The effect of renewable energy on carbon dioxide emission in Taiwan: Quantile mediation analysis

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Abstract
In this paper, we propose an integrated method, called quantile mediation analysis, which combines quantile regression and mediation analysis, to examine the impact of renewable energy on carbon dioxide emissions, whether connected to or separate from through economic growth, from 1990 to 2018 in Taiwan. The results of this novel approach indicate that Taiwan’s renewable energy did not affect carbon dioxide emissions through the mediation effect of economic growth from the period of 1990 to 2018, and that there is only a direct effect from renewable energy to carbon dioxide emissions at any distribution. Moreover, this result is remarkably different from the result of the traditional ordinary least square approach, which shows that Taiwan’s renewable energy affects carbon dioxide emissions through the partial mediation effect of economic growth. In conclusion, we suggest that the Taiwanese government should increase the use of renewable energy in reducing local and global carbon dioxide emissions.

Keywords
Quantile mediation analysis, carbon dioxide emission, economic growth, renewable energy

Introduction
Reducing global carbon dioxide (CO₂) emissions has been a core subject of researchers and government concern.1,2 Due to the low CO₂ emissions of renewable energy sources, renewable energy plays an important role in reducing global CO₂ emissions. Indeed, some empirical studies concluded that renewable energy improves environmental quality.3–5 For instance, Baek3 used the USA data to examine the effects of renewable energy on CO₂ emissions. The author found that renewable energy consumption only has a negative effect.
impact on reducing CO₂ emissions in the short run. However, according to Panayotou, renewable energy also results in environmental costs through the impact of economic activities which use more energy resources, that is, causing more carbon emission given a certain level of technology. This perspective concludes that increased economic activities stimulated by renewable energy worsens environmental quality. For example, Grossman and Krueger provided a systematic explanation for the relationship between gross domestic product (GDP) and environmental pollutants. They divide the economic development stage into three parts: scale effect, composition effect, and technique effect. The scale effect asserts that an increase in production impedes environmental quality; therefore, economic growth causes a data negative effect on environmental quality. Several empirical studies demonstrated that economic growth correlates with CO₂ emissions.

On the other hand, some empirical studies have found a favorable linkage between renewable energy consumption and economic growth. For instance, Yao, Zhang, and Zhang found that there exists a long-run relationship between renewable energy, CO₂ emissions, and economic growth for 17 major developing and developed countries and for six geo-economic regions in the world. In summary, previous literature reflects an emphasis on renewable energy consumption and CO₂ emissions, economic growth and CO₂ emissions, and renewable energy consumption and economic growth. Therefore, there is an apparent scarcity of empirical evidence on the relationship amongst renewable energy consumption, economic growth and CO₂ emissions. This knowledge gap provides stronger motivation for investigating the interaction among these factors in the context of Taiwan. The purpose of this paper is to investigate whether there is a direct relationship between renewable energy and CO₂ emissions in Taiwan, or an indirect relationship between renewable energy and CO₂ emissions, via economic growth in Taiwan; or if there exist both direct and indirect relationships.

To decrease CO₂ emissions, the Taiwanese government issued the Renewable Energy Development Act in 2009, and actively promotes the use of renewable energy, from sources such as biomass and waste, solar thermal, conventional hydropower, geothermal, solar photovoltaic, and wind energy. Table 1 shows renewable energy supplies in Taiwan from 1990 to 2018. According to the statistics of the Taiwan Bureau of Energy, Ministry of Economic Affairs, biomass and waste energy are widely used and accounted for approximately 63.88% of Taiwan’s total renewable energy supply in 2018. Since 2009, the use of geothermal, solar photovoltaic, and wind energy supply has rapidly increased from 3.48% of total renewable energy supply to 16% in 2018.

Moreover, in this study, we propose an innovative methodology that is totally different from past research studies. We combine mediation analysis and quantile regression, proposed by Koenker and Bassett to investigate the dynamic short-run causal impact of renewable energy on CO₂ emissions, whether connected to or separate from through economic growth, across different conditional CO₂ emissions from 1990 to 2018 in Taiwan. The main advantage of using this quantile regression model is that it does not require strong assumptions for error terms and is generally considered more robust because it estimates the median and the full range of the conditional distribution of the explained variables, rather than traditional ordinary least squares (OLS) regression to simply analyze the conditional expectation of the explained variables. Moreover, the effects of explanatory variables on the explained variables are different across quantiles.
Certain studies\textsuperscript{26–28} used a panel quantile regression approach to analyze CO\textsubscript{2} emissions. For example, Cheng et al.\textsuperscript{26} propose panel quantile regression to explore technological innovation to mitigate CO\textsubscript{2} emissions in 35 OECD countries. The authors found out that technological innovation directly reduces CO\textsubscript{2} emissions, but it is significantly heterogeneous and asymmetric across quantiles.

\section*{Literature review}

In line with rapidly increasing levels of renewable energy consumption, many studies have examined the impact of renewable energy consumption on CO\textsubscript{2} emissions. They conclude that increasing renewable energy consumption mitigates CO\textsubscript{2} emissions for the economies of the USA\textsuperscript{3}; China\textsuperscript{4}; and OECD economies.\textsuperscript{5} For instance, Baek\textsuperscript{3} used

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|}
\hline
Year & Biomass and waste & Solar thermal & Conventional hydropower & Geothermal, solar photovoltaic, and wind energy \\
\hline
1990 & 50.0 & 19.6 & 610.0 & 2.7 \\
1991 & 67.9 & 24.9 & 368.4 & 1.7 \\
1992 & 90.2 & 32.0 & 626.8 & 1.8 \\
1993 & 81.9 & 38.7 & 392.8 & 1.3 \\
1994 & 125.6 & 46.5 & 483.9 & 0.0 \\
1995 & 192.9 & 54.6 & 462.7 & 0.0 \\
1996 & 261.4 & 60.4 & 453.4 & 0.0 \\
1997 & 465.4 & 66.0 & 501.5 & 0.0 \\
1998 & 568.8 & 70.1 & 592.9 & 0.0 \\
1999 & 781.5 & 73.2 & 482.9 & 0.0 \\
2000 & 943.6 & 77.3 & 435.9 & 0.1 \\
2001 & 1205.8 & 81.1 & 486.6 & 1.2 \\
2002 & 1304.3 & 84.3 & 265.7 & 1.6 \\
2003 & 1567.3 & 87.9 & 290.1 & 2.3 \\
2004 & 1599.5 & 92.7 & 306.9 & 2.5 \\
2005 & 1595.0 & 97.5 & 381.1 & 8.8 \\
2006 & 1628.1 & 102.4 & 390.8 & 26.5 \\
2007 & 1689.0 & 105.5 & 422.3 & 42.2 \\
2008 & 1729.8 & 109.5 & 411.6 & 56.7 \\
2009 & 1638.0 & 113.2 & 358.3 & 76.1 \\
2010 & 1706.9 & 114.3 & 401.0 & 100.6 \\
2011 & 1732.4 & 113.2 & 382.4 & 149.4 \\
2012 & 1758.9 & 114.0 & 542.0 & 151.7 \\
2013 & 1764.0 & 112.8 & 518.4 & 189.1 \\
2014 & 1730.1 & 112.2 & 412.8 & 196.2 \\
2015 & 1743.4 & 113.5 & 427.3 & 229.5 \\
2016 & 1686.0 & 112.1 & 627.3 & 247.5 \\
2017 & 1621.9 & 113.1 & 520.7 & 326.4 \\
2018 & 1689.3 & 104.7 & 427.2 & 423.1 \\
\hline
\end{tabular}
\caption{Renewable energy (RENEW) supply in Taiwan (1990–2018) unit: 10\textsuperscript{3} KLOE.}
\end{table}

\textit{Note:} KLOE = kiloliter of oil equivalent.
\textit{Source:} The statistics of the Taiwan Bureau of Energy, Ministry of Economic Affairs (2020).
the US data to examine the effects of renewable energy on CO2 emissions and found that renewable energy consumption only has a negative impact on reducing CO2 emissions in the short run.

On the other hand, many researchers have studied the relationship between economic growth and CO2 emissions. For instance, Balsalobre-Lorente et al.\textsuperscript{14} explores the relationship between economic growth and CO2 emissions in countries in the European Union – Germany, France, Italy, Spain, and the United Kingdom – between 1985 and 2016. They found that economic growth has a positive impact on CO2 emissions.

In addition to the above factors affecting CO2 emissions, many recent studies\textsuperscript{29–39} propose other factors, including innovation shocks, higher education, fiscal policy, monetary policy, commercial policy, eco-innovation, foreign direct investment, etc., as having an effect. For instance, Ahmad et al.\textsuperscript{33} explored the relationship between innovation shocks and CO2 emissions in the OECD economies. The results indicated that positive shocks to innovation improve environmental quality. However, the negative innovation shocks disrupt environmental quality. The authors suggested that the government should adopt innovation shocks as a policy instrument to formulate better environmental policies for a sustainable future. Chishti et al.\textsuperscript{34} discovered a novel predictor of CO2 emissions, namely fiscal and monetary policies, in BRICS economies. The authors found that the expansionary fiscal policy intensifies the harmful repercussions of CO2 emissions. However, the contractionary fiscal policy serves as an effective measure to mitigate the detrimental effects of CO2 emissions. Similarly, expansionary monetary policy also deteriorates CO2 emissions and contractionary monetary policy mitigates environmental quality.

**Methodology**

This paper integrates quantile regression and mediation analysis to examine the impact of renewable energy on CO2 emissions, whether through economic growth or not, from 1990 to 2018 in Taiwan. Through this novel methodology, the results can be provided as a reference for Taiwan’s government to make policy decisions regarding the promotion of renewable energy supplies.

**Quantile regression**

Quantile regression is a statistical technique intended to estimate and conduct inference about a conditional quantile function. Koenker and Bassett\textsuperscript{23} proposed the quantile regression approach as an alternative to ordinary least squares regression in a wide range of applications. This approach takes into consideration the skewness of distributions and gives a more complete picture of the performance affected by various independent variables. This technique was further developed by Koenker, and Hallock and Koenker.\textsuperscript{24,25}

According to Koenker,\textsuperscript{25} quantile regression is used when an estimate of the various quantile of a population is desired. One of the advantages of using quantile regression to estimate the median and the full range of other conditions, rather than ordinary least squares regression to estimate the mean, is that a quantile regression will be more robust in response to large outliers. Like the least absolute deviations, the quantile regression objective function is a weighted sum of absolute deviations, which gives a robust
measure of location, so that the estimated coefficient vector is not sensitive to outlier observations on the dependent variable. Moreover, a quantile regression also provides a more efficient approach than the ordinary least squares method when the disturb term is non-normal. A quantile regression can be considered as a natural analog in regression analysis to the practice of using different measures of central tendency and statistical dispersion to obtain a more comprehensive and robust analysis. Lastly, a further advantage of quantile regression is that any quantile can be estimated when we have enough data.

According to Koenker and Bassett’s method,23 we first let \( y_t, t = 1,2,\ldots,T \) be a random sample on the following regression process:

\[
y_t = u_t + x_t \beta
\]  

Equation (1) has a conditional distribution function as equation (2).

\[
F_{y/x} = F(Y_t \leq y) = F(y_t - x_t \beta)
\]

where \( x_t, t = 1,2,\ldots,T \) denote a sequence of (row) k-vectors of a known design matrix.

The \( \theta \)th regression quantile, \( Q_{y/x}(\theta) \), \( 0 < \theta < 1 \) is defined as any solution to the following minimization problem:

\[
\min_{\beta} \left\{ \theta \sum |y_t - x_t \beta| + (1 - \theta) \sum |y_t - x_t \beta| \right\}
\]

where \( \{t: Y_t \geq X_t \beta\} \) and \( \{t: Y_t < X_t \beta\} \) (3)

The resulting solution to equation (3) is denoted as \( \beta_\theta \), from which we obtain the \( \theta \)th conditional quantile \( Q_{y/x}(\theta) = x \beta_\theta \)

**Meditation analysis on economic growth**

We can use mediation analysis to investigate the causality from renewable energy to CO2 emissions through economic growth and the direct relation between renewable energy and CO2 emissions in equations (4) to (6). The most common approach to examine mediation effect is the causal steps procedure popularized by Baron and Kenny.40 This analysis involves the following set of regression equations relating to the independent variable, mediator variable, and dependent variable:

\[
CO2 = b_0 + b_1 \text{RENEW} + e_1
\]

(4)

\[
\text{GROW} = c_0 + c_1 \text{RENEW} + e_2
\]

(5)

\[
CO2 = d_0 + d_1 \text{RENEW} + d_2 \text{GROW} + e_3
\]

(6)

Here, the degree of renewable energy (RENEW) is measured as solar photovoltaics energy, solar thermal energy, wind energy, hydropower, geothermal energy; as well as renewable biomass energies, such as waste energy, biogas electrification, biofuel, and so on in kiloliter of oil equivalent. The variable of CO2 is per capita carbon dioxide emissions in metric tons. Economic growth (GROW) is measured as the real Gross Domestic Product. Technically, \( e_i, i = 12,3 \) is the stochastic error term. According to Baron and Kenny,40 meditation analysis on economic growth processes comprise the following
procedures:

Procedure 1: The independent variable RENEW should relate to the dependent variable CO2, such that $b_1$ in equation (4) is significant. This condition is used to establish that there is a relationship between RENEW and CO2 to be mediated.

Procedure 2: The independent variable RENEW should relate to the mediator variable GROW, such that $c_1$ in equation (5) is significant. This condition establishes the first stage of the mediated effect.

Procedure 3: The mediator variable GROW should relate to the dependent variable CO2, such that $d_2$ in equation (6) is significant. This condition establishes the second stage of the mediated effect.

Procedure 4: The independent variable RENEW should no longer relate to the dependent variable CO2 after the mediator variable GROW is controlled, such that $d_1$ in equation (6) is not significant. This condition shows that the relationship between RENEW and CO2 examined under the first condition disappears when the mediated effect transmitted through GROW is considered.

Satisfying all four steps provides evidence for complete mediation, whereas satisfying the first three steps indicates partial mediation if $d_1$ in equation (6) is still significant and is smaller than $b_1$ in equation (4).

**Quantile mediation analysis**

An integrated method proposed by Hsu\textsuperscript{41} combines quantile regression and mediation analysis, which substitutes equation (3) into equations (4) to (6) and can be described to equations (7) to (9). This analysis provides a useful supplement to the standard constant-parameter regression estimate (only one $b$ or $c$ or $d$) for studying all possible parameters (for all quantiles) varying across high dependent variable and low dependent variable. This novel method also leads to a more dynamic and complete understanding of what might really underlie the stories of great effect or non-effect for renewable energy on CO2 emissions. The quantile regression minimizes a weighted sum of the positive and negative error terms in equations (7) to (9).

\[
\min_b \theta \sum |CO_2_t - b_0 - b_1 \text{RENEW}_t| + (1 - \theta) \sum |CO_2_t - b_0 - b_1 \text{RENEW}_t| \quad (7)
\]

\[
\min_c \theta \sum |\text{GROW}_t - c_0 - c_1 \text{RENEW}_t| + (1 - \theta) \sum |\text{GROW}_t - c_0 - c_1 \text{RENEW}_t| \quad (8)
\]

\[
\min_d \theta \sum |CO_2_t - d_0 - d_1 \text{RENEW}_t - d_2 \text{GROW}_t| \\
+ (1 - \theta) \sum |CO_2_t - d_0 - d_1 \text{RENEW}_t - d_2 \text{GROW}_t| \quad (9)
\]

**Results**

This study uses annual official Taiwan data that covers the period 1990–2018. The data on carbon dioxide emissions (CO2) and renewable energy (RENEW) are from the
governmental Bureau of Energy, a branch of the Ministry of Economic Affairs. The variable of GROW is compiled from the Taiwan Economic Journal. All variables are in logarithmic form.

Before estimating equations (7) to (9), we use the augmented Dickey–Fuller (ADF) unit root test to determine the order of integration of these three variables. Table 2 shows the unit root test results in levels and first differences with trend and intercept. The results demonstrate that we cannot reject the null hypothesis of the unit root for three variables in levels. However, we reject the null hypothesis of a unit root at the 1% significance level for the first difference of these three variables. Based on the results from the ADF test, these three data series are integrated into order one.

Regarding the causal relationship between renewable energy and CO2 emissions, and renewable energy and economic growth in equations (7) and (8), we demonstrate the causality test results in Table 3. The notation of RENEW $\neq$ CO2 means that the variable renewable energy does not affect the variable CO2 emissions. Similarly, RENEW $\neq$ GROW means that the variable renewable energy does not affect the variable economic growth.

We found the following results. First, there is the causal relationship from renewable energy to CO2 emission by using the traditional ordinary least square method (OLS) and using a quantile approach at any distributions of CO2 emissions. In other words, there is a direct relationship between renewable energy and CO2 emissions by using a quantile regression. This result shows that the negative effects of renewable energy on the low quantile CO2 emissions are greater than those of the high quantile CO2 emissions (see Table 3 and Figure 1). Moreover, there exists causality running from renewable energy to economic growth by using the traditional OLS method and using a quantile approach at any distributions of CO2 emissions in Table 3. In other words, this result shows that the positive effects of renewable energy on the low quantile economic growth are closer than those of the high quantile economic growth. In summary, these results establish the first stage of the mediated effect.

Table 4 and Figure 2 show that $d_2$ is significant when using traditional OLS in equation (9); that is, the mediator variable GROW relates to the dependent variable CO2. This result establishes the second stage of the mediated effect. However, $d_2$ is not significant when using a quantile approach at any distribution of CO2 emissions. It means that the second stage of the mediated effect is not established by using a quantile approach.

**Table 2. Results from the augmented Dicker–Fuller (ADF) unit root test.**

|        | Level | P-value | First difference | P-value |
|--------|-------|---------|------------------|---------|
| RENEW  | -0.545| 0.974   | -14.041          | 0.000*  |
| CO2    | -1.398| 0.839   | -4.520           | 0.007*  |
| GROW   | -1.928| 0.613   | -5.297           | 0.001*  |

*Indicates the parameter is significant at the 1% level.

CO2: carbon dioxide; RENEW: renewable energy; GROW: economic growth.
Moreover, through the OLS method, the variable RENEW relates to the dependent variable CO2 after the mediator variable GROW is controlled for, such that $d_1$ is significant in equation (9) and is smaller than $b_1$ in equation (7). This result illustrates partial mediation because of satisfying three steps in equations (7) to (9).

| Quantile | RENEW $\neq$ CO2 | RENEW $\neq$ GROW |
|----------|------------------|------------------|
|          | $b_1$            | $P$-value        | $c_1$            | $P$-value        |
| 0.20     | $-1.035$         | 0.001*           | 0.987            | 0.000*           |
| 0.40     | $-0.932$         | 0.000*           | 1.072            | 0.000*           |
| 0.50     | $-0.923$         | 0.000*           | 0.941            | 0.000*           |
| 0.60     | $-0.879$         | 0.000*           | 0.888            | 0.000*           |
| 0.80     | $-0.888$         | 0.000*           | 0.968            | 0.000*           |
| OLS      | $-0.972$         | 0.000*           | 0.949            | 0.000*           |

*Indicates the parameter is significant at the 1% level.

CO2: carbon dioxide; RENEW: renewable energy; GROW: economic growth; OLS: ordinary least squares.

Figure 1. Changes in quantile regression coefficients.

Notes: The x-axis denotes the conditional quantiles of carbon dioxide (CO2), and the y-axis presents the coefficient values of the renewable energy variable. The red lines correspond to the 95% confidence intervals of the quantile estimation.
Table 4. Results from RENEW and GROW to CO₂ at different quantiles.

| Quantile | RENEW → CO₂ | GROW → CO₂ |
|----------|-------------|-------------|
|          | d₁          | P-value     | d₂          | P-value     |
| 0.20     | −0.511      | 0.107       | 0.427       | 0.194       |
| 0.40     | −0.750      | 0.000*      | 0.181       | 0.246       |
| 0.50     | −0.708      | 0.000*      | 0.203       | 0.256       |
| 0.60     | −0.822      | 0.000*      | 0.058       | 0.738       |
| 0.80     | −0.874      | 0.000*      | 0.016       | 0.916       |
| OLS      | −0.638      | 0.000*      | 0.351       | 0.011**     |

*Indicates the parameter is significant at the 1%.
**Indicates the parameter is significant at the 5%.

CO₂: carbon dioxide; RENEW: renewable energy; GROW: economic growth; OLS: ordinary least squares.

Third, through a quantile method, although the variable RENEW still relates to the dependent variable CO₂ after the mediator variable GROW is controlled for at higher than 0.2 distributions of CO₂ emissions in Table 4, the mediator variable GROW does not correlate to the dependent variable CO₂. In other word, these results show that the negative effects of renewable energy on the high quantile CO₂ emissions are greater than those of the low quantile CO₂ emissions. These results are similar to Cheng et al. 26,43 findings that renewable energy supply reduces CO₂ emissions with the strongest effect at the high quantile even though the authors used panel quantile regression to examine the impact of renewable energy on CO₂ emissions in OECD countries and the six developing countries, respectively. However, this condition suggests that the relationship between RENEW and CO₂ examined under the second condition disappears

Figure 2. Changes in quantile regressions coefficients.
Notes: The x-axis denotes the conditional quantiles of carbon dioxide (CO₂), and the y-axis presents the coefficient values of the different variables. The red lines correspond to the 95% confidence intervals of the quantile estimation.
when the mediated effect transmitted through GROW is considered. This result evidences no mediation effect because of not satisfying all four steps in equations (7) to (9).

Applying the traditional OLS method, we found that not only does renewable energy affect CO₂ emissions through the partial mediation effect of economic growth for the period of 1990–2018, but there is also a direct relationship between renewable energy and CO₂ emissions. Moreover, by utilizing quantile mediation regression, we demonstrate that renewable energy does not affect CO₂ emissions through the mediation effect of economic growth at any distributions of CO₂ emissions, which contrasts with previous empirical findings. However, there is only a direct effect from renewable energy to CO₂ emissions at any distributions of CO₂ emissions in Taiwan. In summary, compared with the OLS regression results, we can assert that the quantile model provides much more useful and complete information on the impact of renewable energy on CO₂ emissions in Taiwan.

To test the stability of the estimated parameters obtained from quantile mediation regression, we applied the export variable which has a high correlation with economic growth, to rerun the regressions. Estimation results of this robust check are consistent with that of quantile mediation regression. Therefore, we conclude that the parameters of our models acquired from quantile mediation regression are stable.

**Conclusion and policy recommendations**

This study examines the effect of renewable energy consumption on CO₂ emissions in Taiwan. Economic growth is considered as a moderating variable. To require more robust results and obtain more information about impacts, this study utilized quantile mediation regression to estimate the median and the full range of the conditional distribution of the explained variables. Moreover, the direct and indirect impacts of renewable energy consumption on CO₂ emissions in Taiwan are analyzed.

The main conclusions of this study are threefold. First, the results of the quantile mediation regression indicated that there is a direct negative effect from renewable energy to CO₂ emissions in Taiwan. This indicates that renewable energy consumption has contributed to mitigating CO₂ emissions in the country. Second, the empirical result reflects that economic growth does not play a mediatory role in CO₂ emissions. Third, the negative effects of renewable energy on the high quantile CO₂ emissions are greater than those of the low quantile CO₂ emissions in Taiwan.

The key contribution of this paper is that we propose an innovative methodology that combines mediation analysis and quantile regression – this allows for obtaining the full characterization of the conditional distribution of the dependent variable, rather than its conditional mean only. That is, we provide a comprehensive picture of renewable energy to CO₂ emissions in Taiwan over the period of 1990 to 2018. The result of this innovative analysis indicates that Taiwan’s renewable energy directly mitigates CO₂ emissions at any distribution. In accordance with this result, this paper recommends that the Taiwanese government should increase the use of renewable energy to reduce CO₂ emissions. First, the Taiwanese government can provide tax relief or investment incentives for manufacturers using renewable energy e.g. biomass and waste, solar thermal, conventional hydropower, geothermal, solar photovoltaic, and wind energy.
Second, the Taiwanese government should adopt either contractionary fiscal policy or contractionary monetary policy or contractionary commercial policy to reduce CO₂ emissions.

The findings of this study must be considered some to have limitations which necessitates further research. Its main limitation is that it only focused on a single economy. Future studies can use a panel of other CO₂ emission nations for comparative analysis. Moreover, this study mainly considers aggregate renewable energy consumption, therefore, researchers can explore a disaggregated level analysis of renewable energy consumption.

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References
1. Shaw HJ and Tzu FM. The strategy of energy saving for smart shipping. Adv Technol Innov 2019; 4: 165–176.
2. Rasyid MUHA, Nadhori IU, Sudarsono A, et al. Pollution monitoring system using Gas sensor based On wireless sensor network. Int J Eng Techno. Innov 2016; 6: 79–91.
3. Baek J. Do nuclear and renewable energy improve the environment? Empirical evidence from the United States. Ecolog Indic 2016; 66: 352–356.
4. Chen Y, Wang Z and Zhong Z. CO2 Emissions, economic growth, renewable and non-renewable energy production and foreign trade in China. Renew Energy 2019; 131: 208–216.
5. Ahmad M, Khan Z, Rahman ZU, et al. Can innovation shocks determine CO₂ emissions (CO₂e) in the OECD economies? A new Perspective. Econ Innov N. Techno 2021; 30: 89–109.
6. Panayotou T. Empirical tests and policy analysis of environmental degradation at different stages of economic development. Intern Labour Org 292778 1993.
7. Grossman GM and Krueger AB. Economic growth and the environment. Q J Econ 1995; 110: 353–377.
8. Lotfalipour MR, Falahi MA, Ashena M., Economic, et al. CO₂ Emissions, and fossil fuels consumption in Iran. Energy 2010; 35: 5115–5120.
9. Chandran VGR and Tang CF. The impacts of transportation energy consumption, foreign direct investment and CO₂ emissions in ASEAN-5 economies. Renew Sustain Energy Rev 2013; 24: 445–453.
10. Yin J, Zheng M and Chen J. The effects of environmental regulation and technical progress on CO₂ kuznets curve: an evidence From China. Energy Pol 2015; 77: 97–108.
11. Dogan E and Turkekul B. CO₂ Emissions, real output, energy consumption, trade, urbanization and financial development: testing the EKC hypothesis for the USA. Environ Sci Pollu Res 2016; 23: 1203–1213.
12. Zoundi Z. CO2 Emissions, renewable energy, and the environmental kuznets curve: a panel CO-integration approach. Renew Sustain Energy Rev 2017; 72: 1067–1075.

13. Alshehry AS and Belloumi M. Study of the kuznets curve for transport carbon dioxide emissions in Saudi Arabia. Renew Sustain Energy Rev 2017; 75: 1339–1347.

14. Balsalobre-Lorente D, Shahbaz M, Roubaud D, et al. How economic growth, renewable electricity and natural resources contribute to CO2 emissions? Energy Pol 2018; 113: 356–367.

15. Apergis N and Payne JE. Renewable energy consumption and economic growth, evidence from a panel of OECD countries, Energy Pol 2010; 38: 656–660.

16. Sadorsky P. Renewable energy consumption and income in emerging economies, Energy Pol 2009; 37: 4021–4028.

17. Apergis N and Payne JE. The renewable energy consumption-growth nexus in Central America. App Energy 2011; 88: 343–347.

18. Lin B and Moubarak M. Renewable energy consumption – economic growth nexus for China. Renew Sustain Energy Rev 2014; 40: 111–117.

19. Nguyen KH and Kakinak M. Renewable energy consumption, carbon emissions, and development stages: some evidence from panel cointegration analysis. Renew Energy 2019; 132: 1049–1057.

20. Zoundi Z. CO2 Emissions, renewable energy, and the environmental kuznets curve: a panel CO-integration approach. Renew Sustain Energy Rev 2017; 72: 1067–1075.

21. Alshehry AS and Belloumi M. Study of the kuznets curve for transport carbon dioxide emissions in Saudi Arabia. Renew Sustain Energy Rev 2017; 75: 1339–1347.

22. Yao S, Zhang S and Zhang X. Renewable energy, carbon emission and economic growth: a revised environmental kuznets curve perspective. J Clean Prod 2019; 335: 1338–1352.

23. Koenker R and Bassett G. Regression quantile, Econometrica 1978; 46: 33–49.

24. Koenker R and Hallock K. Quantile regression, J Econo Persp 2001; 15: 143–156.

25. Koenker R. Quantile Regression, econometric society monograph series. 2005; Cambridge University Press.

26. Cheng C, Ren X, Dong K, et al. How does technological innovation mitigate CO2 emissions in OECD countries? Heterogeneous analysis using panel quantile regression. J Environ Manag 2021; 280: 1–11.

27. Yan D, Ren X, Kong Y, et al. The heterogeneous effects of socioeconomic determinants on PM2.5 concentrations using a two-step panel quantile regression. App Energy 2020; 272: 1–10.

28. Yan D, Kong Y, Ren X, et al. The determinants of urban sustainability in Chinese resource-based cities: a panel quantile regression approach. Sci Tot Environ 2019; 686: 1210–1219.

29. Ren X, Cheng C, Wang Z, et al. Spillover and dynamic effects of energy transition and economic growth on carbon dioxide emissions for the european union: a dynamic spatial panel mode. Sustain Develop 2020; 29: 228–242.

30. Zhu H, Duan L, Guo Y, et al. The effects of FDI, economic growth and energy consumption on carbon emissions in ASEAN-5: evidence from panel quantile regression. Econo Mod 2016; 58: 237–248.

31. Zhang X, Jiang Q, Khattak SI, et al. Achieving sustainability and energy efficiency goals: assessing the impact of hydroelectric and renewable electricity generation on carbon dioxide emission in China. Energy Pol 2021; 155: 1–12.

32. Li H, Khattak SI and Ahmad M. Measuring the impact of higher education on environmental pollution: new evidence from thirty provinces in China. Environ Ecol Stat 2021; 28: 187–217

33. Ahmad M, Khan Z, Rahman ZU, et al. Can innovation shocks determine CO2 emissions (CO2e) in the OECD economies? A new Perspective. Econo Innov N. Techn 2021; 30: 89–109.

34. Chishti MZ, Ahmad M, Rehman A, et al. Mitigations pathways towards sustainable development: assessing the influence of fiscal and monetary policies on carbon emissions in BRICS economies. J Cleaner Prod 2021; 292: 1–14.
35. Jiang Q, Khattak SI, Ahmad M, et al. Mitigation pathways to sustainable production and consumption: examining the impact of commercial policy on carbon dioxide emissions in Australia. *Sustain Prod Consum* 2021; 25: 390–403.

36. Ding Q, Khattak SI and Ahmad M. Towards sustainable production and consumption: assessing the impact of energy productivity and eco-innovation on consumption-based carbon dioxide emissions (CCO2) in G-7 nations. *Sustain Prod Consum* 2021; 27: 254–268.

37. Jiang Q, Khattak SI, Ahmad M, et al. A new approach to environmental sustainability: assessing the impact of monetary policy on CO2 emissions in asian economies. *Sustain Develop* 2020; 28: 1331–1346.

38. Ahmad M, Khattak SI, Khan A, et al. Innovation, foreign direct investment (FDI), and the energy–pollution–growth nexus in OECD region: a simultaneous equation modelling approach. *Environ Ecolo Stat* 2020; 27: 203–232.

39. Khattak SI, Ahmad M, Khan ZU, et al. Exploring the impact of innovation, renewable energy consumption, and income on CO2 emissions: new evidence from the BRICS economies. *Environmental Science and Poll Resea* 2020; 27: 13866–13881.

40. Baron RM and Kenny DA. The moderator-mediator variable distinction in social psychological research: conceptual, strategic, and statistical considerations. *J Person Soci Psych* 1986; 51: 1173–1182.

41. Hsu TK. The effect of trade openness on carbon dioxide emission in Taiwan: a quantile mediation analysis. *WSEAS Trans Environ Develop* 2020; 16: 434–439.

42. Said E and Dickey DA. Testing for unit roots in autoregressive moving average models of unknown order. *Biometrika* 1984; 71: 599–607.

43. Cheng C, Ren X, Wang Z, et al. Heterogeneous impacts of renewable energy and environmental patents on CO2 emission-evidence from the BRIICS. *Sci. Total Environ* 2019; 668: 1328–1338.

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