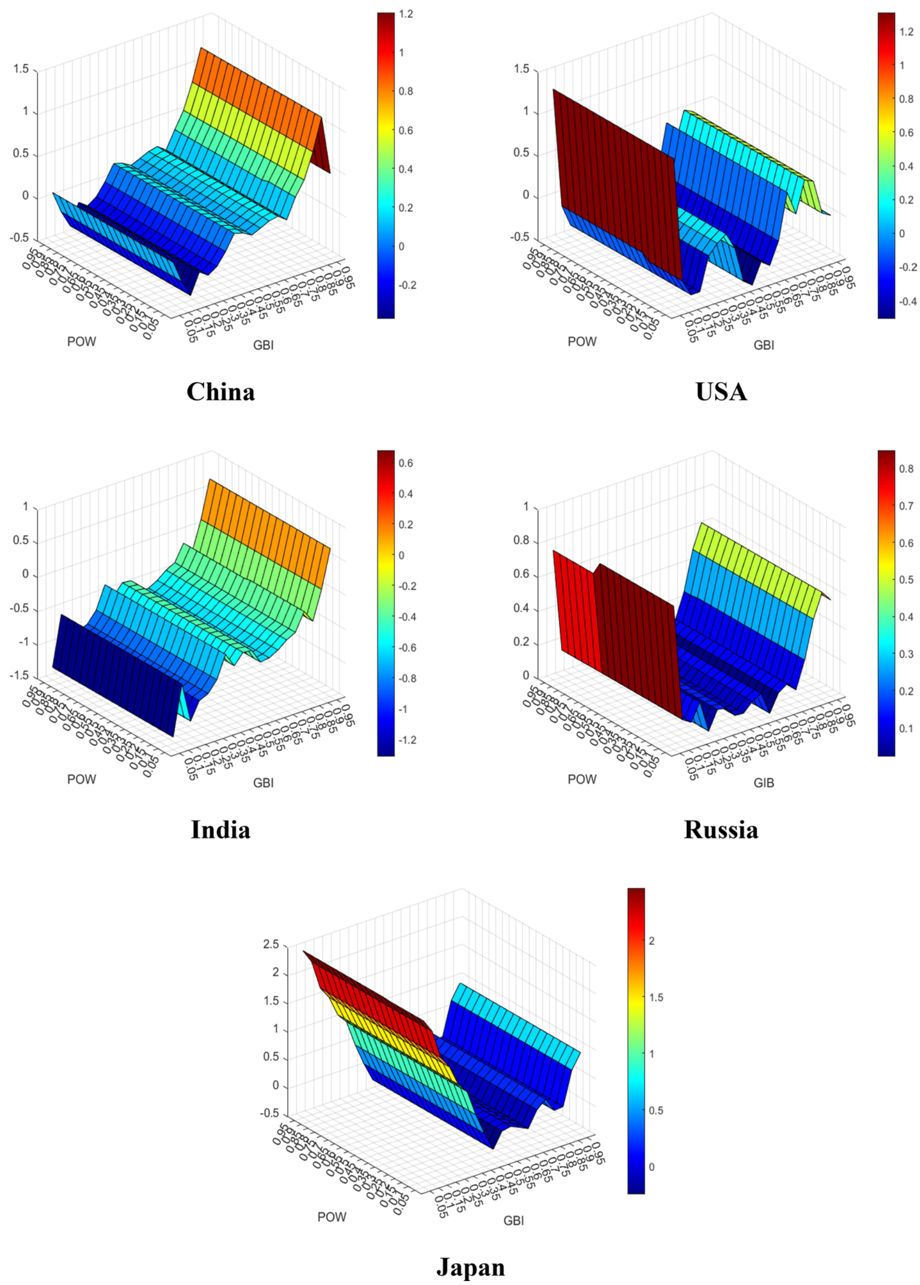

Fig. 8 QQR Results for GBI impact on power sector CO_2 emissions

The QQR results are almost identical to the QR approach, implying consistency and confirming the robustness of the empirical results.

Conclusion and policy implications

Compatible with the increasing impacts of climate change on all countries and societies, the importance of GF has been increasing. Hence, this study investigated the impact of GF, specifically green bonds, on the sectoral CO_2 emissions of the top five global

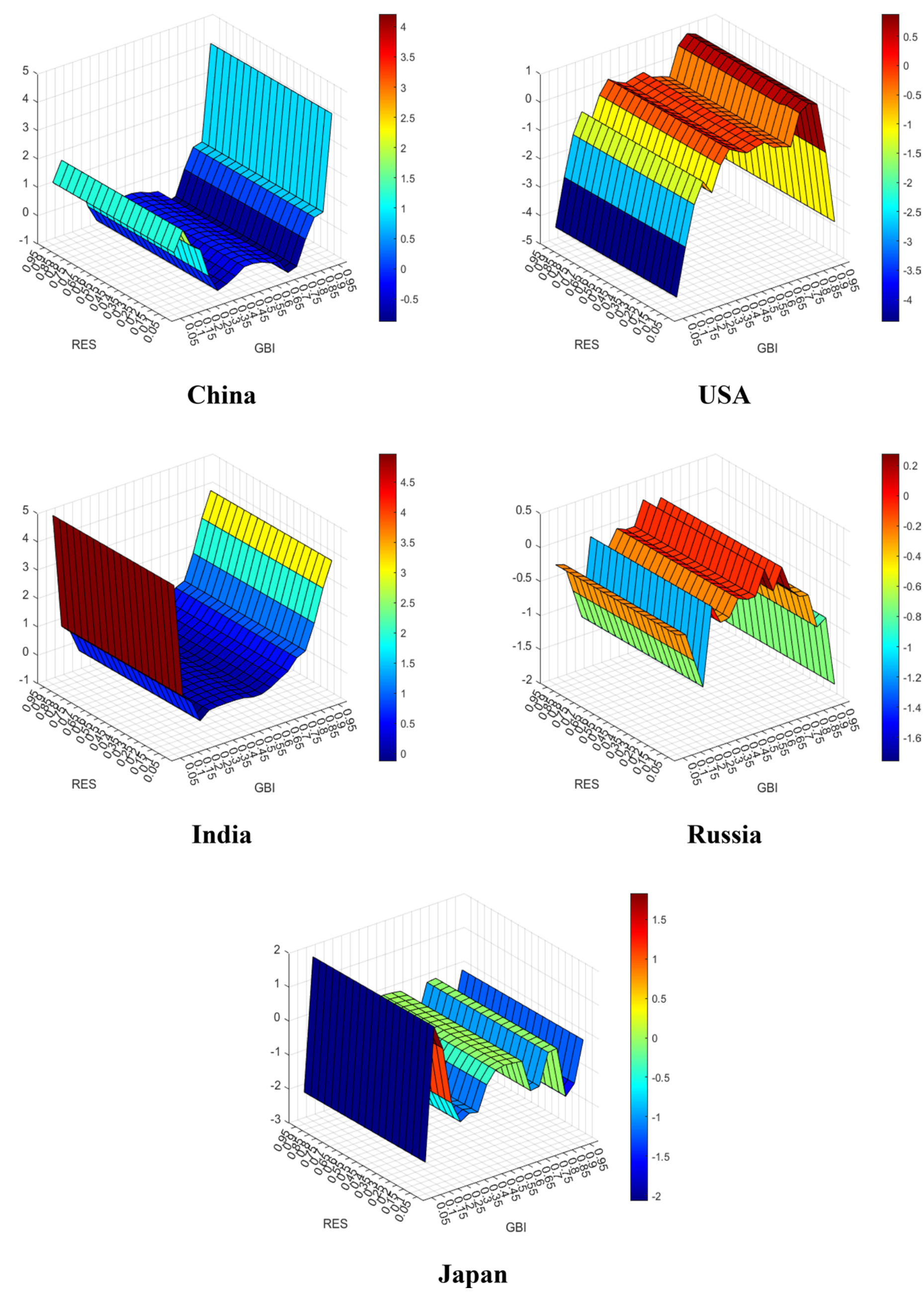

Fig. 9 QQR Results for GBI impact on residential sector CO_2 emissions

emitters. The study employed daily data from January 2, 2019 through December 30, 2022 and performed WTC, QQR, and GCQ approaches.

The study demonstrated that there is a strong relationship between green bonds and sectoral CO_2 emissions across time and frequencies. Further, green bonds decrease CO_2 emissions from the transport sector in China, the US, and Japan, whereas it has the opposite effect in India and Russia. Moreover, green bonds reduce CO_2 emissions from the industrial sector only in the US. Moreover, at lower quantiles, green bonds decrease CO_2 emissions from the energy sector in India, China, and the US, whereas the

Table 4 GCQ results

Country	Path	Quantiles																		
		0.05	**0.10**	**0.15**	**0.20**	**0.25**	**0.30**	**0.35**	**0.40**	**0.45**	**0.50**	**0.55**	**0.60**	**0.65**	**0.70**	**0.75**	**0.80**	**0.85**	**0.90**	**0.95**
China	GBI⇒TRA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.21	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.12
	GBI⇒IND	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.25	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	GBI⇒POW	0.65	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	GBI⇒RES	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.37	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.34
USA	GBI⇒TRA	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	GBI⇒IND	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.13	1.00	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.15
	GBI⇒POW	0.74	0.00	0.00	0.02	0.00	0.00	0.01	0.12	0.77	0.31	0.01	0.00	0.00	0.00	0.00	0.00	0.02	0.15	0.29
	GBI⇒RES	0.36	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.90	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.32
India	GBI⇒TRA	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	GBI⇒IND	0.22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.81	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	GBI⇒POW	0.76	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.20	0.43	0.03	0.00	0.00	0.00	0.00	0.00	0.00
	GBI⇒RES	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.66	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
Russia	GBI⇒TRA	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	GBI⇒IND	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.78	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	GBI⇒POW	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.21	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	GBI⇒RES	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.11	0.86	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.08
Japan	GBI⇒TRA	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	GBI⇒IND	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.77	0.08	0.05	0.04	0.00	0.00	0.00	0.00	0.05
	GBI⇒POW	0.26	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.06	0.72	0.20	0.22	0.01	0.00	0.00	0.00	0.27
	GBI⇒RES	0.73	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.29

Numbers represent *p*-values

Fig. 10 QQR and QR comparison for GBI impact on transport sector CO_2 emissions

impact increases at higher quantiles. Furthermore, green bonds reduce CO_2 emissions from the residential sector in the US, Russia, and Japan. Overall, the empirical results demonstrated that GF has multifaceted impacts on sectoral CO_2 emissions in different countries. The results of the study are utilized below to develop a policy framework that optimizes and streamlines the role of GF in carbon neutrality.

Policy framework

Influential development of a policy framework requires a phased approach to development so that subsequent phases can build on the outcomes of the previous phase. Economic growth in the selected countries is largely shaped by the structure of industrial production. Reducing industrial CO_2 emissions requires a transformation of the

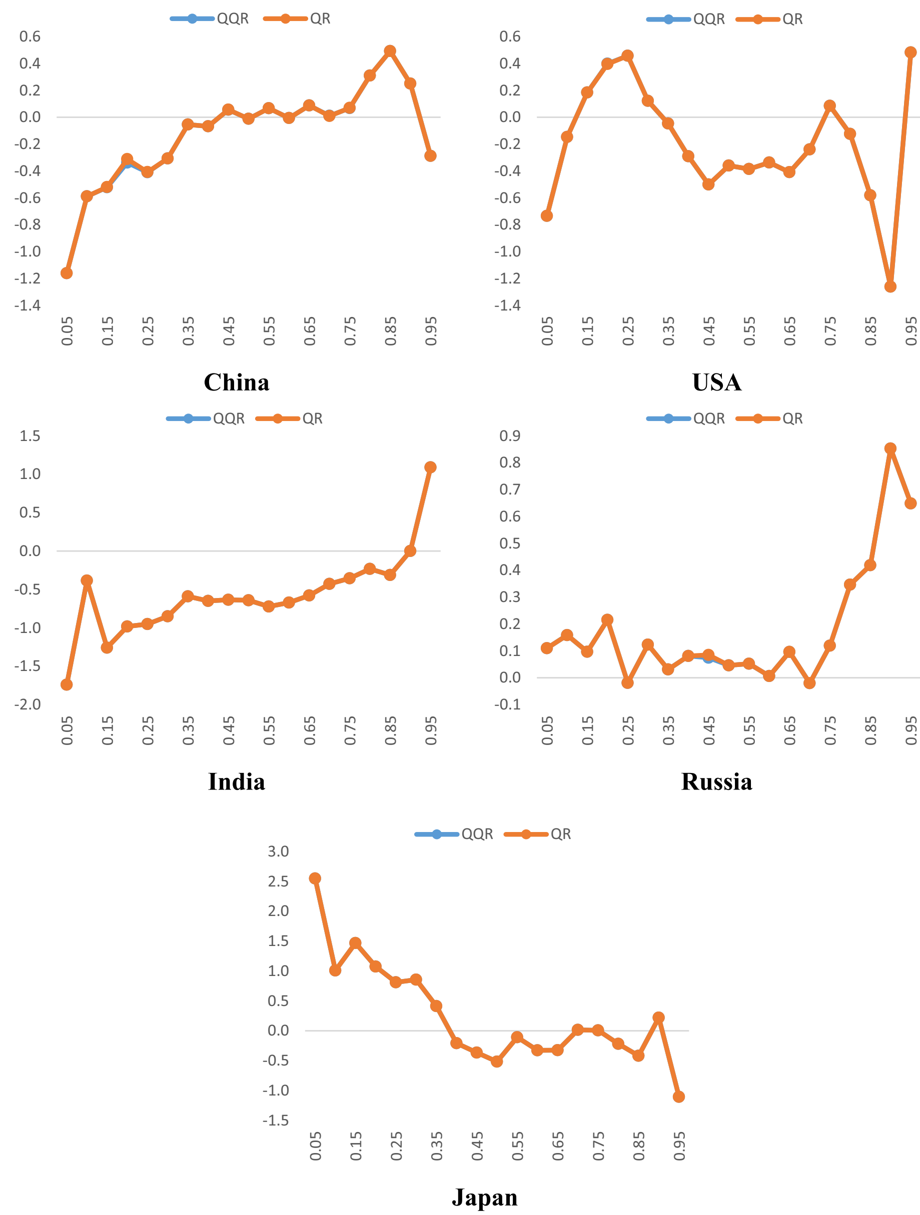

Fig. 11 QQR and QR comparison for GBI impact on industry sector CO_2 emissions

industrial production process. GF can support this transformation. The major source of CO_2 emissions in the industrial sector is fossil fuel-based production technologies. The gradual replacement of these technologies will impact energy consumption and subsequent energy production patterns.

Technological shift in the production process can be initiated by transforming the financing channels. Financial institutions should play the role of a catalyst in this transformation by introducing the mechanism of the Pigouvian tax on the carbon footprint of companies. The interest rate on financing channels, including loans and advances requested by companies should be linked to their carbon footprint (i.e., companies with higher carbon footprints should bear higher financing costs). Increasing operating costs

Fig. 12 QQR and QR comparison for GBI impact on power sector CO_2 emissions

and decreasing price competitiveness will force companies to move away from dirtier technologies to cleaner technologies.

Companies may also face higher financing costs (i.e., interest rates) on working capital loans for environmentally damaging projects. The rising cost burden will push companies to refrain from causing negative environmental externalities through their operations and may gradually increase the scope for cleaner technologies and projects. In addition to increasing cost burdens, financial institutions should support these companies in issuing green bonds to embrace environmentally friendly operational changes. As these bonds are issued by companies to promote environmental protection, they provide benefits in the form of tax rebates that reduce operating costs.

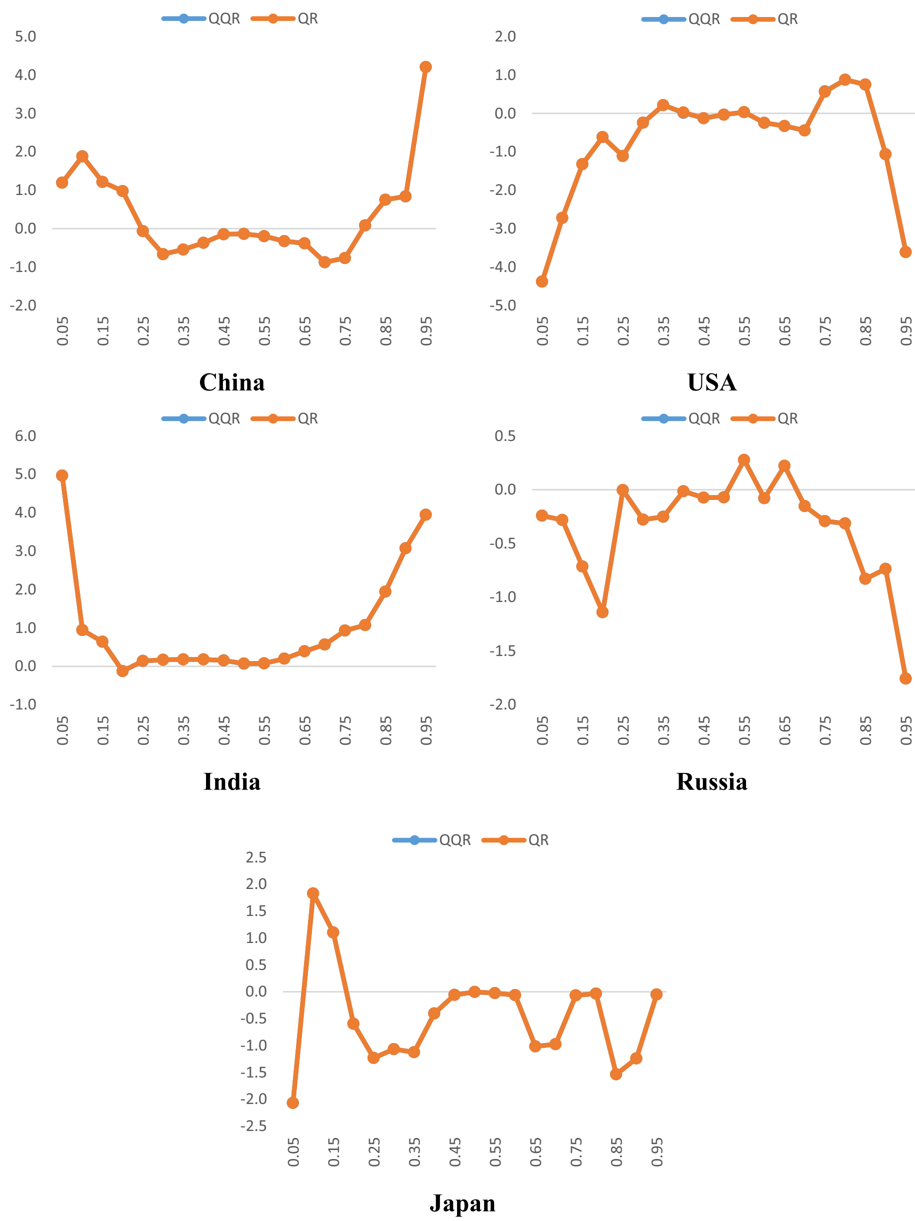

Fig. 13 QQR and QR comparison for GBI impact on residential sector CO_2 emissions

Table 5 Comparison summary of QQR and QR results

Country	TRA & GBI	IND & GBI	POW & GBI	RES & GBI
China	99.96	99.98	99.99	99.99
USA	99.99	99.99	99.99	99.99
India	99.99	99.99	99.99	99.99
Russia	99.99	99.99	99.97	99.99
Japan	99.99	99.99	99.99	99.99

Before the initiation of the second stage of the policy context, the domestic market will gradually be characterized by the rising demand for cleaner energy solutions. This will lead financial institutions to demand higher interest rates on loans and credits from producers of fossil fuel-based energy solutions. It will become more expensive for companies to maintain their operations, and the rise in operating costs will gradually be reflected in energy prices. This will augment the demand for clean energy solutions due to the substitution impact. Transformations in energy generation patterns can have a waterfall impact on the transportation sector as fossil fuel-based energy solutions become more expensive and their supply shrinks. As operating costs rise due to increases in fuel prices, transportation companies will need to invest in vehicles that run on clean energy. These companies can issue green bonds to invest in new vehicles while applying for loans and advances at lower interest rates tied to carbon footprints.

Households may not benefit directly from green bonds in terms of their green purchasing or consumption behavior. They will certainly have benefits in the form of tax advantages for their green bond investments, but the environmental impacts of their behavior may be marginal or insignificant. Industrial sector products may be affordable to high-income or upper-middle-income households, but the issue is whether they will be affordable to lower-middle and lower-income households. As the latter make up a large portion of consumers, the role of public sector companies is critical. Public sector companies can introduce low-cost green products for these households, and special low-cost green bonds can be issued to finance these projects.

Following the principle of circular income distribution in a two-sector model, consumers from two income segments will finance the production of these products, receive tax benefits, and use them themselves. This will help reduce household CO_2 emissions at the consumer level. Moreover, real estate projects that aim to develop green buildings, energy-efficient buildings, and cool rooftops can issue green bonds to fund these projects. Financial institutions can charge higher interest rates for projects that have space heating issues or do not comply with green building codes, thereby reducing demand for such projects. This will help reduce household CO_2 emissions at the construction level.

These three phases of the policy framework are focused on reducing CO_2 emissions at the sectoral level. Effective channeling of GF will enable the top five CO_2-emitting countries to make steady progress toward achieving SDG 13.

Policy caveats

As attracting investments through green bonds is expected to have a significant impact on the ESG performance of companies, the possibility of greenwashing behavior cannot be ruled out. In addition, measuring the actual environmental impact of green bonds is necessary to decide on the tax benefits and credits granted to companies. Moreover, the rising demand for green bonds will inevitably increase supply, so the acquisition cost of these bonds should decrease as the supply increases. The price of these bonds must reflect the economies of scale achieved by them. This will encourage more retail investors to invest in these bonds. In this way, the respective governments can reach the predetermined threshold for total investment in these green bonds to achieve carbon neutrality.

The social impact of green bonds must also be considered. Diversification toward green and clean energy sources can put demand pressure on traditional power generation companies. This negative demand pressure can lead to an increase in unemployment in the sector. This increase in unemployment can lead to a social imbalance, which can hinder the implementation of the policy framework. Therefore, policymakers need to address the reintegration of the unemployed by providing them with training and development opportunities so that they can be employed in other emerging sectors of the economy.

Future directions

The study considered only (i) the top five CO_2-emitting countries as a research context and (ii) green bonds as a measure of GF. A broader research context and the choice of other alternative green financing channels can provide additional insights for policy design in future studies. In addition, researchers can use Fourier transforms to examine the relationship between green bonds and environmental degradation, considering structural breaks. A final suggestion is that the impacts of green bonds on air, water, and soil pollution can be analyzed by focusing on the ecological footprint and load capacity factor. In this way, the GF literature can provide more detailed information about the environmental impacts of green bonds.

Abbreviations

BDS	Broock, scheinkman, dechert, and lebaron
CO_2	Carbon dioxide
COP	Conference of parties
CS-ARDL	Cross-sectional ARDL
EF	Ecological footprint
GBI	Green bond index
GCQ	Granger causality-in-quantiles
GDP	Gross domestic product
GF	Green finance
IEA	International energy agency
QAR	Quantile autoregressive approach
QQR	Quantile-on-quantile regression
QR	Quantile regression
SDG	Sustainable development goal
UN	United nations
WTC	Wavelet coherence

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UKP: Conceptualization, Writing—original draft, Writing—review & editing; MTK: Conceptualization, Investigation, Methodology, Formal analysis, Methodology, Software Data Collection, Writing—original draft, Writing—review & editing; ZA: Writing—original draft; AS: Writing—original draft.

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Declarations

Competing interests
The authors declare that they have no competing interests.

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