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ORIGINAL PAPER

Revealing the effectiveness of hydropower innovations on emission level in Japan: evidence from machine-learning algorithm

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Abstract

This study explores how oil efficiency and hydropower innovation affect carbon emissions in Japan. In this direction, the novel multivariate quantile on quantile regression technique is applied to explore the period from 2000 to 2020. In addition, to prevent omitted variable bias, the environmental implications of industrialization, urbanization, and economic growth are also observed. The empirical findings indicate that oil efficiency, industrialization, and hydropower innovations are all lower carbon emissions. However, urbanization and economic growth harm the environmental quality. Lastly, a robustness check is performed using a kernel-based regularized least squares technique based on machine learning. The results of this investigation support the claim that oil efficiency and hydropower innovation can reduce emissions. Furthermore, it is found that the emission-reducing impact of both gets stronger as the emission level rises.

Keywords Hydropower innovations · Oil efficiency · Emissions · Multivariate QQR · Japan

Abbreviations

CO	Carbondioxide emissions
EQ	Environmental quality
SDG	Sustainable development goals
HU	Hydroenergy usage
REN	Renewable energy
OEF	Oil efficiency
ECG	Economic growth
IND	Industrialization
URB	Urbanization
HPI	Hydropower innovations
QQR	Quantile-on-quantile regression
MQQR	Multivariate quantile-on-quantile regression

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Introduction

One of the main objectives of sustainable development is the need to address climate change and reduce global warming. Therefore, one of the core objectives of sustainable development has been recognized as moving toward an urgent action plan for handling climate change in order to promote the battle against it and its effects (SDG 13) (UN 2023a, b). To attain this objective, the existing literature engages in a thorough discourse on the factors influencing environmental quality, a crucial indicator of climate change (Ibrahim and Ajide 2021; Salahuddin and Gow 2019).

Without a doubt, a steady increase in the use of fossil fuels is the main element that seriously compromises environmental quality (EQ) within this framework of sustainable development (Raihan et al. 2022a, b, c; Ma et al. 2023a,

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b). Fossil fuel consumption is accountable for over 90% of global carbon dioxide emissions (CO) and more than 75% of greenhouse gas emissions (UN 2023a, b). However, sustainable global growth cannot be achieved independently of fossil energy use (Wang et al., 2023a, b; Doganalp et al. 2021; Xu et al. 2022). Many solutions are being put forward to reduce the damage caused by fossil energy use to nature. As clearly stated in the sustainable development goals, the two main points that are emphasized the most are the use of sustainable and modern renewable energy (SDG 7) and increasing energy efficiency (SDG 7.3) (UNEP 2023). In this context, energy efficiency and renewable energy use can be said to be the "twin pillars" of sustainable energy policy (ACEEE 2007). The expected progress in these two areas is based on environmental technological advances (Paramati et al. 2022). Technological advances encompassing pollution control, waste management, recycling, monitoring and a range of evaluation methods are the main drivers of energy efficiency and renewable energy deployment (Habiba et al. 2022).

Japan is one of the countries that aims to make technological investments in the field of energy efficiency and renewable energy. Japan is one of the countries that focuses on supporting the energy sector with technology, which consumes the most energy and imports energy worldwide (IEA 2024). Japan focusing on the development of technology-supported green energy since the 1990s (Taghizadeh-Hesary, et al. 2023). Japan is a country that needs to create a technology-enabled energy sector. Although it aims to reduce carbon emissions by 26% by 2030 as part of the Paris Agreement, the country's actual carbon emissions are much higher than these estimates. Considering that Japan is the sixth largest greenhouse gas emitter globally, it needs to shift to using more renewable energy, especially in terms of oil efficiency (Liu et al. 2023a, b). Because 2023 data also shows that Japan still gets 38% of its energy consumption from oil sources (Asia Natural Gas & Energy Association, 2024). When it comes to the use of renewable energy sources, Japan has historically put a high priority on the generation of electricity from hydroelectric energy. One of the areas of activity that Japan supports with technology to provide energy efficiency and create an energy sector rich in renewable energy resources is hydropower energy. Hydropower plants, called the "blue battery" in the country, have recently served as a complementary energy type. The increasing global environmental concerns have particularly contributed to the further growth of hydropower energy usage in Japan (Hennequin 2016). Because Japan, which receives abundant rainfall, offers great advantages to the country for the development of this energy. Additionally, hydropower generation has the advantage of producing electricity steadily, as it is less affected by changes in weather conditions than solar and wind power. While Japan's energy self-sufficiency rate is only 4%, hydropower generation is a completely local form of energy, supplying 35% of Japan's locally produced energy (Inoue and Shiraishi 2010). According to Global Data (2023), it is projected that the installed capacity will increase by 2035 with hydropower energy expected to constitute 11% of the total installed production capacity at that point (Global Data 2023). Despite the maturity level of hydropower in Japan, Japanese manufacturers continue to invest in technology research to increase hydropower efficiency, reduce costs, and make the distribution of hydropower turbines increasingly attractive at all scales (Hennequin 2016). In Japan, the innovative activities in increasing hydropower production capacity are also crucial. According to OWD (2023) data, there have been significant increases in the number of patents related to hydropower technology, especially between 2010 and 2012. The number of patents, which was 178 in 2000, rose to 212 in 2010 and 337 in 2012 (OWD 2023). However, although various technological investments have been made in the field of hydroelectric energy in Japan, there is still criticism from a certain group that these investments are not sufficient to improve environmental quality. It cannot be said that environmental friendliness applies universally to all hydropower production plants. In some hydropower plants, the accumulation of organic matter at the bottom of the reservoir, in areas where oxygen is depleted during the utilization of hydropower energy, the release of methane gas, a potent greenhouse gas, may occur. Furthermore, both the construction and operation of these facilities are associated with emissions. Emissions may escalate during the construction phase due to the combustion of fossil fuels and steel/cement production. An essential aspect in this regard is the effective design of production areas with innovative features to increase the efficiency of production facilities (Hulley 2022; Bilgili et al. 2021). Therefore, the current study focuses on analyzing the effects of technological developments in the field of hydropower in Japan on environmental pollution through empirical tests.

It is anticipated that the study will add to the literature in several ways. (i) The influence of oil efficiency (OEF) and hydropower innovation on Japan's CO is being investigated for the first time in this study. (ii) Multivariate quantile on quantile regression is employed, and this is the first time such a relationship has been studied in the literature. This allows one to distinguish between how different levels of carbon emissions are affected by low and high values of independent variables. (iii) The KRLS technique, which is designed for robustness checks and is based on an algorithm based on machine learning, can be used to assess the marginal impacts of independent variables on carbon emissions.

The study follows a structured process: the subsequent section presents an in-depth literature review, followed

by the introduction of data and a comprehensive discussion of the methodology in the Sect. "Data, model, and methods". Sect. "Empirical Results" presents the findings, while Sect. "Conclusion and Policy Recommendations" engages in discussions, drawing comparisons with existing literature. The concluding section encapsulates the study's outcomes and their policy implications.

Literature review

Environmental quality is influenced by numerous parameters, and various indicators have been discussed over the long term to determine and assess environmental quality. It is evident from analyzing the body of research throughout time that CO are primarily used as a gauge of EQ (Destek et al. 2023; Depren et al. 2023; Li et al. 2022; Mehmood 2021). Therefore, carbon emissions are utilized as a parameter representing environmental pollution in this research. To present the literature review more clearly, this section is addressed in five different subheadings.

Hydropower energy innovation and carbon emissions

In studies examining the nexus between hydroenergy usage (HU) and environmental quality (EQ), particularly focusing on hydroelectric consumption, diverse findings have been reported. According to Lau et al. (2016), over the long term, from 1965 to 2010, a correlation between HU and CO developed in Malaysia. Bildirici and Gökmenoğlu (2017) concluded that there is a unidirectional causal relationship from HU to CO for the G7 countries during the period 1961–2013. Bello et al. (2018) discovered that from 1971 to 2016, Malaysia's use of hydroelectricity decreased environmental pollutants. Similar findings were obtained in studies by Sinaga (2019) for Malaysia (1978–2016), Bandyopadhyay et al. (2023a, b) for India (1980–2019), and Saadaoui et al. (2023) for the Turkish economy (1985–2021). Conversely, studies by Pata (2018) for Turkey (1974–2014) and Pata and Kumar (2021) for the Chinese economy (1980–2016) found no correlation hydroelectric consumption and carbon emissions, with emissions increasing as a result of hydroelectric usage. Additionally, Bilgili et al. (2021) investigated the relationship between HU and CO in China and the U.S. employing a wavelet transform method. They determined that in the short term HU increased CO [1990:01–1992:12, 1994:01–1994:12, and 2002:07–2007:11], while in the long term hydroenergy consumption reduced carbon emissions [1983:01–2001:12 and 2011:01–2017:03]. The literature review reveals divergent views on the influence of HU on EQ, emphasizing the need for innovative activities and support for the energy source to address the disadvantages of hydroelectricity on the environment.

Ummalla and Samal (2018) identified a link between hydropower innovations and carbon emissions for China. In this regard, they suggested that priority should be given to research and development (R&D) expenditures in HU as a policy recommendation. A similar view is advocated for Nigeria in the study by Sanni (2018). The study states that hydroelectric power plants based on renewable energy technology are of critical value for Nigeria's low-carbon future. Similarly, Liang et al. (2020) found that the innovative hydropower industry is effective in reducing CO for China. In the study of Cao et al. (2023) observing 30 Chinese provinces, they revealed that the environmental effectiveness of developments in hydroelectric technology is low and pointed out that the main reason for this situation is the neglect of intellectual property rights. Furthermore, the carbon emission reducing impact of hydropower innovation is confirmed by Li and Shao (2021). This research uses hydroenergy patents to examine the link between EQ and innovation in renewable energy (REN) for OECD countries between 1990 and 2018. The findings suggest that a raise in innovation activities in renewable energy positively impacts environmental quality. Consistent positive results regarding for China are reported in Cheng and Yao (2021) for the period 2000–2015, Razzaq et al. (2023) for 2007–2019, Hu et al. (2022) for 2011–2018, Ma et al. (2023a, b) for 2006–2019, and Dong et al. (2023) for 2006–2019. Similarly, Solarin et al. (2022) also reported positive findings for BRICS countries during the period 1993–2018, and Similar findings were found by Adebayo et al. (2023a, b) for the top 10 nations in terms of labor income from 1990 to 2021. These studies collectively suggest that an raise in innovation activities in the field of REN, including HU, contributes to EQ and may help in mitigating CO. A similar finding was obtained in the study of Dogan et al. (2024) for the ten countries that produced the most hydroelectricity in the period 1992–2019. As a result of the analysis, it was concluded that hydroelectricity production is an important driving force on environmental quality.

Some of the studies addressing environmental pollution with HU argue that hydropower use creates pressure on the environment and reduces environmental quality. Among these studies, Koç (2022) evaluated the activities of hydroelectric producers in the Büyük Menderes and Western Mediterranean basins in Turkey between 2010 and 2019, carried out by public institutions or private sectors. The findings obtained indicate that significant damage has occurred in the environment, especially in terms of the decrease in biodiversity. The finding of Bölük and Mert (2015) that hydroelectric use has no statistically significant effect on environmental

pollution for the period 1961–2019 in Turkey is also consistent with the findings obtained for the period 1974–2014 in Turkey in the study of Pata (2018). The effect of HU on carbon emissions and carbon footprint, which are important indicators of environmental pollution, was tested for China and India in the study of Pata and Kumar (2021). The study, which investigated the period between 1980 and 2016, shows that hydropower consumption led to an increase in carbon emissions and carbon footprint in China. In the case of India, it was concluded that HU had no effect on environmental degradation. The study emphasized that hydroelectric energy is not an effective way to control pollution in these countries, and that it damages the environment by changing the flow of rivers and lakes by increasing high reserves and land use. In addition, in the study of Pata and Aydın (2020), it is stated that it is not an effective type of energy to reduce the ecological footprint, which is one of the environmental pollution indicators, between 1965 and 2016, especially in the 6 countries that consume the most hydroelectricity.

Additionally, some studies compare the environmental impacts of hydropower and other renewable energy types (wind, solar, etc.) based on quantiles, but these studies focus on the consumption of these renewable energy types rather than on innovation. For example, Sharif et al. (2021) investigated the relationship between disaggregated renewable energy consumption and the environment for the United States, concluding that hydropower is harmful to the environment at low emission quantiles, while wind and solar energy are beneficial.

Oil efficiency and carbon emissions

The research carried out to check the connection between energy efficiency (EE) and EQ, as indicated by CO, commonly affirms that an enhancement in EE leads to a reduction in environmental impact, notably a decline in CO. The outcomes have been derived from research by Akram et al. (2020) for 66 developing countries during the period 1990–2014, by Javid and Khan (2020) for the period 1971–2016 for the United States, India, China, Germany, and Japan, and by Danish et al. (2020) for the period 1985–2017 for the United States.

Research exploring the influence of EE on CO, particularly those focusing on oil efficiency (OEF), are relatively scarce in the literature. In this field, which has been the subject of a limited number of studies, Liu et al. (2023a, b) investigate the relationship between OEF and CO for Japan during the period from 1990/Q1 to 2020/Q4. According to findings obtained through novel quantile-based approaches, petroleum efficiency reduces CO_2 emissions in the majority of percentile ranges. According to Du et al. (2019), an increase in petroleum efficiency is found to decrease carbon intensity, thereby improving environmental quality in China. Similarly, Anser et al. (2023) reveal, through Fourier ARDL estimates for Finland during the period 1990–2020, the efficiency of petroleum has an negative impact on CO., leading to a reduction. Wang et al. (2023a, b) demonstrate, using a traditional quantile regression model for Finland from 1990/Q1 to 2021/Q4, that petroleum efficiency reduces CO_2 across all percentiles (0.01–0.99) in the long term.

Other observed factors and environment

Economic expansion (ECG), industrialization (IND), and urbanization (URB) parameters are closely interconnected indicators. Therefore, their direct and indirect effects on EQ indicators have been empirically tested according to numerous studies. In the study by Ahmad and Zhao (2018), covering the period from 2000 to 2016, it was detecting that ECG decrease CO in more developed regions while increasing them in less developed regions in China. Liu et al. (2016) analyzed the influence of URB and ECG on CO in China for the period 1997–2010 is analyzed. Findings indicate a bidirectional causality between URB, ECG, and CO in the long term. Sun and Huang (2020) address the relationship between urbanization and carbon efficiency for China from 2000 to 2016. Findings indicate a reverse U-shaped relationship between URB and CO efficiency. In other words, an initial increase in urbanization enhances carbon efficiency, followed by a decrease in the later stages. Raihan et al. (2022a, b, c) conclude that ECG, URB, and IND increase CO in Bangladesh for the period 1990–2019. Sikder et al. (2022) present long-term results for 23 developing countries from 1995 to 2018, indicating that a 1% increase in ECG, IND, and URB raises CO by 0.17%, 0.54%, and 2.32%, respectively. Raihan and Tuspekova (2022) study for Turkey from 1990 to 2020, revealing that a 1% increase in ECG, URB, and IND would result in a 0.39%, 1.22%, and 0.24% increase in CO, respectively. Azam et al. (2022) finds that industrialization and urbanization increase CO for OPEC countries during the period 1975–2018.

However, there is a divergence of views in studies examining the correlation between industrialization and EQ (Majeed and Luni 2019; Idowu et al. 2023). The study suggests that industrialization alleviates environmental degradation by influencing per capita income through an indirect mechanism. In the study by Elfaki et al. (2022), encompassing the timeframe spanning from 1994 to 2018 for 8 countries, it is concluded that industrial developments have a reducing effect on CO. Similar findings were obtained by Raheem and Ogebe (2017) for 20 African countries during the period from 1980 to 2013. The research implies that industrialization mitigates environmental degradation by means of the indirect impact mechanism on per capita income. Similarly, Idowu et al. (2023) obtained similar

results for OPEC countries during the period from 1985 to 2020. The general consensus in the current literature is that industrial developments supported by technological progress in later stages will result in a reduction of carbon emissions (Aunan and Wang 2014; Chikaraishi et al., 2015; Mehmood et al. 2024). Generally speaking, the viewpoint offered in these research, which claims that growing IND lowers CO, is ascribed to technical developments that reduce the amount of energy used in industrial operations (Idowu et al. 2023).

According to the literature research, the factors included in this study have not been examined using the same model framework in the Japanese context. This report is distinct from others that concentrate only on hydro energy in Japan since it highlights cutting-edge advancements in the hydro energy sector.

Materials and methods

Data

To reveal the impact of hydropower innovations (HPI) and OEF on CO_2 in Japan, we utilize the annual data spanning from 2000 to 2020, dictated by data availability of HPI. By following Özkan et al. (2024), we calculate OEF by dividing GDP to oil energy consumption. In order to control omitted variable bias, the study also includes ECG, IND, and URB as control variables, given their documented impact on CO_2 in the empirical literature (for example, see, Zhang et al. 2021; Sikder et al. 2022; Xu et al. 2023a, b; Bambi et al. 2024; Işık et al. 2024; Pradhan et al. 2024). The details of the variables and their data are presented in Table 1. It is important to note that, by following Destek et al. (2025), we convert the raw series into the quarter frequency series by using the match(sum) type of the quadratic method to obtain enough sample size. In addition, by converting these series into natural logarithms, we converge the data series and reduce the potential heteroskedasticity problem as suggested by the recent research (e.g., see Iorember et al. 2026). Finally, for stationarity concerns, we take first differences as in Olanrewaju et al. (2025).

Model and methods

In this study, we develop the following model in Eq. (1) to examine the impact of HPI and OEF on carbon dioxide emissions in Japan, controlling ECG, industrialization, and urbanization:

$$CO_2 = f(HPI, OEF, ECG, IND, URB) \quad (1)$$

In Eq. (1), f represents the function. Furthermore, CO_2, HPI, OEF, ECG, IND, and URB symbolize carbon dioxide emissions, hydropower innovations, oil efficiency, economic growth, industrialization, and urbanization, respectively. Our empirical model can also be explained theoretically by the stochastic IPAT model developed by Dietz and Rosa (1994). Based on this model, which states that the main determinants of environmental pollution (I) are population (P), affluence (A) and technology (T), industrialization is used as an affluence indicator, urban population as a population indicator and hydropower innovation and oil efficiency as technology indicators.

The analyses to be performed in the study are shown step by step in Fig. 1. It can be seen that a set of preliminary analyses such as multicollinearity, descriptive statistics, quantile–quantile (q–q) (non)normality plots, BDS, and stability tests are carried out in the study before the main analyses. Particularly, in the preliminary analyses, we first try to determine the series that is suitable for given in Eq. (1) with the multicollinearity analysis. Afterwards, the characteristics of these determined series within the sample period are tried to be revealed with the descriptive statistics, q–q (non)normality plots, Broock et al.'s (1996) BDS test, and stability test developed by Andrews (1993), Andrews and Ploberger (1994), and Hansen (1997) to see whether or not the chosen methods are suitable for this study.

The main analyses of the study start with the novel multivariate quantile-on-quantile regression (MQ-QR). The

Table 1 Variables and data details

Variable name	Symbol	Data detail	Data source
Carbon dioxide emissions	CO_2	Metric tons, per person	OWD (2023)
Hydropower innovations	HPI	Annual patents filed for hydropower technologies	OWD (2023)
Oil efficiency	OEF	$\frac{\text{GDP, per capita (constant 2015USD)}}{\text{Oil energy (consumption), per capita (kWh)}}$	WDI (2023) OWD (2023)
Economic growth	ECG	GDP, per capita (constant 2015USD)	WDI (2023)
Industrialization	IND	Industry (including construction), value added (% of GDP)	WDI (2023)
Urbanization	URB	Urban population (% of total)	WDI (2023)

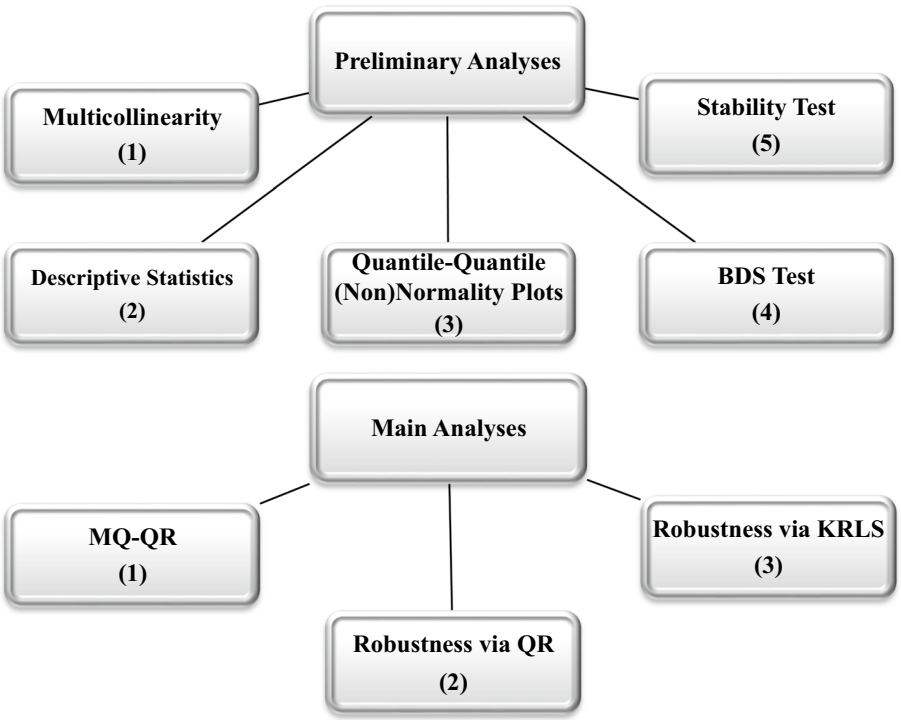


Fig. 1 Analyses of the Study

Table 2 Multicollinearity Results

	CO_2	HPI	OEF	ECG	IND	URB
Panel A: Correlations						
CO_2	1					
HPI	0.265	1				
OEF	−0.424	−0.535	1			
ECG	0.659	0.358	−0.245	1		
IND	0.202	−0.308	0.078	0.609	1	
URB	0.197	0.272	−0.110	0.098	−0.221	1
Panel B: VIF Test Results						
	VIF	1/VIF				
HPI	2.815	0.355				
OEF	1.420	0.704				
ECG	3.479	0.287				
IND	3.449	0.290				
URB	1.156	0.865				

VIF and 1/VIF results are obtained from the model: CO_2 = f(HPI, OEF, ECG, IND, URB). The threshold value of correlation, VIF and 1/VIF are ± 0.8, 5, and 0.2, respectively (Caglar et al. 2023)

MQ-QR was developed by Alola et al. (2023) as a multivariate version of Sim and Zhou's (2015) QQR method. By including multiple independent variables, the MQ-QR addresses the omitted variable bias occurred in the QQR analysis. The MQ-QR investigates the impact of each independent variable's conditional distribution on the dependent variable'sconditional distribution by utilizing both dependent and independent variables' quantiles. In other words, the MQ-QR unveils how quantiles of the dependent variable respond to the quantiles of multiple independent variables simultaneously. Since the MQ-QR considers the entire distribution of the data series instead of the mean-based models such as OLS or standard VAR-based approaches, it is highly suitable against all non-normality, non-linearity, or instability properties seen in most data series (Koenker &

Hallock 2001; Koenker 2005). Because of these important advantages, the MQ-QR is chosen as the main procedure.

For this study, the MQ-QR is specified in Eq. (2) as follows:

$$\begin{aligned}\text{MQ - QR} = {} & \Theta_0(\phi_1,\phi_2,\phi_3,\phi_4,\phi_5,\omega)+\Theta_1(\phi_1,\omega)(\text{HPI - HPI}_{\phi 1}) \\ & +\Theta_2(\phi_2,\omega)(\text{OEF - OEF}_{\phi 2})+\Theta_3(\phi_3,\omega)(\text{ECG - ECG}_{\phi 3}) \\ & +\Theta_4(\phi_4,\omega)(\text{IND - IND}_{\phi 4})+\Theta_5(\phi_5,\omega)(\text{URB - URB}_{\phi 5}) \\ & +\mathrm{e}(\phi_1,\phi_2,\phi_3,\phi_4,\phi_5,\omega)\end{aligned} \tag{2}$$

In Eq. (2), ω, ϕ_1, ϕ_2, ϕ_3, ϕ_4, and ϕ_5 symbolize the conditional quantiles of CO_2, HPI, OEF, ECG, IND, and URB, respectively. Furthermore, $\Theta_0(\phi_1,\phi_2,\phi_3,\phi_4,\phi_5,\omega)$ and $e(\phi_1,\phi_2,\phi_3,\phi_4,\phi_5,\omega)$ stands for the constant and error terms at the ω-, ϕ_1-, ϕ_2-, ϕ_3-, ϕ_4-, and ϕ_5-th conditional quantile of CO_2, HPI, OEF, ECG, IND, and URB, respectively. Additionally, $\Theta_1(\phi_1,\omega)$, $\Theta_2(\phi_2,\omega)$, $\Theta_3(\phi_3,\omega)$, $\Theta_4(\phi_4,\omega)$, and $\Theta_5(\phi_5,\omega)$ specify the slope coefficients representing the impact of ϕ_1-, ϕ_2-, ϕ_3-, ϕ_4-, and ϕ_5-th conditional quantile of HPI, OEF, ECG, IND, and URB on the ω-th conditional quantile of CO_2, respectively.

As a robustness check for the MQ-QR results, we also employ Koenker and Bassett's (1978) and Koenker's (1981) Quantile Regression (QR) approach. In the study, the QR is specified in Eq. (3) as follows:

$$\begin{aligned}\text{QR} = {} & \Theta_0(\omega)+\Theta_1(\omega)\text{HPI} + \Theta_2(\omega)\text{OEF} + \Theta_3(\omega) \\ & \text{ECG} + \Theta_4(\omega)\text{IND} + \Theta_5(\omega)\text{URB} + \mathrm{e}(\omega)\end{aligned} \tag{3}$$

In Eq. (3), $\Theta_0(\omega)$ and e(ω) symbolize the constant and error terms at the ω-th conditional quantile of CO_2, respectively. Furthermore, $\Theta_1(\omega)$, $\Theta_2(\omega)$, $\Theta_3(\omega)$, $\Theta_4(\omega)$, and $\Theta_5(\omega)$ stand for the slope coefficients indicating the impact of HPI, OEF, ECG, IND, and URB on the ω-th conditional quantile of CO_2, respectively.

In particular, we compare the estimated slope coefficients $\Theta_1(\omega)$, $\Theta_2(\omega)$, $\Theta_3(\omega)$, $\Theta_4(\omega)$, and $\Theta_5(\omega)$ of the QR with the average of the estimated slope coefficients $\Theta_1(\phi_1,\omega)$, $\Theta_2(\phi_2,\omega)$, $\Theta_3(\phi_3,\omega)$, $\Theta_4(\phi_4,\omega)$, and $\Theta_5(\phi_5,\omega)$ of the MQ-QR as in the study of Özkan et al. (2023).

We also use the machine learning kernel-based regularized least squares (KRLS) approach from Hainmueller and Hazlett (2014) and Ferwerda et al. (2017) in the study to validate the MQ-QR results by adhering to Usman et al (2025). KRLS focuses on point marginal effects (PME) to investigate the heterogeneous or nonlinear effect of independent variables on the dependent variable. For non-normality, non-linearity, or instability properties found in the studied data series, this approach is thus highly appropriate. More precisely, KRLS serves as a robustness tool that allows us to assess whether the patterns revealed by the MQ-QR model remain consistent when using a flexible, non-parametric machine learning method that does not impose strong linearity assumptions. Importantly, KRLS internally determines kernel bandwidths and regularization parameters through a data-driven optimization procedure, which avoids arbitrary choices by the practitioners and ensures that the estimates are robust and reliable. We examine the average PME table and PME graphs provided by KRLS to evaluate the consistency and reliability of our main findings.

Results and discussion

Pre-estimation check

In the first section of empirical analysis, we estimate the variance inflation factor (VIF) test results and correlations to control possible multicollinearity problem. Both estimated correlations and VIF test results show that the studied series do not present multicollinearity as shown in Table 2.

Table 3 reports the descriptive statistics of each variable's series. Mean values divulge that CO_2, HPI, and IND

Table 3 Descriptive statistics

Stats	CO_2	HPI	OEF	ECG	IND	URB
Mean	−0.0007	−0.0077	0.0021	0.0002	−0.0004	0.0005
Median	−0.0007	−0.0024	0.0022	0.0006	−0.0002	0.0004
Maximum	0.0068	0.0496	0.0090	0.0078	0.0109	0.0015
Minimum	−0.0077	−0.1400	−0.0098	−0.0093	−0.0099	0.0000
Std. Dev	0.0024	0.0295	0.0023	0.0019	0.0024	0.0005
Skewness	0.2113	−2.4576	−1.4651	−1.3029	0.0104	0.3864
Kurtosis	4.3500	10.5992	10.9730	13.1146	11.3853	1.6034
Jarque–Bera	6.9207■■	283.2659■■■	249.5324■■■	377.2856■■■	243.1692■■■	8.8112■■
	[0.0314]	[0.0000]	[0.0000]	[0.0000]	[0.0000]	[0.0122]

The table presents the summary statistics for the quarterly difference series. ■■■[p] < 0.01, ■■[p] < 0.05, ■[p] < 0.1

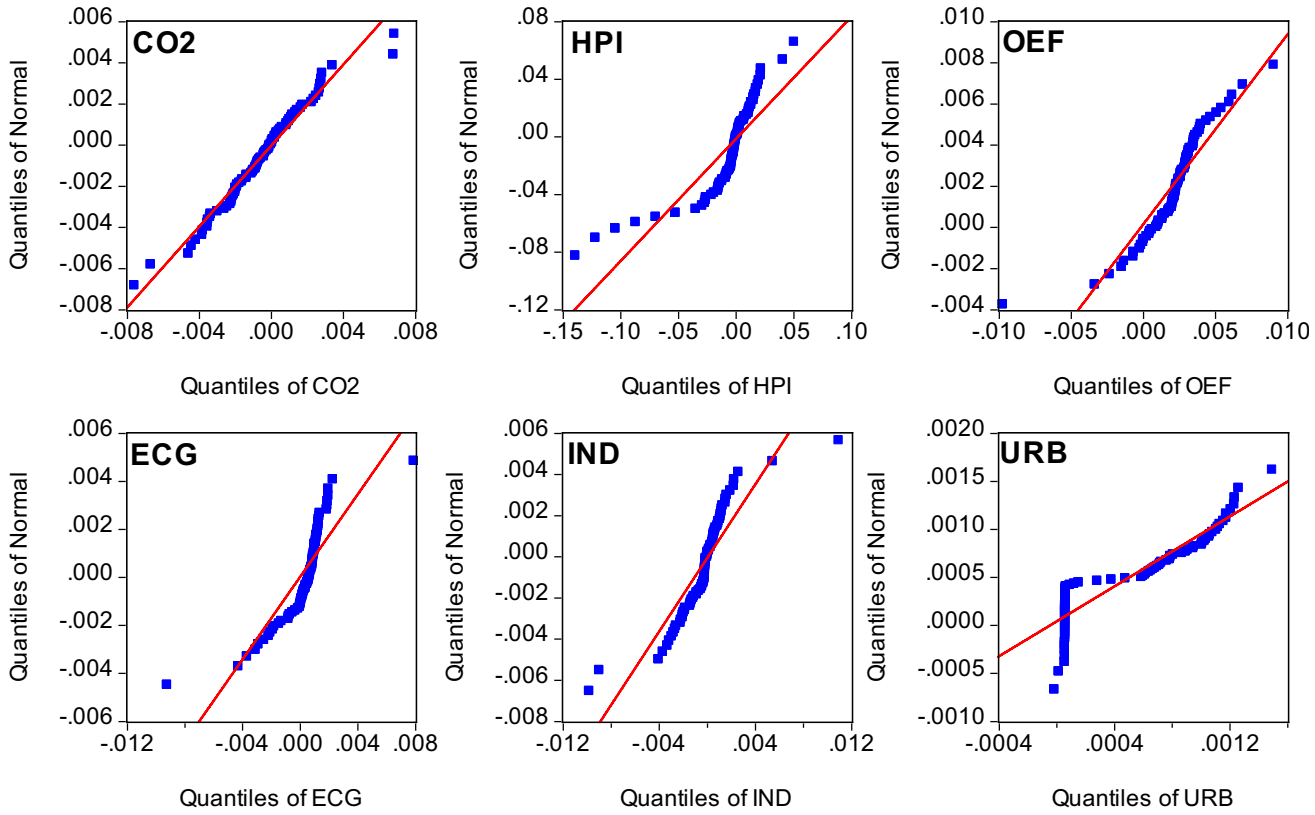


Fig. 2 Quantile–Quantile (Non)Normality plots of the opted series

have a negative, while OEF, ECG, and URB have a positive average in the sample period. Furthermore, standard values disclose that HPI has the highest and URB has the lowest volatility. We observe from the skewness values that CO_2, IND, and URB have a positively, whereas HPI, OEF, and ECG have a negatively skewed distribution. From the kurtosis values, we see that CO_2, HPI, OEF, ECG, and IND have a leptokurtic and URB has a platykurtic distribution. The series of the variables present non-normality in the sample period. The non-normality of the series can also be seen in the q–q (non)normality plots provided in Fig. 2.

Table 4 presents the BDS test results of the considered series. The results indicate that the null hypothesis asserting that the data under consideration is independently and identically distributed is strongly rejected across all dimensions for all series. The BDS test results disclose that the used series of the variables present non-linearity in the sample period.

Table 4 BDS Test Results

Dimension	CO_2	HPI	OEF	ECG	IND	URB
Two	7.364■■■	5.843■■■	5.730■■■	6.856■■■	9.824■■■	28.849■■■
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]
Three	6.082■■■	4.956■■■	4.571■■■	5.956■■■	9.568	31.050■■■
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]
Four	5.062■■■	4.016■■■	4.136■■■	5.542■■■	9.712■■■	33.197■■■
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]
Five	6.026■■■	3.589■■■	4.755■■■	5.628■■■	10.815■■■	36.323■■■
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]
Six	6.633■■■	2.854■■■	5.280■■■	5.597■■■	11.799■■■	40.560■■■
	[0.000]	[0.004]	[0.000]	[0.000]	[0.000]	[0.000]

■■■ $[p] < 0.01$, ■■ $[p] < 0.05$, ■ $[p] < 0.1$

Table 5 Stability test results

	CO_2	HPI	OEF	ECG	IND	URB
Sup-F	17.815***	52.697***	12.857***	9.671**	14.763***	495.225***
	[0.000]	[0.000]	[0.007]	[0.031]	[0.003]	[0.000]
Exp-F	6.347***	22.390***	3.472***	1.885*	5.203***	243.564***
	[0.000]	[0.000]	[0.008]	[0.061]	[0.000]	[0.000]
Ave-F	6.167***	14.954***	2.792*	1.831	6.282***	169.531***
	[0.002]	[0.000]	[0.053]	[0.137]	[0.002]	[0.000]

***[p] < 0.01, **[p] < 0.05, *[p] < 0.1

Table 5 reports the stability test results of the series under investigation. The results imply that the null hypothesis asserting that the studied data is stable is rejected with all three tests for CO_2, HPI, OEF, IND, and URB and with two tests (Sup-F and Exp-F) for ECG. The stability test results reveal that the series of the variables exhibit instability in the sample period.

In summary, the preliminary analyses demonstrate that the series of variables present instability, non-linearity, non-normality. As the considered series have all these features, it can be concluded that the chosen methods (i.e., the MQ-QR, QR, and KRLS) are suitable for us.

Multivariate quantile-on-quantile regression results

Since the considered temporal variables possessed non-normality as well as instability in the chosen time span. Thus, the MQ-QR technique is used in this study, and Fig. 3 shows the projected findings visually. In the stated figure, the connection of each variable with CO_2 emissions is portrayed in isolation. Specifically, the figure consists of five parts, where (a) designates the influence of HPI on CO, (b) reports the influence of OEF on CO, (c) demonstrates the effects of ECG on CO, (d) reveals the influx of IND on CO, while (e) indicates the association between URB and CO in Japan. From the estimation outcomes, it can be noticed that three of the total variables, i.e., HPI, OEF, and IND, have a significant adverse influence on CO_2 emissions with negative 0.1–0.04, 0.6–0.3, and 1–0.5 coefficient values, respectively. Besides, the influence of HPI and OEF is found stronger in the lower quantiles of CO_2, while in the middle quantiles for IND. On the other hand, the results demonstrate that ECG and URB significantly enhance environmental quality. In other words, the coefficient values range from 1 to 2 for ECG, and from 0 to 2 for URB. The positive influence of ECG is found to be stronger in the lower quantiles, while for URB, the impression is stronger in the upper quantiles.

Robustness analyses results

This research typically tests the validity of the connection for each study variable once the coefficients are obtained using MQ-QR. In this sense, the present research uses QR versus Averaged MQ-QR approaches and the estimation outcomes are reported in Fig. 4. The quantile estimate offered the exact coefficient statistics at each specific quantile ranging from Q0.05 to Q0.95. As can be seen from the data under examination, the coefficient values for IND, OEF, and HPI are negative. However, the estimated coefficients for ECG and URB are positive. Although the coefficients in the robust analysis are slightly different than in the magnitude. Still, the overall influence across the specified quantiles remains consistent and in line with the above-mentioned results. Therefore, the empirical findings are found reliable and helpful for scholars and policymakers.

This study tends to assess the pointwise marginal effects of each explanatory variable on the CO_2 emissions in the study area since the quantile estimators are used to produce the estimated findings. Regarding this, Fig. 5 reports the estimated results. It is evident from the analyzed findings that the marginal (red) lines fluctuate across the chosen time period. Still, the overall influence remains consistent as depicted and discussed above. That is, the influence of HPI, OEF, and IND is harmful to the CO_2 emissions, which consequently helps environmental sustainability goals achievement. Yet, the impacts of ECG and URB are noted as harmful to the environmental quality as it multiplies the CO_2 emissions in Japan during the selected period.

After attaining the marginal pointwise marginal effects, the average-based coefficients are also computed, which are presented in Table 6, and reported in Fig. 6 for clarity. The estimation outcomes asserted that a percentage enhancement in HPI, OEF, and IND significantly reduces the CO by 0.082, 0.628, and 0.342% respectively. However, the average pointwise marginal influence of ECG and URB is noted as positive, which accelerates the CO_2 emissions level by 1.225 and 1.127%, respectively. These results of the average marginal effects are highly significant at 1% levels. Based on these results, this study claims the estimated predictions are reliable and trustworthy, which could help future researchers and policymakers concerning the appropriate policies for attaining a sustainable environment.

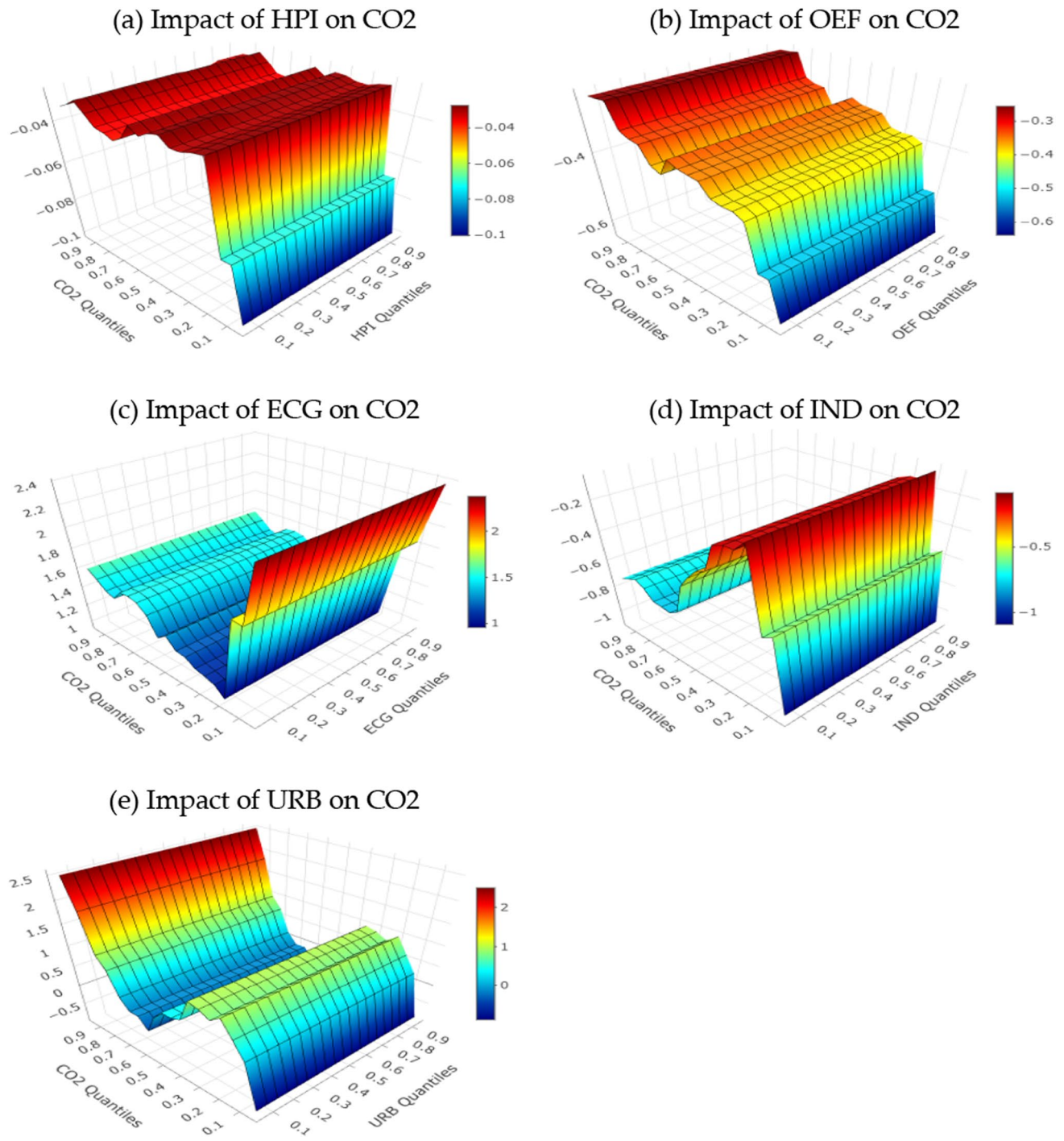


Fig. 3 Impact of HPI, OEF, ECG, IND, and URB on CO_2. Note: The plots illustrate the estimated slope coefficients $\Theta_1(\phi_1,\omega)$, $\Theta_2(\phi_2,\omega)$, $\Theta_3(\phi_3,\omega)$, $\Theta_4(\phi_4,\omega)$, and $\Theta_5(\phi_5,\omega)$ of the MQ-QR for the model: CO_2 = f(HPI, OEF, ECG, IND, URB). The colorscale represents the estimated slope coefficients in ascending order from dark blue to dark red.

Discussions

Analyzing the impacts of HPI, OEF, ECG, IND, and URB on CO_2 emissions in Japan might provide insight into the intricate process of establishing a sustainable environment. The factors influencing CO_2 emissions must be thoroughly understood in order to apply the Brock, Dechert, and Scheinkman (BDS) test, which detects temporal dependency, successfully. When dealing with asymmetric data distributions and temporal variability, particular analytical

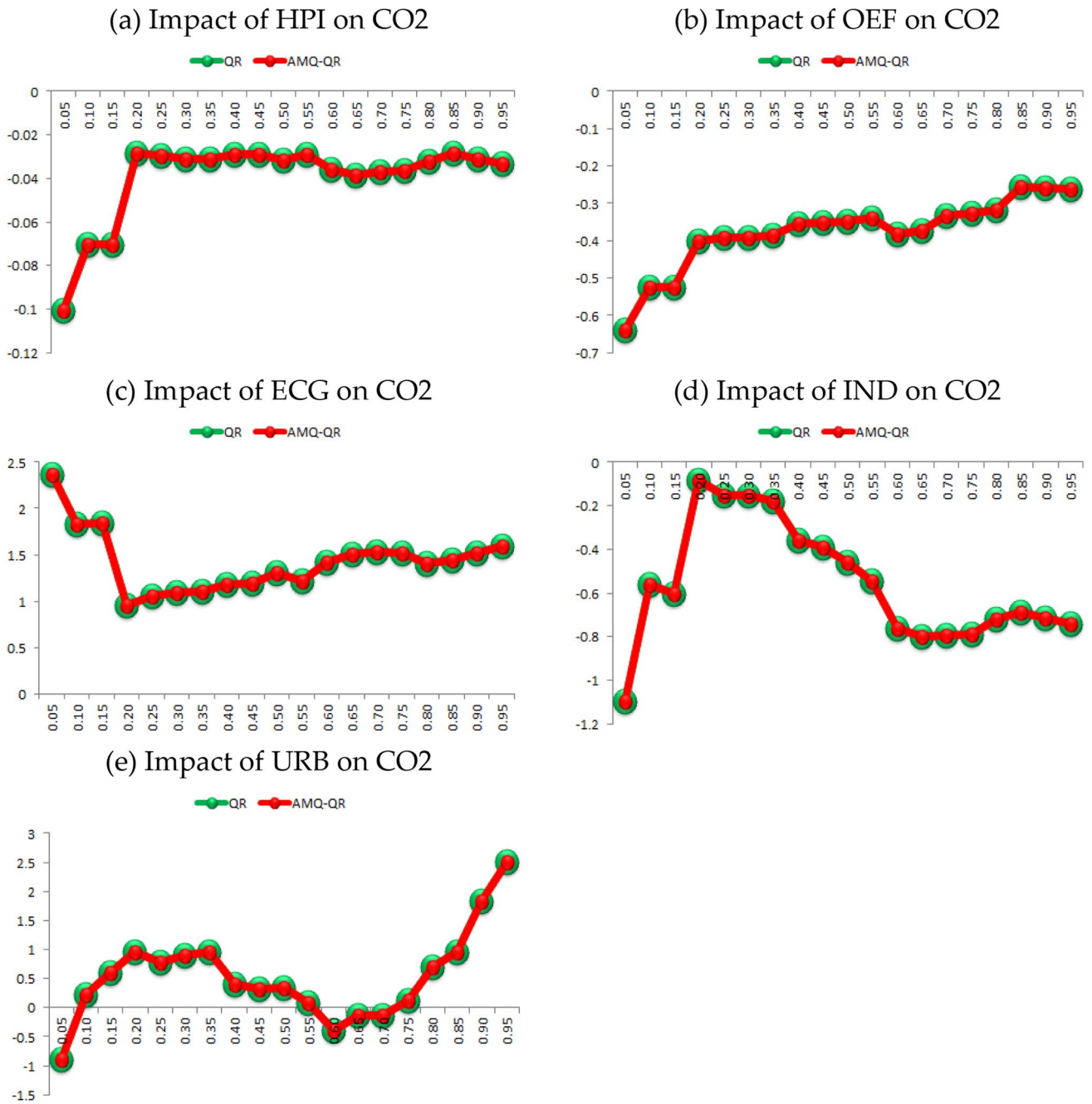


Fig. 4 QR Versus Averaged MQ-QR. Note: The plots illustrate the estimated slope coefficients $\Theta_1(\omega)$, $\Theta_2(\omega)$, $\Theta_3(\omega)$, $\Theta_4(\omega)$, and $\Theta_5(\omega)$ of the QR (green) and average of the estimated slope coefficients $\Theta_1(\phi_1,\omega)$, $\Theta_2(\phi_2,\omega)$, $\Theta_3(\phi_3,\omega)$, $\Theta_4(\phi_4,\omega)$, and $\Theta_5(\phi_5,\omega)$ of the MQ-QR (red) for the model: CO_2 = f(HPI, OEF, ECG, IND, URB). The quantiles are shown in the x-axis and corresponding slope coefficients are shown in y-axis.

techniques are required. This is highlighted by the significance of each estimate, the independence of the null hypothesis, and its rejection of the same distribution.

The results of the MQ-QR analysis provide extensive information for investigating the complex relationships between independent factors and CO_2 emissions. Although HPI is generally regarded as environmentally benign, this may have a negative impact on emissions. The challenges of successfully adopting and integrating sustainable HPI technologies into existing infrastructures are highlighted by this research (Llácer-Iglesias et al. 2021; Quaranta et al. 2020). Similarly, the negative effects associated with OEF and IND highlight the difficulties in reconciling economic growth with technical innovation and environmental conservation.

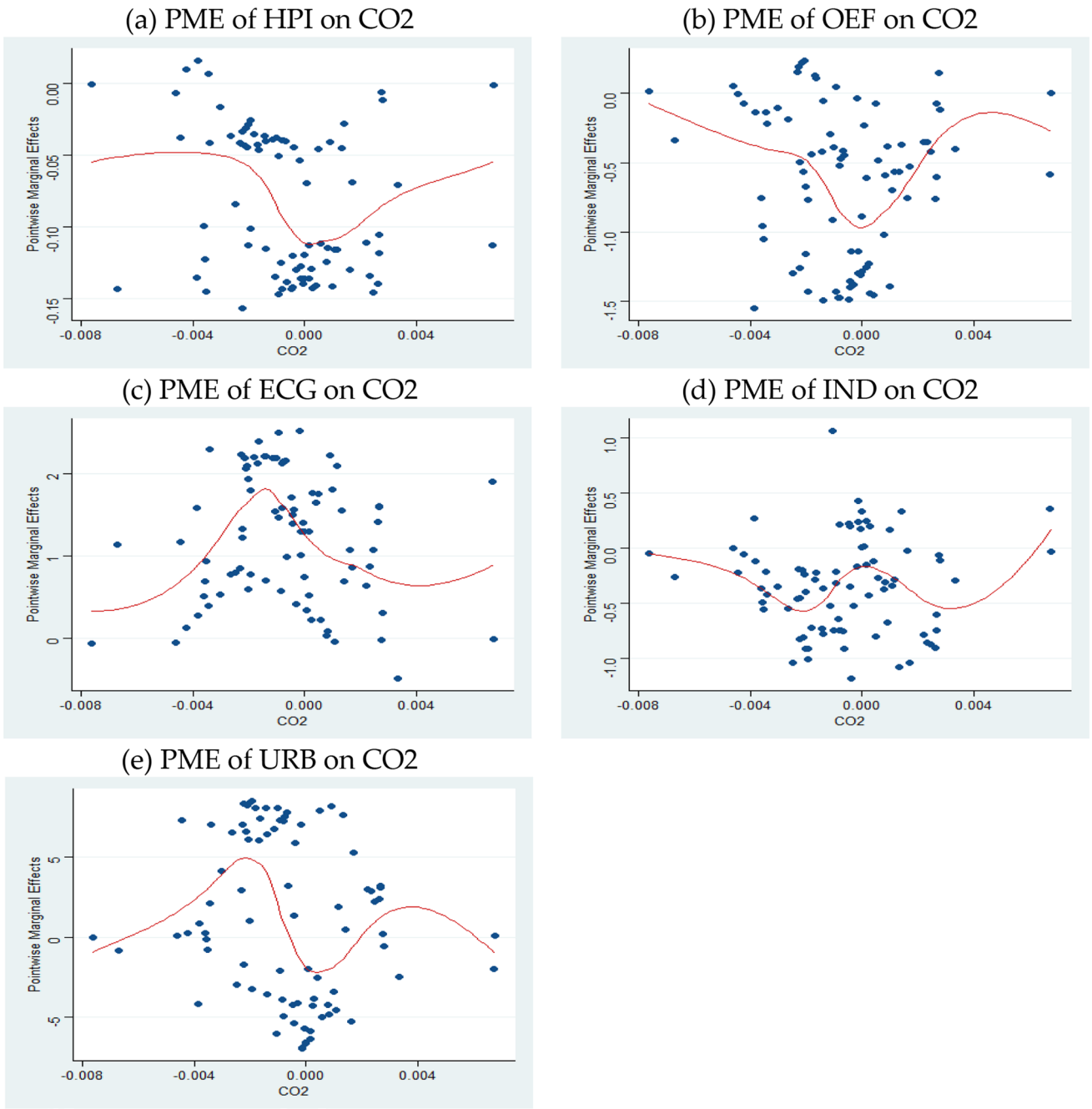


Fig. 5 Pointwise Marginal Effects of HPI, OEF, ECG, IND, and URB on CO_2

This validates research results on the effects of industrial wastes on the environment (Adebayo and Ullah 2023; Phadkantha and Tansuchat 2023) and growth (Lin and Teng 2022; Yue et al. 2023). OEF and IND may grow negatively because of higher energy use and production processes. The drawbacks of advancements in OEF, HPI, and IND procedures underscore the challenges associated with implementing environmentally friendly solutions in these domains.

However, the carbon emissions increasing impact of URB and ECG on draws attention to the harmful environmental impacts resulting from the rapid proliferation of URB and ECG. These findings support previous research highlighting the complex link between environmental degradation, URB, and ECG. The negative environmental implications of URB expansion and ECG are highlighted by the positive connections between these variables, which can be explained by increasing energy consumption and traffic congestion

Table 6 Average effects of HPI, OEF, ECG, IND, and URB on CO_2

	Average	Std. error	t-Value	1st Qr	2nd Qr	3rd Qr
HPI	−0.082*** [0.000]	0.007	−10.998	−0.130	−0.099	−0.040
OEF	−0.628*** [0.000]	0.064	−9.744	−1.148	−0.526	−0.163
ECG	1.225*** [0.000]	0.097	12.672	0.621	1.302	1.859
IND	−0.342*** [0.000]	0.070	−4.892	−0.735	−0.335	−0.054
URB	1.127*** [0.000]	0.196	5.758	−3.706	0.482	6.550
Diagnostics						
R^2 0.957	Lambda	0.053	Sigma	5	Looloss	0.096

Qr Quartile; ***[*p*] < 0.01, **[*p*] < 0.05, *[*p*] < 0.1

(Kłos-Adamkiewicz et al. 2023; Raihan et al. 2022a, b, c). It is essential to comprehend these channeling interactions in order to create practical solutions that deal with the underlying causes of emissions.

The study's conclusions are reinforced by robustness analysis employing a variety of methods, such as QR vs mean MQ-QR, KRLS, and mean PME regressions. Employing diverse methodologies enhances the precision of the identified structures and advances a more profound comprehension of the intricate connections governing carbon dioxide emissions in Japan. These findings have significant policy implications since they show that, in Japan's changing environment, tailored interventions are necessary to strike a balance between economic aspirations and ecological aims. The study provides significant fresh insights into the discussion around ecologically friendly development techniques.

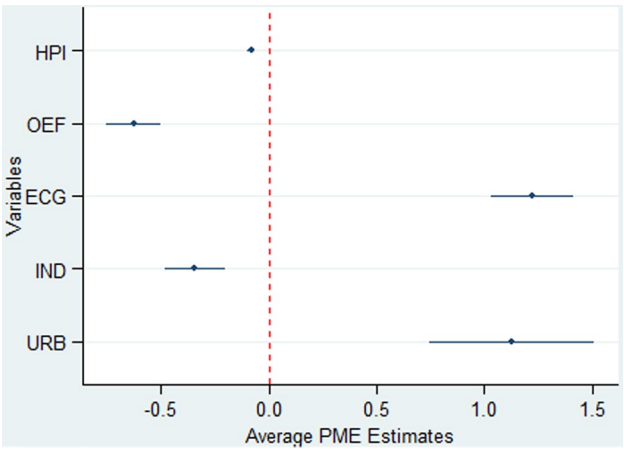


Fig. 6 Average PME of HPI, OEF, ECG, IND, and URB on CO_2. Note: Diagnostics: R^2: 0.957, Lambda: 0.053; Sigma: 5; Looloss: 0.096. PME: Pointwise Marginal Effects.

The empirical analysis findings on the relationship between hydropower innovation and carbon emissions conflict with studies in the literature that claim that hydropower generation does not have any impact on the environment. The primary reasons for this may be that these studies are applied to countries other than Japan or that they generally focus on energy consumption or production rather than innovation. From a theoretical perspective, it can be explained through the lens of ecological modernization theory (EMT), which suggests that technological progress and environmental innovation can decouple economic growth from environmental degradation. In the context of Japan, a technologically advanced and energy-constrained economy, innovations in hydropower, such as more efficient turbines, improved reservoir management, and smart grid integration, can increase the use of renewable energy while displacing fossil fuel-based generation. Unlike previous studies that may have focused on countries with underdeveloped hydro infrastructure or high dependence on coal, Japan's energy mix and innovation ecosystem support the emission reduction potential of hydropower innovation. Therefore, our findings reflect a context-specific manifestation of EMT, where hydropower acts as both an energy security measure and a low-carbon development tool.

In quantile perspective, our results show that both hydropower innovations (HPI) and oil efficiency (OEF) have the most pronounced emission-reducing effects at lower carbon emission levels. This suggests that these tools are particularly effective at stabilizing and sustaining low emission trajectories rather than reducing high emission growth. From a global sustainability perspective, this highlights Japan's role as a mature, technologically advanced economy contributing to climate stability—an important complement to the high mitigation strategies seen in emerging economies. These findings align with international frameworks such as the UN Sustainable Development Goals (SDGs 7 and 13),

the Paris Agreement's Global Stocktake, and the OECD's Green Growth Strategy, which emphasize not only emissions reduction but also the long-term institutionalization of low-carbon growth through innovation and efficiency.

Conclusion

This research uses a thorough analytical technique to investigate the complex relationships between several factors that affect CO_2 emissions in Japan. The denial of the null hypothesis that the time-series data is i.i.d, as revealed by the BDS test, highlights the complexities present in the considered variables. The stability assessment emphasizes the dynamic character of the time series, underscoring the need for an in-depth comprehension of emissions in the context of Japan. The use of multivariate quantile-on-quantile regression provides significant insights into the distinct effects of hydropower innovations, oil efficiency, industrialization, urbanization, and economic growth on CO_2 emissions. The negative consequences of advancements in hydropower, improvements in oil efficiency, and the growth of industry pose significant obstacles to the integration of sustainable energy practices and the enhancement of industrial processes, while also potentially worsening emissions. In contrast, the favorable connections between urbanization, economic growth, and emissions highlight the ecological implications of rapid urbanization and prosperity. The inclusion of several regression approaches in the robustness evaluation improves the reliability of the results. The quantile-on-quantile regression, Kernel-Based Regularized Least Squares, and Average Pointwise Marginal Effects regressions all confirm and support the discovered trends, demonstrating that the results are consistent across various analytical frameworks.

The results have significant implications for policy formation in Japan. Governments should give sustainable practices priority while developing hydropower technology, with a focus on innovations that minimize harm to the environment, in order to mitigate negative effects. Stricter laws and financial incentives for the adoption of cleaner energy sources are needed to boost oil consumption efficiency. To lessen the detrimental effects of industrialization on emissions, a well-planned approach is required, one that promotes environmentally friendly industrial practices and technological innovation in the production process. Ecologically friendly urban growth should be prioritized more in urbanization efforts to limit emissions linked to rapid urban expansion. Promoting green spaces and public transport can help achieve this. Simultaneously, a comprehensive and all-encompassing approach is required to capitalize on the positive correlations between economic expansion and emissions. It recommends that policymakers subsidize environmentally friendly technologies, encourage the adoption of sustainable corporate practices, and find ways to decouple economic growth from carbon-intensive activities. Japan's all-encompassing policy framework needs to balance economic goals with ecological sustainability. To deliver a new era of sustainable growth, this can be achieved by prioritizing the adoption of the latest technology, creating effective regulatory frameworks, and engaging the public.

Based on the finding that hydropower innovations and oil efficiency are more effective in low-emission quantiles, it is possible to make some policy recommendations. Based on our findings, Japanese policymakers should view hydropower innovation and oil efficiency as important tools not only to achieve carbon reductions but also to sustain low-emission trajectories in already decarbonized sectors. Policy interventions should therefore focus on scaling up innovation in low- or declining-emission regions to strengthen long-term sustainability. Furthermore, incorporating these tools into Japan's differentiated climate policy design—aligned with the Green Growth Strategy and SDGs—can provide maximum impact and practical relevance on the country's path to carbon neutrality.

Although the techniques used in this study are cross-sectional in nature and do not directly distinguish between time horizons, the stronger effects of HPI on lower quantiles of CO_2 emissions suggest that HPI may be more effective in maintaining long-term stability of low emissions rather than producing immediate short-term reductions during peak emission periods. This interpretation is consistent with Japan's mature technological landscape, where innovation plays a greater role in consolidating previous gains rather than achieving sudden reductions. Future research could usefully complement QQR and KRLS with time-series models (e.g. ARDL or NARDL) to explicitly examine dynamic temporal effects and distinguish between short-term and long-term effects. This would further enrich our understanding of the timing and persistence of the impact of hydropower innovation on carbon emissions.

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

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval This article does not contain any studies with human participants.

Consent for publication Our study does not contain individual person's data.

Consent to participate No human or animal subjects were used in our study, and no questionnaire was conducted.

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