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Dynamic Economic Analysis between Renewable Energy, Carbon Dioxide Emissions, Trade and GDP based on VECM Granger test and Wavelet Analysis

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Abstract

In this study, we explored the dynamic economic relationship between Taiwan's GDP growth, renewable energy consumption, foreign trade openness, and CO_2 emissions from 1965 to 2016. Our analysis is based on using updated data to test the existence of Taiwan's EKC model and discuss the causal relationship between CO_2 emissions and variables such as GDP growth, renewable energy consumption, and foreign trade opening. We used multicollinearity analysis to test the stationarity of the quadratic form of the EKC model, ADF and KPSS techniques, and Johansen and Juselius cointegration tests and found that there is a long-term equilibrium. By using VECM Granger causality test and wavelet coherence analysis, we further explored the causal relationship between CO_2 emissions and other related variables, and found that there is a two-way causal relationship between carbon dioxide emissions and renewable energy consumption in the short term. In addition, from the wavelet correlation analysis of GDP growth and CO_2 emissions, it can be seen that 1992 was a turning point in Taiwan's economic development.

Keywords: renewable energy, economic growth, carbon dioxide emissions,VECM Granger test, wavelets

1. Introduction

Energy is the one of the most basic driving forces for world development and economic growths and is the basis for human survival. Since the era of fuel wood economy, coal economy and oil economy, the energy structure of the world today has changed. Renewable energy sources such as hydro-power, light energy, electricity, and solar energy have become the focus of economic development and many countries are gradually transitioning to a green energy market. Taiwan has great advantages in the development of the energy industry. However, the remoteness and high population density have also brought challenges to these industries. In recent years, Taiwan has faced increasingly serious environmental problems. The balance between energy policy and environmental protection and public interests has compromised the stable power supply in the renewable energy market. The two most prominent forms of renewable energy are offshore wind and solar. In order to get on the right track, the Taiwanese government launched a renewable energy policy after the promulgation of the Renewable Energy Development Law in combination with regional characteristics and the development of the renewable energy industry has accelerated and is expected to reach 20\% of the total power supply. Taiwanese government vigorously promotes the development of offshore wind farms and formulated regulations to reward the establishment of offshore wind farms. Not only the government invests in demonstration offshore wind farms, many experienced foreign companies are also investing in offshore wind farms in Taiwan, most of which are located in the Taiwan Strait and the western part of the island. The development of offshore wind farms is one of the earliest cooperation strategies in the renewable energy policy and the supervision of these investments is relatively strict. In most cases, foreign investors sign development and power purchase contracts with the Taiwanese government to achieve the goal of public power. In few cases, it is expected that only certain entities will receive electricity. For example, a leading technology company Taiwan Semiconductor Manufacturing Company (TSMC) announced a power purchase agreement totaling 1.2 GW, most of which were purchased from wind farms with 4 offshore wind farms on the west coast of Taiwan. Case such as this shows that the status quo of renewable energy transactions involving public interest is no longer limited to contracts signed with the government. On the other hand, the solar energy industry, as one of the most mature forms of renewable energy in the world, has grown substantially at an average annual rate of 89.6\% in the past few years. The Taiwanese government predicts that the cumulative installed capacity of solar photovoltaic will reach 25GW by 2025. With the introduction of the Renewable Energy Development Act, Taiwan solar photovoltaic has quadrupled from 2016 to 2019 and the cumulative installed capacity has reached 3.9GW.

The impact of social and economic development on the environment has been thoroughly studied and investigated. The validity of the Environmental Kuznets Curve (EKC) test and the analysis of the causal relationship between variables such as economic growth, trade, and gas emissions are examples. In-depth research and investigations on the environmental impact of impact of socio-economic development have been extensively carried out, including testing the effectiveness of the Environmental Kuznets Curve (EKC), and analyzing the causal relationship between economic growth, trade and natural gas emissions. Environmental Kuznets Curve (EKC) is a hypothetical relationship between environmental quality and economic development. It shows that the environmental degradation indicators tend to deteriorate during the process until the average income reaches a certain level. In other words, the EKC can be used to analyze the relationship between per capita national income and environmental pollution. An environmental Kuznets curve hypothesis for East African countries is provided in (Beyene, S. & Kotosz, B., 2020). The study of Malaysia's economic output, pollutant emissions and energy consumption using the EKC analysis is introduced in (Ang JB., 2008) and their results showed that there is a strong causal relationship between economic growth and energy consumption growth in both short-term and long-term. The research of using cross-country panel data to analyze the EKC relationship between income inequality and CO_2 emissions in different countries is conducted in (Coondoo, D. & Dinda, S., 2008). Moreover, Lantz and Feng (Lantz, V. & Feng, Q, 2006) used five regional panel data sets in Canada from 1970 to 2000 and showed that technological and demographic changes conform to the EKC assumptions. The study of France's EKC for CO_2 and nuclear power generation is investigated in (Iwataa, H., Okada, K & Samreth, S., 2010) and the results not only support the EKC hypothesis, but also show the unidirectionality of CO_2 emissions variable through the casualty test. The existence and causality of EKC-CO_2 emissions is investigated for both Japan and South Korea and results show that both countries have EKC phenomena (Sun, X., Zhou, M. & Zhang, M., 2011). Recently, a generalized Moments method (GMM) in panel data analysis of both the developed and developing countries is adopted and the EKC phenomenon between that significantly affects income- Emission relationship significantly is confirmed in (Disli, M., Ng, A. & Askari, H., 2016). Furthermore, the impact of economic growth on the ecological footprint focusing on countries of low-, middle-, and high-income levels is studied and the results indicate that there is an increase in EKC ecological footprint data between economic growth and high-income countries (Ulucak, R. & Bilgili, F., 2018). The impact of oil price changes on the Turkish economy from 1960 to 2010 is studied and the existence of EKC phenomenon is confirmed (Katircioglu, S., 2017). In addition, the existence of EKC in China is confirmed through the application of various statistical analysis (Riti, J.S., Song, D., Shu, Y. & Kamah, M., 2017), and the study of the EKC phenomenon in Malaysia through the potential of renewable energy in controlling greenhouse gases is conducted in (Gill, A. R., Viswanathan, K. K. & Hassan, S. A., 2018). Besides, the EKC models addressing the relationship between globalization and carbon dioxide (CO_2) emissions in South Africa from is introduced (Mehmood, U. & Tariq, S., 2020). The causal relationship between energy consumption and economic activities in Taiwan was investigated in (Cheng, S. & Lai, T. W., 1997), and the causal relationship between energy consumption and GDP from 1954 to 1997 was tested in (Yang, H. Y., 2000) to show that there was a two-way causal relationship between total energy consumption and GDP. Moreover, the study of stability of Taiwan's energy consumption and GDP from 1954 to 2003 is conducted and found that there are different causal relationships between GDP and various energy consumption (Lee, C. C. & Chang, C. P., 2005). The EKC hypothesis between Taiwan's energy consumption and economic growth from 1955 to 2003 is confirmed (Lee, C. C. & Chang, C. P., 2007) and the topic of two-way Granger causality between employment-output and employment-energy consumption in Taiwan is addressed in (Chang, T. Y., Fang, W. S. & Wen, L. F., 2001). The study of one-way causal relationship between economic growth and coal consumption can be found in (Yang, H. Y., 2000). The relationships between Taiwan's energy consumption and GDP regarding a two-way relationship was observed in the contraction system, while a one-way causal relationship between GDP and energy consumption was detected in the expansion system (Kao, C. W. & Wan, J. Y., 2017). In addition, in the case of fractional co-integration and use of annual data of Taiwan to test the causal relationship between growth and energy consumption, it was found that the Energy Conservation Policy has a negative impact on economic growth (Maneschiold, P. O., 2015).

This study mainly explores the causal relationship between carbon dioxide emissions, GDP per capita, renewable energy consumption, and the proportion of imports and exports to Taiwan GDP. In addition, we use the latest data in (\url{https://ourworldindata.org/country/taiwan}) to analyze Taiwan's EKC model as well as the Multicollinearity Analysis.

2. Multicollinearity Analysis

2.1 Statistical Modeling

Following the empirical literature in recently related studies, we set the long-run linear relationship between CO_2 and GDP, RE and TR as follows:

$$\Delta \mathrm{CO2}_t = a_1 + b_1 GDP_t + c_1 RE_t + d_1 TR_t. \tag{1}$$

In order to examine the existence of EKC the quadratic form of GDP is included as follows:

$$\Delta \mathrm{CO2}_t = a_2 + b_2 GDP_t + c_2 GDP_t^2 + d_2 RE_t + e_2 TR_t, \tag{2}$$

where a_1, b_1 are constants and we expect the sign of c_1 to be negative which meets the cleanness of renewable energy, and the sign of d_1 could be either positive or negative. If it is positive, it implies that the trade openness is not environmentally friendly. If it is negative, then we could draw the conclusion that the trade openness is environmental friendly and the increase of trade open degree will have a negative impact on CO_2 emission. By checking the existence of EKC quadratic form, one can test the sign and significance of b_2, c_2 at the same time. The positive sign of b_2 and the negative sign of c_2 are expected to confirm the existence of Taiwan's EKC pattern. In view of the fact that the quadratic form of GDP contained in Eq. (2) may lead to multicollinearity, we point out that when a multicollinearity problem occurs, the sign of the regression coefficient may be completely opposite to the actual situation, and the independent variable that should be significant is not significant, but the independent variables that should not be significant become significant. Therefore collinearity issues can lead to serious deviations or even completely opposite conclusions in data research, so we follow the prescriptions in (Pao, H. T.,Yu, H. C. & Yang, Y. H., 2011) to study the variance inflation factor (VIF), adjusting R^2 and Jarque and Bera coefficient (JB) to analyze multicollinearity. If the adjusted R^2 of Eq. (2) is slightly larger than Eq. (1) (≤ 0.01) and the VIF in Eq. (2) is greater than 10 based on experience, then we may think that including quadratic form of GDP is not desirable in our analysis and regression coefficients are poorly estimated due to multicollinearity. It can be concluded that the monotonic relationship between CO_2 and GDP indicates that there is no EKC model in this case. In this case, the Eq. (1) is desirable and will be studied in this study.

2.2 Stationary Test

Econometrics research needs a stationarity test. Time series data are prone to non-stationary problems, which will lead to the destruction of the consistency of large-sample statistics and the problem of "false regression". Before the follow-up test, the stationarity of each variable is tested by the Augmented Dickey Fuller (ADF) unit root test (Dickey, D. A. & Fuller, W. A., 1979). The DF statistic is expressed as follows:

$$DF = \frac{\hat{\gamma}}{SE(\hat{\gamma})}, \tag{3}$$

where $\hat{\gamma}$ is the coefficient before lag 1. Furthermore, in order to compare the results from ADF test, we also employ the Kwiatkowski-Phillips-Schmidt-Shin (KPSS) test (Kwiatkowski, D., Phillips, C. B., Schmidt, P. & Shin, Y., 1992) where the LM statistic in the KPSS test is expressed as

$$LM = \frac{\sum_t S(t)^2}{T^2 f_0}, \tag{4}$$

where f_0 is an estimator of the residual spectrum at frequency zero and $S(t)$ is a cumulative residual function. We note that such a method is suitable for determining the order of integration of variables for small sample sizes (Pao, H. T.,Yu, H. C. & Yang, Y. H., 2011), although time series with structural breakpoints are also widely used in various situations (Ng, S. & Perron, P., 2001), (Phillips, P. C. B. & Perron, P., 1988), (Zivot, E. & Andrews, D. W. K., 1992).

2.3 Causality Analysis

It should be noted that when using the unit root test to determine the stationarity and integration order of variables, we used the Johansen and Juselius cointegration test (JJ test). The purpose of the cointegration test is to determine whether the linear combination of a set of non-stationary time series has a long-term equilibrium relationship. If two or more time series variables are not stationary, but their difference of the same order is stationary, then these non-stationary time series variables have a long-term cointegration relationship. In an economic sense, the existence of this co-integration relationship can cause variables to have long-term mutual influences. The JJ test starts from building a vector autoregressive model with the lag order p being constructed as $VAR(p)$:

$$y_t = A_1 y_{t-1} + \cdots + A_p y_{t-p} + Bx_t + \varepsilon_t, \tag{5}$$

where the optimal lag is determined by LogL, LR, FPE, AIC, SC and HQ, and each component of $y_t = (CO2_t, GDP_t, RE_t, TR_t)$ is $I(1)$ which means each component is first order difference stationary. Here x_t represents the trend and ε_t is the error. Taking the difference of Eq. (5), one gets

$$\Delta y_t = \Pi y_{t-1} - \sum_{i=1}^{p-1} \sum_{j=i+1}^{p} A_j \Delta y_{t-i} + Bx_t + \varepsilon_t, \tag{6}$$

where

$$\Pi = \sum_{i=1}^{p} A_i - I. \tag{7}$$

Therefore, there is a cointegration relationship between the components of y_{t-1}, which are determined by the matrix Π. Since the rank of the matrix Π is equal to the number of its nonzero eigenvalues, we can determine the cointegration relationships by examining the number of nonzero eigenvalues of the matrix. In our research, we mainly focus on the trace and maximum eigenvalue testing. As long as there is a cointegration relationship between the variable vectors, the vector error correction model can be derived from the autoregressive distributed lag model. In this study, our vector error correction model (VECM), which belongs to a category of multiple time series models is constructed as follows:

$$\Delta \mathrm{CO2}_t = c_1 + \alpha_{11} ECT_{t-1} + \sum_{j=1}^{p-1} \phi_{ij} \Delta GDP_{t-j} + \sum_{j=1}^{p-1} \theta_{ij} \Delta RE_{t-j} + \sum_{j=1}^{p-1} \psi_{ij} \Delta TR_{t-j}, \tag{8}$$

$$\Delta GDP_t = c_2 + \alpha_{21} ECT_{t-1} + \sum_{j=1}^{p-1} \phi_{2j} \Delta CO2_{t-j} + \sum_{j=1}^{p-1} \theta_{2j} \Delta RE_{t-j} + \sum_{j=1}^{p-1} \psi_{2j} \Delta TR_{t-j}, \tag{9}$$

$$\Delta RE_t = c_3 + \alpha_{31} ECT_{t-1} + \sum_{j=1}^{p-1} \phi_{3j} \Delta CO2_{t-j} + \sum_{j=1}^{p-1} \theta_{3j} \Delta GDP_{t-j} + \sum_{j=1}^{p-1} \psi_{3j} \Delta TR_{t-j}, \tag{10}$$

$$\Delta TR_t = c_4 + \alpha_{41} ECT_{t-1} + \sum_{j=1}^{p-1} \phi_{4j} \Delta CO2_{t-j} + \sum_{j=1}^{p-1} \theta_{4j} \Delta GDP_{t-j} + \sum_{j=1}^{p-1} \psi_{4j} \Delta RE_{t-j}, \tag{11}$$

Here ECT_{t-1} reflects the impact on the short-term changes when the relationship between related variables deviates from the long-run equilibrium state, and its coefficient vector α reflects the adjustment speed or adjustment strength when the short-run fluctuation between variables deviates from the long-run equilibrium state. VECM in Eqs. (8)-(11) could be used to test the causality. In this study, we conduct three mainstream causalities, namely the short-run causality, long-run causality (weak exogeneity causality test), and joint long and short run causality (strong exogeneity causality test). Those analysis could be conducted by testing statistical hypothesis (examining the statistical significance of coefficients before lagged terms) by utilizing Wald test. Take both factors of GDP and CO_2 as an example, we are able to illustrate the short run causality running from GDP to CO_2. One could examine the statistical hypothesis as follows:

$$H_0 : \phi_{1j} = 0, \qquad \forall j = 1, \ldots, p-1, \tag{12}$$

and note that the rejection of H_0 represents GDP is caused by CO_2 in short run. On the other hand, as for weak exogeneity causality test, one can examine the statistical hypothesis as follows:

$$H_0 : \alpha_{11} = 0, \qquad \forall j = 1, \ldots, p-1, \tag{13}$$

and note that rejection of H_0 represents GDP is affected and caused by CO_2 in the long-run equilibrium state. Therefore, rejection hypothesis

$$H_0 : \phi_{1j} = \alpha_{11} = 0, \qquad \forall j = 1, \ldots, p-1, \tag{14}$$

stands for the strong exogeneity causality running from GDP to CO_2.

In view of the limitations of Granger causality analysis: First, Granger causality essentially uses the VAR model to test the significance of a set of coefficients. Granger causality can be used to test whether all lagged terms of a variable affect the current value of another or more variables, which requires that each variable should be in a stable state, rather than true causation. Second, Granger causality analysis does not take into account that different time periods and time series may have different interrelationships on different time and frequency scales. In this study, we use wavelet coherence analysis and compare the results with the results of VECM Granger causality analysis. Wavelet coherence analysis can reveal the resonance area and phase relationship of two time series, which is used to measure the local correlation of two time series on the time-frequency scale. The wavelet coherence coefficient is defined as the ratio of the cross wavelet power spectrum of two time series divided by the square root of each wavelet power, as follows:

$$R_n(s) = \frac{\left|S\left[S^{-1}W_n^{xy}(s)\right]\right|}{S\left[S^{-1}W_n^{xx}(s)\right]^{1/2} S\left[S^{-1}W_n^{yy}(s)\right]^{1/2}}, \tag{15}$$

where S means smoothing operator defined by

$$S(W) = S_{scale}\left(S_{time}\left(W_n(s)\right)\right), \tag{16}$$

where S_{scale} means smoothing along the wavelet scale axis, S_{time} means smoothing along the wavelet time axis and $W_n^{xy} = W_n^x W_n^y$ with W_n^x being defined as discrete wavelet transformation as

$$W_{n,m}{}^x = \frac{\delta_t}{\sqrt{s}} \sum_{n=0}^{N-1} x_n \psi_{\tau,s}(t)^* \left((n-m)\delta_t / s\right), \qquad m = 0,1,\ldots,N-1, \tag{17}$$

where $\psi_{\tau,s}(t) \in L^2(R)$ being a wavelet basis. Here we choose Morlet wavelet and the phase difference of two time series (Torrence, C. & Compo, G. P., 1998) can be written as follows:

$$\phi_{xy} = \tan^{-1}\left[\frac{I\left(W_n^{xy}\right)}{R\left(W_n^{xy}\right)}\right], \qquad \phi_{xy} \in [-\pi, \pi] \tag{18}$$

where *I, R* are the imaginary and real parts of the smoothed cross-wavelet transform. As for the phase mode, the causality can be judged from the direction of the arrow in the wavelet coherence diagram, that is, when the arrow points to the right, the sequence *x, y* is in phase (that is, *x, y* are positively correlated). When the arrow points to the left, the sequence *x, y* is inverted (meaning that *x, y* are negatively correlated). In addition, when the arrow points to the upper right or lower left, $\phi_{xy} \in (0, \pi/2), (-\pi, -\pi/2)$ means that *x* causes/causes *y*. Similarly, the arrow points to the lower right or upper left corner $\phi_{xy} \in (-\pi/2, 0), (\pi/2, \pi)$ means that *y* causes / causes *x*.

3. Multicollinearity Analysis

The unit root test results of ADF and KPSS tests are shown in Table 1. It shows that for the ADF test, all variables do not reject the null hypothesis that the sequence has a unit root at the level, and all variables are rejected after the first difference at the 1% level; for the KPSS test, all variables reject the original hypothesis that the sequence is 1. Hypothesis. The null hypothesis at the 1 % level is stable, and all variables do not reject the null hypothesis, except that RE rejects the null hypothesis at the level of 10% but cannot reject the level of 5%. Therefore, we conclude that all variables are I(1) at the 5% level.

The results of multicollinearity analysis are shown in Table 2. According to our analysis criterion, it is not advisable to add the quadratic form of GDP to the regression equation for that the growth of both R^2 and Adj-R^2 is less than 0.01; The criterion error is reduced by 0.3637. In addition, the VIF of GDP and the coefficient before GDP^2 in Eq. (2) are both greater than 10, indicating that this variable is different from others. Note that the correlation of variables is high. Therefore we conclude that EKC does not hold in this case, and there is a monotonic relationship between per capita carbon dioxide emissions and per capita real GDP. Our results are consistent with those in (Pao, H. T., Yu, H. C. & Yang, Y. H., 2011). Given that all variables are found to be stable at I(1), we use the Johansen and Juselius (JJ) test. In order to determine the optimal lag, an infinite VAR model is established for each variable data and the corresponding lag order p is determined by the values of AIC, SC, FPE, HQ and LR. Given the sample size, we choose the largest lag to be 3. The results in Table 3 suggest that the VAR model with hysteresis was selected. In addition, Johansen's cointegration test is based on VAR(3). For the trace test (the test process of the maximum eigenvalue test is similar), it is found that if the corresponding probability p-value is greater than the 5% confidence level, the null hypothesis is accepted and there is no cointegration relationship. The test is considered completed if the trace statistic is greater than the critical value or the corresponding probability p value is less than 5% confidence level where the null hypothesis is rejected and there is at least one cointegration relationship and next null hypothesis will be considered.

The second primitive hypothesis of trace statistics is introduced in Table 5 in which the term at most 1 means that there is at most one cointegration relationship. If the corresponding probability p value is greater than the 5% confidence level, then the null hypothesis is accepted, and only one cointegration relationship is considered to complete the test. However, if the trace statistic is greater than the critical value or the corresponding probability p value is less than the confidence level 5%, then the null hypothesis is rejected and we perform trace statistical test on the next null hypothesis and repeat the procedure. The Johansen cointegration test is shown in Table 4, and it is found that there is a cointegration between variables at the 0.05 level. Through the cointegration relationship,

$$\Delta CO2_t = 1.5717 + 0.0003 GDP_t - 0.0021 RE_t + 0.0129 TR_t, \tag{19}$$

we can obtain the long-term equilibrium relationship in which GDP and TR are both positively correlated with real GDP per capita. For every 1% increase, per capita carbon dioxide emissions will increase by 0.0003%, and for every 1% increase in the proportion of imports and exports in GDP, per capita carbon dioxide emissions will increase by 0.0129%. In the long run, per capita carbon dioxide emissions are negatively correlated with per capita renewable energy consumption, i.e., for every 1% increase in per capita renewable energy consumption, per capita carbon dioxide emissions will decrease by 0.0021%. This also means that GDP growth is not environmentally friendly, but has little impact on CO_2 emissions. It should be noted that per capita renewable energy consumption has eased the CO_2 emissions to a certain extent, which is in line with our expectations. It is noted that opening up to foreign trade is also not environmentally friendly, and has the most significant impact on carbon dioxide emissions compared with other variables.

Fig. 1 demonstrates the trend of all variables against time including CO_2, GDP, RE, and TR, suggesting that the trends are steadily increasing. It can be seen that both CO_2 and GDP are rising steadily, with almost no major fluctuations. However, both RE (per capita renewable energy consumption) and TR (import and export GDP ratio) fluctuate over time, with renewable energy fluctuating the most. Here we use raw data instead of taking logarithms. Although logarithm does play an important role in data processing such as eliminating the dimensional difference between different variables, it has two obvious shortcomings, that is, logarithm can compress data information and destroy data integrity. On the other hand, we have also noticed that logarithm is an effective method widely used in related research, which can reduce the heteroscedasticity of time series. But this method is only suitable for a small range of time series, that is, the standard deviation of the series should be proportional to the average $\sigma_t = \mu_t$. This is also the simplest hypothesis that has appeared in different studies and hypothesis. However, this assumption is still very simple as heteroscedasticity has many characteristics and it is impossible to transform all heteroscedastic sequences into homogeneous sequences through a simple logarithmic transformation. In addition, the essence of sequence logarithmic transformation is the operation of variance transformation. In fact, in order to use the homogeneity of the variance transformation, we must know the form of the heteroscedasticity function in advance, which is also not possible for all sequences.

Fig. 2 shows the wavelet coherence diagram between per capita real GDP (x-axis) and per capita carbon dioxide emissions (y-axis). In general, it is mostly $\phi_{xy} \in [-\pi/2, \pi/2]$, indicating that there is a positive correlation between GDP and CO_2 which is consistent with the cointegration relationship we obtained. Compared with the VECM Granger causality test, the time-frequency analysis results we found are more profound.

Fig. 3 is a wavelet coherence diagram of per capita renewable energy consumption and per capita carbon dioxide emissions. The results show that, with the exception of the four-year cycle around 1980, there is no significant causal relationship at all times and frequencies. The arrow points to the lower left, indicating that there is a negative correlation between RE and CO_2, which is consistent with our previous negative coefficient of RE and the previous cointegration relationship is confirmed.

Fig. 4 is a wavelet correlation diagram of the ratio of imports and exports to GDP and per capita carbon dioxide emissions. It is found that in the mid-to-low cycle, the arrow points to the upper right, indicating that the opening of foreign trade leads to CO_2 emissions, but the persistence is only concentrated in a short time interval (1975-1980). In the long run, from 1985 to 1995, CO_2 emissions led to the opening of foreign trade. Interestingly, in the low-cycle region, there are two short-term significant regions, i.e., around 1995-1997 and 2002-2008, when the degree of foreign trade openness is positively correlated with CO_2 emissions.

The results of VECM Granger causality analysis are shown in Table 5, and the visualization of the relationship between variables is shown in Fig. 5. In the short term, there is a two-way causal relationship between per capita carbon dioxide emissions and per capita renewable energy consumption. There is insufficient evidence to show that recent renewable energy policies are effective in reducing environmental burdens. At the same time, in the short term, there is a one-way causal relationship between per capita real GDP and per capita carbon dioxide emissions at the level of 10%, and there is a one-way causal relationship between foreign trade opening and per capita carbon dioxide emissions. It should be noted that in the short term, per capita carbon dioxide emissions will reach 5% and there is strong evidence that there is a long-term causal relationship between per capita real GDP, per capita renewable energy consumption, foreign trade openness, and per capita carbon dioxide emissions of 1%. In addition, the long-term and short-term joint causality tests also support the short-term and long-term tests, indicating that there is an overall strong exogenous causality between per capita real GDP and per capita CO_2 emissions.

On the 5-year cycle time axis, the areas with significant resonance cycles are concentrated on the left and right sides, and they are not significant from 1980 to 1995. From 1965 to early 1980, the arrow almost pointed to the right $\phi_{x,y} \approx 0$, indicating that the carbon dioxide emissions during this period were positively correlated with Taiwan pre-industrial GDP growth. After 2005, some arrows point to the lower right corner of $\phi_{xy} \in [-\pi/2, 0]$. The cycle is 5 years, which means that in this time frame, carbon dioxide emissions usually drive GDP growth in turn. In the mid-term (5-10 years) domain, areas with significant resonance periods are only distributed on both sides of the time domain. In the high period (10-16 years) domain, the areas with significant resonance periods in the conical confidence interval are only distributed in 1985-2000. Almost all the arrows in the figure point to the lower right corner, indicating the impact of CO_2 emissions on GDP from 1985 to 2000. In particular, from 1975 to 1992, most of the arrows point to the upper right corner ($\phi_{xy} \in [0, \pi/2]$), which indicates that GDP growth leads to carbon dioxide emission. After 1992, most of the arrows point to the lower right ($\phi_{xy} \in [-\pi/2, 0]$), indicating that CO_2 emissions are leading GDP growth. Therefore, from the analysis of the causal relationship between GDP growth and CO_2 emissions, the inflection point of Taiwan's GDP in 1992 is obtained. This was also in line with the laws of Taiwan's economic development at that time. It should be noted that in the 1990s, due to Taiwan's industrialization, various environmental pollution in various regions became more and more serious. At the same time, the awareness of environmental protection has begun to increase, and civil unrest caused by development disputes has continued to increase, which has increased the impact of the environmental movement on public policies. Therefore, the Taiwanese government passed the Public Dispute Resolution Law in 1992 to resolve public issues. In the 1990s, Taiwan's environmental protection movement developed against the background of the continuous occurrence of pollution incidents, the gradual spread of democracy and local awareness, and the increasing importance of international environmental issues. The movement is also indirectly related to the United Nations hosting the Earth Summit in 1992. In addition, there were reports in 1994 that a foreign company (RCA) was found to have been digging wells for a long time, dumping organic solvents and other toxic wastes, especially trichloroethylene and perchloroethylene. As a result, the soil and groundwater in the plant area were severely polluted. According to official statistics, at least more than 300 RCA employees have died of cancer, and more than 1,000 people have been diagnosed with cancer. The themes of Taiwan's environmental movement in the early 1990s included nuclear power, nuclear waste, petrochemicals, cement, forests, golf courses, and local pollution.

4. Concluding Remarks

Through empirical analysis, we use the updated data from 1965 to 2016 to conclude that there is no EKC model in Taiwan. On the other hand, the J-J test suggests that there is a long-term co-integration relationship between per capita CO_2 emissions, per capita real GDP, per capita renewable energy consumption, and foreign trade openness. The co-integration equation shows that both GDP growth and foreign trade opening may cause a certain degree of damage to the environment, while the consumption of renewable energy will reduce carbon dioxide emissions and be environmentally friendly. We also found that the per capita real GDP growth has the smallest positive impact on per capita CO_2 emissions (the change is only 0.0003%), and the opening of foreign trade has the largest negative impact on per capita CO_2 emissions (0.0129%). Using the VECM Granger Causality Test, we found weak evidence of a two-way causal relationship between per capita carbon dioxide emissions and per capita renewable energy consumption in the short term. Our results of one-way causality with actual per capita GDP and CO_2 emissions as factors are consistent with the situation in China (Chen, Y., Zhao, J., Lai, Z., Wang, Z. & Xia, H., 2019). In order to make up for the shortcomings of the traditional Granger causality test, we also adopted wavelet coherence analysis, from which we observed the most profound relationship between GDP and CO_2. We found that around 1992, there was a turning point in the leading relationship between GDP and CO_2 emissions in economic development, that is, GDP led CO_2 before 1992, and CO_2 led GDP after 1992, similar to the turning point of the EKC model. We have also found that renewable energy cannot play an important role in causing carbon dioxide emissions. In this regard, it is necessary and important for the government to implement the policy of developing new energy as one of the solutions to reduce fossil energy consumption. The government should continue to adopt necessary energy management policies, encourage the development of renewable energy power generation industry, and support enterprises to optimize business models in an environmentally friendly manner. In addition, under the trend of green supply chain and environmental protection, the Taiwanese government should maintain correct energy legal systems and policies to improve the industrial environment and infrastructure, and be ready to invest in this huge potential energy market at any time. Although the growth of renewable energy in Taiwan industry has been affected by the covid-19 pandemic, under an effective epidemic prevention system, the energy industry is recovering, and the solar energy industry has received a large amount of foreign investment in recent years. In addition to developing environmentally friendly power generation methods, energy conservation is also another pillar of Taiwan's energy policy. It is recommended that the Taiwan government should vigorously assist the Industrial Technology Research Institute in clarifying relevant legal issues, including reviewing updated documents submitted to the WTO. Through cooperation with the industry, the effectiveness and efficiency of the legal system have been improved, and the legitimate rights and interests of relevant entities have been protected. On the other hand, the Taiwanese government should continue to maintain high-level energy management system standards to monitor energy consumption and adjust internal costs to achieve energy conservation goals. It is recommended that the government formulate an energy management system and effective plans to support the upgrading of enterprises and industries to benefit from the global green supply chain trend, especially when manufacturing industry needs sufficient energy operations.

Table 1. Unit Root Tests

Variable	*ADF*	*KPSS*	*ADF*	*KPSS*
CO2	-0.7756[0]	0.8232[6]*	-7.7083[0]*	0.1646[4]
GDP	0.7998[0]	0.9612[5]*	-6.3733[0]*	0.2914[0]
RE	0.5359[2]	0.5913[4]**	-6.4141[2]*	0.3730[37]
TR	-2.2647[0]	0.7095[5]**	-7.9484[0]*	0.2041[1]

Here *,**,*** represent 1\%, 5\% and 10\% significance levels respectively. Numbers in $\left[\right]$ represent the optimal lag for ADF test selected based on AIC and Newey-West bandwidth for KPSS test by Barlett kernel respectively.

Table 2. Results of Multicollinearity Analysis

	Independent Variables								
Equations	GDP	GDP^2	RE	TR	CONSTANT	r^2	Adj-R^2	S.E.	JB
Eq. (1)	0.0003	-	-0.0021	0.0129	1.5717	-	-	-	-
Eq. (1)	(34.1660)	-	(−3.7374)	(2.9741)	(3.8421)	0.9856	0.9847	0.4427	2.3384
Eq. (1)	[2.5579]	-	[1.3348]	[2.7241]	-	-	-	-	-
Eq. (2)	0.0004	-2.11×10^{-19}	-0.0020	0.0135	0.8603	-	-	-	-
Eq. (2)	(18.0419)	(−4.860)	(−4.3429)	(3.7616)	(2.3467)	0.9905	0.9897	0.3637	0.0737
Eq. (2)	[24.4746]	[23.4765]	[1.3372]	[2.7265]	-	-	-	-	-

Here *, **, *** represent 1\%, 5\% and 10\% significance levels respectively. Numbers in [ ] represents t-statistics. Figures in ( ) presents VIF.

Table 3. Johansen cointegration test- Trace statistics

Hypothesized CE(s)	Eigenvalue	Trace		
Statistics	0.05 Critical value	Prob.**		
None*	0.450184	52.63958	47.85613	0.0166
At most 1	0.304646	23.32921	29.79707	0.2302
At most 2	0.105072	5.525821	15.49471	0.7507
At most 3	0.001759	0.086254	3.841466	0.7690

Here * denotes rejection of the hypothesis at the 0.05 level, ** denotes the Mackinnon (1996) one-side p-value.

Table 4. Johansen cointegration test- Maximum Eigenvalue

Hypothesized CE(s)	Eigenvalue	Max-Eigen Statistics	0.05 Critical value	Prob.**
None*	0.450184	29.31037	27.58434	0.0297
At most 1	0.304646	17.80339	21.13162	0.1374
At most 2	0.105072	5.439566	14.26460	0.6856
At most 3	0.001759	0.086254	3.841466	0.7690

Here * denotes rejection of the hypothesis at the 0.05 level and ** denotes the Mackinnon (1996) one-side p-value.

Table 5. VECM Causality Analaysis

	Short-run causality				long-run causality	Joint-run causality			
Variables	Δ GDP	Δ GDP	Δ RE	Δ TR	ETC	$(\Delta CO2, \text{ETC})$	$(\Delta GDP, \text{ETC})$	$(\Delta RE, \text{ETC})$	$(\Delta TR, \text{ETC})$
$\Delta CO2$	-	5.1901	6.2532	0.8646	8.9672	-	10.1091	9.0826	15.9305
	-	[0.0746]	[0.0439]	[0.6490]	[0.0027]	-	[0.0177]	[0.0282]	[0.0012]
ΔGDP	2.3291	-	2.2947	0.8876	2.0198	2.5232	-	2.4845	9.9593
	[0.3121]	-	[0.3175]	[0.6416]	[0.1553]	[0.4695]	-	[0.4781]	[0.0189]
ΔRE	4.6823	0.2649	-	7.3492	21.4371	32.8369	24.8164	-	31.0920
	[0.0962]	[0.8759]	-	[0.0254]	[0.0000]	[0.0000]	[0.0000]	-	[0.0000]
ΔTR	3.7216	4.4058	2.2358	-	2.8733	4.6683	7.6908	2.9768	-
	[0.1555]	[0.1105]	[0.3270]	-	[0.0901]	[0.1978]	[0.0529]	[0.3952]	-

Here *, **, *** represent 1\%, 5\% and 10\% significance levels respectively; Figures in [ ] represent the corresponding p-value. Figures without brackets are Wald statistic.

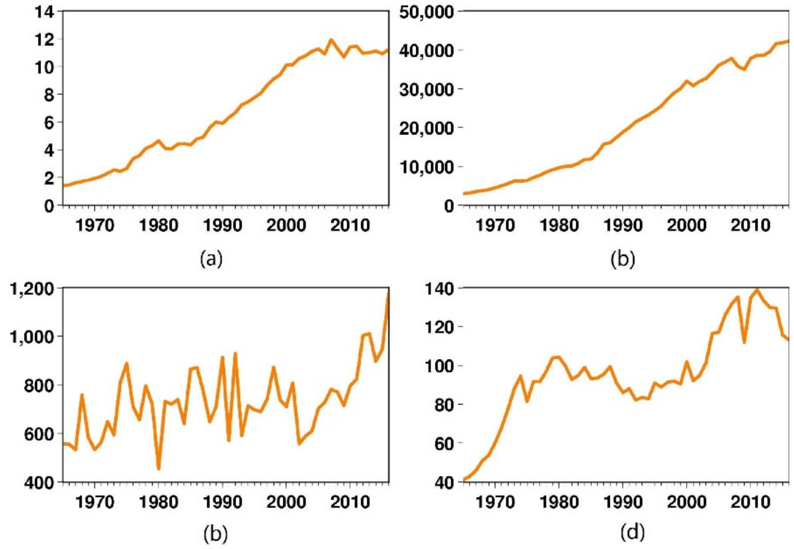

Figure 1. Trends of variables against time from 1965 to 2016. (a) CO_2; (b) GDP; (c) RE; (d) TR.

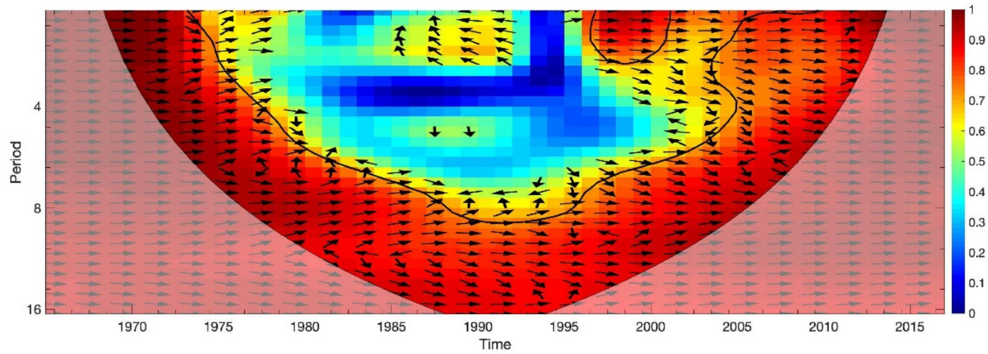

Figure 2. Wavelet coherence of GDP(x) and CO_2(y). The cone curve is the influence cone curve, and the area outside the influence cone curve is of little value due to the influence of boundary effect. The range surrounded by the thick black line passed the test of red noise standard spectrum at $\alpha = 0.05$ significance level. The directions of arrorws represent the causality relationships between two variables.

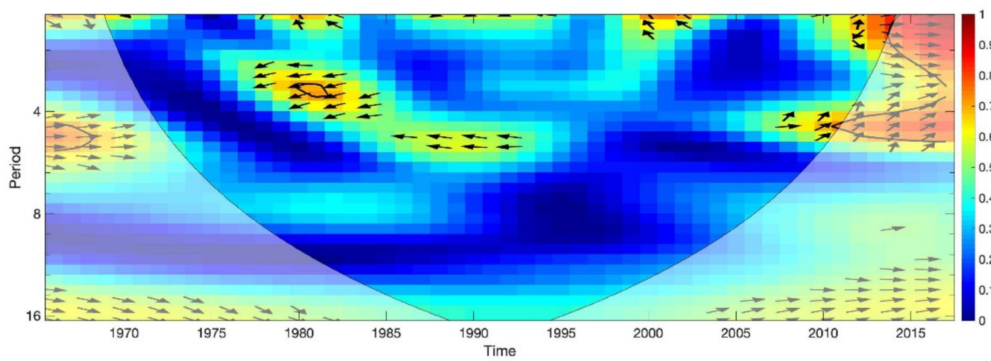

Figure 3. wavelet coherence of RE(x) and CO_2(y). The cone curve is the influence cone curve, and the area outside the influence cone curve is of little value due to the influence of boundary effect. The range surrounded by the thick black line passed the test of red noise standard spectrum at $\alpha = 0.05$ significance level. The directions of arrorws represent the causality relationships between two variables.

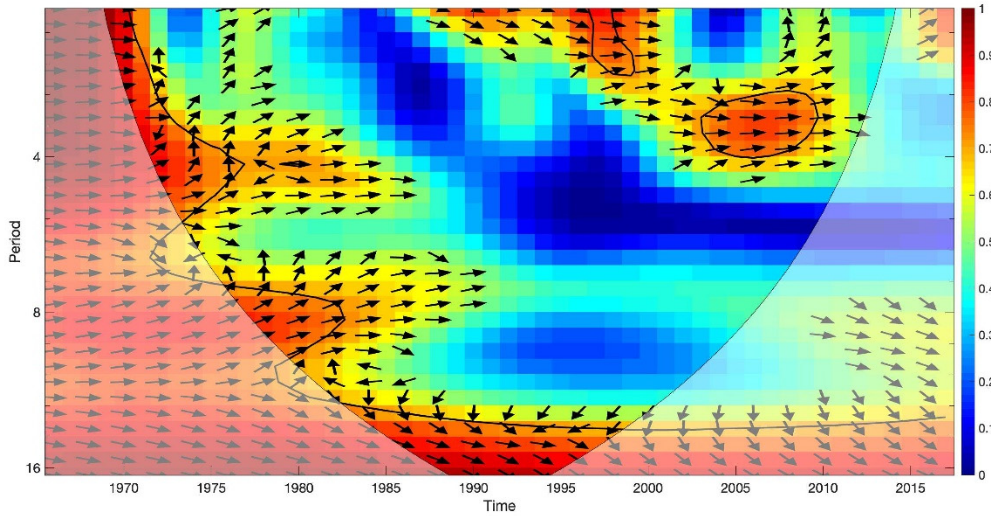

Figure 4.wavelet coherence of RE(x) and CO_2(y).The cone curve is the influence cone curve, and the area outside the influence cone curve is of little value due to the influence of boundary effect. The range surrounded by the thick black line passed the test of red noise standard spectrum at $\alpha = 0.05$ significance level. The directions of arrorws represent the causality relationships between two variables.

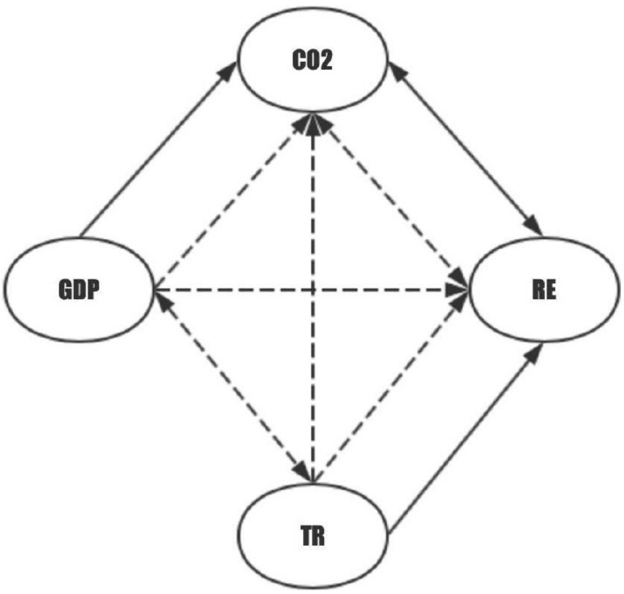

Figure 5. Process Of VECM Granger causality analysis. The single arrow represents unidirectional causality and the double arrow represents bidirectional causality.The solid line represents short run causality and the dotted line represents strong exogeneity causality.

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