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Does Non-Fossil Energy Usage Lower CO_2 Emissions? Empirical Evidence from China

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Abstract: This paper uses an autoregressive distributed lag model (ARDL) to examine the dynamic impact of non-fossil energy consumption on carbon dioxide (CO_2) emissions in China for a given level of economic growth, trade openness, and energy usage between 1965 and 2014. The results suggest that the variables are in a long-run equilibrium. ARDL estimation indicates that consumption of non-fossil energy plays a crucial role in curbing CO_2 emissions in the long run but not in the short term. The results also suggest that, in both the long and short term, energy consumption and trade openness have a negative impact on the reduction of CO_2 emissions, while gross domestic product (GDP) per capita increases CO_2 emissions only in the short term. Finally, the Granger causality test indicates a bidirectional causality between CO_2 emissions and energy consumption. In addition, this study suggests that non-fossil energy is an effective solution to mitigate CO_2 emissions, providing useful information for policy-makers wishing to reduce atmospheric CO_2.

Keywords: non-fossil energy consumption; CO_2 emissions; ARDL model

1. Introduction

Climate change and global warming are among the most urgent environmental problems confronting modern societies, posing a growing threat to human survival and development. Greenhouse gas emissions, mainly containing carbon dioxide (CO_2), represent the principal cause of climate change. CO_2 primarily results from fossil fuels combustion for energy production and transportation, producing about the 85% of global CO_2 emissions. Thus, it is important to find alternative energy sources to mitigate CO_2 emissions.

China has overtaken the USA as the biggest consumer of energy and largest contributor of CO_2 emissions, with 20% of global energy consumption and 29% of total CO_2 emissions. The country relies on fossil fuels, and in particular coal whose burning releases large amounts of CO_2 into the atmosphere, as the main energy source. There are two main solutions to increasing energy consumption, greenhouse gas (GHGs) emission, and environmental pollution. One is to establish markets where emissions allowances can be traded and priced [1–4]. The other is to improve the proportion of renewable energy and nuclear resources in the energy structure.

To mitigate CO_2 emissions while sustaining economic and social development, China has undertaken initiatives to develop renewable and nuclear energy resources to replace traditional fossil fuels. The government has created energy policies to promote the use of clean energy. As a result, non-fossil energy consumption increased from 3.8% to 10.9% from 1965 to 2014. In addition, China plans to raise the share of non-fossil energy in the energy mix to around 20% by 2030.

Although the government has made great efforts to develop clean energy sources and obtained remarkable results, the effects of non-fossil energy on GHG emissions requires further empirical tests. There is a debate on whether non-fossil energy reduces carbon emissions, as their use may lead to extra emissions [5]. For example, greenhouse gas emissions for the life cycle of solar panels account for approximately 32–79 g CO_2eq/kWh, while for solar collectors it is 11–68 g CO_2eq/kWh [6]. Therefore, this paper aims to assess whether an increase in the share of non-fossil energy would have a statistically significant effect on the reduction of CO_2 emissions.

Previous researchers investigated the contribution of non-fossil energy consumption to CO_2 emissions. Most of these studies used different econometric methodologies to measure the effects of renewable and nuclear energy for emissions reduction. However, the results are contradictory and inconclusive.

Silva et al. [7] examined the causal relationship between renewable energy sources and CO_2 emissions between 1960 and 2004 in the USA, Spain, Portugal, and Denmark, concluding that the increase in the proportion of renewable energy in the energy mix reduced CO_2 emissions in nearly all countries except the USA. Al-Mulali et al. [8] found that renewable energy consumption cuts down on CO_2 emissions in Western, Central and Eastern Europe, East Asia and the Pacific, the Americas and South Asia. Irandoust [9] provided evidence supporting that renewable energy mitigates CO_2 emissions in four Nordic countries. Dogan and Seker [10] confirmed that expanding the use of renewable energy decreases CO_2 emissions in the top renewable energy countries. Bento et al. [11] and Tiwari [12] arrived at the same conclusions for Italy and India; Bilgili et al. [13], Bölük and Mert [14], Saidi et al. [15], Sebri et al. [16], Özbuğday et al. [17], and Dogan et al. [18] provided similar results for 17 panel Organisation for Economic Co-operation and Development (OECD) countries, 16 European Union countries, nine developed countries, BRICS countries, thirty-six countries and the European Union, respectively.

However, Apergis et al. [19] noted that use of renewable energy does not affect carbon emission reduction in the short-run. Menyah and Rufael [20] explored the causal relationship between renewable energy consumption and CO_2 emissions in the US between 1960 and 2007, discovering that renewable energy does not significantly contribute to the reduction of CO_2 emissions. Chiu and Chang [21] found that the renewable energy will begin to mitigate CO_2 emissions when it represents at least 8.3889% of the total energy supply.

As for nuclear energy, Al-mulali [22] found that it plays a major role in decreasing CO_2 emissions in both the short and the long term, since it positively affects GDP growth without enhancing CO_2 emission. Baek [23] showed that nuclear energy and CO_2 emissions have a negative long-run relationship in USA, France, Japan, Korea, Canada, and Spain. Nuclear energy has a favorable impact on mitigating CO_2 emissions in Korea, USA and in in 12 major nuclear generating countries [20,24–26].

On the contrary, Iwata et al. [27] concluded that nuclear energy plays a minimal role in curbing CO_2 emissions in most OECD countries. According to Jaforullah et al. [12], CO_2 emission are unrelated to nuclear energy utilization in the USA when energy prices are not considered as a possible driving force of energy demand.

While numerous studies investigated the link between renewable energy, nuclear energy use, and CO_2 emissions, little empirical work examined the association between total non-fossil energy consumption and CO_2 emissions employing modern econometric methods. In addition, the empirical research largely focused on the short term impact of renewable and nuclear energy on CO_2 emissions. Furthermore, to the best of our knowledge, few scholars investigated the effect of nuclear and renewable energy utilization on CO_2 emissions specifically in China.

To fill these gaps, this paper aims to study the dynamic effects of non-fossil energy utilization on CO_2 emissions within the cointegration framework. In particular, it investigates the short and long term impacts of non-fossil energy, economic growth, energy consumption, and trade openness on CO_2 emissions in China employing autoregressive distributed lag (ARDL) and error correction models (ECM) and then testing their Granger causal relationship.

2. Materials and Methods

2.1. Model Equation

To investigate the changes in CO_2 emissions employing time-series data, Equation (1) took into consideration variables that substantially affect CO_2 emissions, as reported in previous studies [15,18,20,25].

$$\ln(co_2)_t = \beta_0 + \beta_1 \ln nf_t + \beta_2 \ln y_t + \beta_3 \ln en_t + \beta_4 \ln t_t + u_t \quad (1)$$

where $(co_2)_t$ represents CO_2 emissions at time t; nf_t is a measure of non-fossil energy consumption; y_t represents economic growth; en_t represents energy consumption; t_t is trade openness; and u_t represents the error term. If increasing non-fossil energy use results in a reduction on CO_2 emissions, the coefficient of this variable would become negative. According to the literature, economic growth occupies a central role in affecting environmental quality; as economic development increases CO_2 emissions, the sign of β_2 could be expected to be positive. In addition, a higher level of energy utilization should lead to an increase in CO_2 emissions, so the sign of β_3 could become positive. Finally, as increasing trade openness will raise CO_2 emissions in developing countries, the coefficient of this variable would become positive.

2.2. Cointegration Analysis

In order to examine the long term equilibrium relationship among non-fossil energy use, economic development, energy usage, trade openness, and CO_2 emissions, this study adopts an ARDL approach developed by Pesaran and Shin [28]. This approach has some advantages compared to those of multivariate cointegration, as confirmed by Narayan [29]. The unrestricted error correction regressions representation of Equation (1) is expressed below:

$$\begin{aligned} \triangle \ln(co_2)_t = {} & \beta_0 + \sum_{k=1}^{n} \beta_{1k} \triangle \ln(co_2)_{t-k} + \sum_{k=0}^{n} \beta_{2k} \triangle \ln nf_{t-k} + \sum_{k=0}^{n} \beta_{3k} \triangle \ln y_{t-k} + \sum_{k=0}^{n} \beta_{4k} \triangle \ln en_{t-k} \\ & + \sum_{k=0}^{n} \beta_{5k} \triangle \ln t_{t-k} + \varphi_0 \ln(co_2)_{t-1} + \varphi_1 \ln nf_{t-1} + \varphi_2 \ln y_{t-1} + \varphi_3 \ln en_{t-1} + \varphi_4 \ln t_{t-1} + \nu_t \end{aligned} \quad (2)$$

where Δ is the first difference of the variable, β is the intercept term, and parameter n represents the lag lengths. The proper lag length is selected based on the Akaike information criterion (AIC) or final prediction error (FPE). The F-test proposed by Pesaran et al., which is highly sensitive to lag order selection, is suitable to determine the joint significance of the coefficients of the lagged level of the variables [30]. The null hypothesis of no long run relationship (H_0: $\varphi_0 = \varphi_1 = \varphi_2 = \varphi_3 = \varphi_4 = 0$) should be tested against the alternative hypothesis (H_1: $\varphi_0 \neq \varphi_1 \neq \varphi_2 \neq \varphi_3 \neq \varphi_4 \neq 0$). *F*-statistics are compared to the critical bounds reported in Pesaran et al. [30]. If the test result exceeds the upper critical value, it means that the null hypothesis is rejected. If the calculated F-statistic is between the upper and lower critical bounds, it implies the test is inconclusive. However, if the test statistic is below the lower bounds value, it means there is no cointegration.

After examining the long term relation among variables, the next step is to continue to estimate the long term coefficient of the ARDL model by using Equation (3).

$$\begin{aligned} \ln(co_2)_t = {} & \beta_0 + \sum_{k=1}^{n} \beta_{1k} \ln(co_2)_{t-k} + \sum_{k=0}^{n_1} \beta_{2k} \ln nf_{t-k} + \sum_{k=0}^{n_2} \beta_{3k} \ln y_{t-k} + \sum_{k=0}^{n_3} \beta_{4k} \ln en_{t-k} \\ & + \sum_{k=0}^{n_4} \beta_{5k} \ln t_{t-k} + \mu_{1t} \end{aligned} \quad (3)$$

When this procedure is completed, Equation (4) estimates the error-correction model examining the short term behaviors of the variables together with the short term adjustment speed towards long term speed.

$$\begin{aligned}\triangle \ln (co_2)_t = \beta_0 + \sum_{k=1}^{n} \beta_{1k} \triangle \ln (co_2)_{t-k} + \sum_{k=0}^{n} \beta_{2k} \triangle \ln nf_{t-k} + \sum_{k=0}^{n} \beta_{3k} \triangle \ln y_{t-k} + \sum_{k=0}^{n} \beta_{4k} \triangle \ln en_{t-k} \\ + \sum_{k=0}^{n} \beta_{5k} \triangle \ln t_{t-k} + \eta ect_{t-1} + \mu_{1t}\end{aligned} \tag{4}$$

Finally, to avoid instability caused by the parameter set resulting in an unreliable model, a stability test is necessary for the resulting estimated parameters. The cumulative sum of recursive residuals (CUSUM) and cumulative sum of squares of recursive residuals (CUSUMSQ) tests [31] are used to examine the stability of the coefficients. Both tests were carried out at the 5% significance level. If the plots of the CUSUM and CUSUMSQ statistics remain within the 5% significance interval, the null hypothesis cannot be rejected, indicating that all coefficients in the given regression are stable.

2.3. Granger Causality Test

The existence of cointegration indicates a causal relation between variables, but the direction of causality is unclear. Therefore, the Granger causality test [32] is used to investigate short and long term causal dynamics among variables. If the variables are non-stationary and there is a cointegration relationship between them, Equation (5) develops a vector error correction model to test for Granger causality between variables:

$$(1-L)\begin{bmatrix} co_{2t} \\ nf_t \\ y_t \\ en_t \\ t_t \end{bmatrix} = \begin{bmatrix} c_1 \\ c_2 \\ c_3 \\ c_4 \\ c_5 \end{bmatrix} + \sum_{i=1}^{q} (1-L) \begin{bmatrix} a_{11i}a_{12i}a_{13i}a_{14i}a_{15i} \\ a_{21i}a_{22i}a_{23i}a_{24i}a_{25i} \\ a_{31i}a_{32i}a_{33i}a_{34i}a_{35i} \\ a_{41i}a_{42i}a_{43i}a_{44i}a_{45i} \\ a_{51i}a_{52i}a_{53i}a_{54i}a_{55i} \end{bmatrix} \begin{bmatrix} co_{2t-1} \\ nf_{t-1} \\ y_{t-1} \\ en_{t-1} \\ t_{t-1} \end{bmatrix} + \begin{bmatrix} \lambda_1 \\ \lambda_2 \\ \lambda_3 \\ \lambda_4 \\ \lambda_5 \end{bmatrix} [ECT_{t-1}] + \begin{bmatrix} \delta_{1t} \\ \delta_{2t} \\ \delta_{3t} \\ \delta_{4t} \\ \delta_{5t} \end{bmatrix} \tag{5}$$

2.4. Data

Annual observations were collected between 1965–2014. CO_2 emissions were measured using total CO_2 emissions (measured in millions of metric tons). Non-fossil energy, including nuclear and renewable energy (hydroelectric, solar, wind, biomass, and geothermal), is measured in millions of tons of oil equivalent. These data are collected from the BP Statistical Review of World Energy. Real GDP per capita is measured in constant 2005 USD. Energy consumption is measured using total primary energy consumption per capita (measured as kg of oil equivalent per capita). The data for these two variables were collected from the World Bank. Trade openness is measured as [(exports + imports)/GDP]. These data were obtained from the China statistical yearbooks. Table A1 summarizes descriptive statistics of each variable used in estimating Equation (1). The descriptive statistics of the growth rates of the variables are shown in Table A2.

3. Results

3.1. Unit Root Tests

Although the ARDL method has many advantages, it is only applied when the variables are I(1) or I(0).When the variable exceeds I(1), the ARDL method is not appropriate for a cointegration test. Therefore, it is necessary to perform a unit root test before applying the ARDL method. With a small sample size, the effects of the augmented Dicky-Fuller (ADF) test and the Phillips-Perron (PP) test will markedly decrease. To improve the unit root test credibility of each variable, this study uses the Dickey Fuller generalized least squares (DF-GLS) [33] test with a constant and a time trend. The test results showed that the logarithmic form of all variables except $\ln(co_2)_t$ was non-stationary at I(0), but all series were stationary after taking the first difference at 1% level (Table 1). Based on this result, ARDL appears to be a suitable method for a cointegration test.

Table 1. Results of unit root test.

Variable	Level		First Difference		
	SIC Lag	DFGLS Stat	SIC Lag	DFGLS Stat	Decision
$\ln(co_2)_t$	1	0.469	0	−3.827 ***	I(1)
$\ln nf_t$	0	3.817	0	−6.085 ***	I(1)
$\ln y_t$	1	1.163	1	−4.590 ***	I(1)
$\ln en_t$	1	−0.017	0	−3.921 ***	I(1)
$\ln t_t$	0	−0.391	0	−5.385 ***	I(1)

Note: Stars indicate statistical significance. *** 1% level.

3.2. ARDL Cointegration Method

Since the choice of lag length can affect the *F*-test, it is necessary to select the proper lag order of the variables prior to employing ARDL bounds testing. Application of the following system-wide methods determines the optimal lag order: Akaike information criterion (AIC), Final Prediction Error (FPE) criterion, Hannan-Quinn (HQ) criterion and Schwarz information criterion (SIC), and likelihood ratio (LR). The test results indicated that the optimal lag length is three (Table 2).

Table 2. Lag order selection criteria.

Lag	LogL	LR	FPE	AIC	SC	HQ
0	54.783	NA	1.29×10^{-6}	−2.207	−2.0489	−2.1484
1	334.788	499.139	1.34×10^{-11}	−13.686	−12.8913	−13.388
2	367.490	52.608	6.60×10^{-12}	−14.412	−12.981 *	−13.876 *
3	388.865	30.668 *	5.45×10^{-12} *	14.646 *	−12.579	−13.871
4	399.251	13.096	7.57×10^{-12}	−14.402	−11.699	−13.389

Note: * indicates the lag order selected by the criterion. LR, Likelihood Ratio; FPE, Final Prediction Error; AIC, Akaike Information Criterion; HQ, Hannan-Quinn criterion; SIC, Schwarz Information Criterion.

After determining the optimal lag order, this study applied the F-test to probe the cointegrating relationship among variables. The results indicated that the *F*-statistics exceeded the upper critical bound at the 1%, 5%, and 10% levels with CO_2 as a dependent variable (Table 3). According to the suggestion by Pesaran et al. [30], the null hypothesis of no long run relationship is rejected. ARDL bounds testing confirmed that these variables are cointegrated for a long term relation among non-fossil energy usage, economic development, energy consumption, trade openness, and CO_2 emissions.

Having identified the existence of a long run relationship between the variables, Equation (3) estimates the long-run coefficient (Table 4). The coefficient of $\ln nf_t$ is negative and significant, suggesting that non-fossil energy consumption decreases CO_2 emissions in the long term. For example, a 1% increase in non-fossil energy utilization leads to a 0.051% decrease in CO_2 emissions.

The coefficient of $\ln y_t$ is negative but statistically insignificant, implying that CO_2 emissions initially declined with an increase in per capita GDP. This conclusion is consistent with what was previously reported for Malaysia [34]. The coefficient of $\ln en_t$ is statistically significant and positive, implying that energy consumption per capita increases CO_2 emissions in the long term. It should be noted that a 1% increase in energy usage increases CO_2 emissions by 0.560%. This is in agreement with previous findings from Friedl and Getzner [35] for Austria, Ang [36] for France, Ang [37] for Malaysia, Shahbaz [38] for Pakistan, and Liu [39] and Jalil and Feridun [40] for China.

Table 3. Results of the bounds tests of Equation (2).

Panel I: Bounds Testing of Cointegration			Panel II: Diagnostic Tests	
Estimated equation	$\ln(co_2)_t$ = f($\ln nf_t$, $\ln y_t$, $\ln en_t$, $\ln t_t$)		R^2	0.858
Optimal lag structure	(3, 1, 1, 0)		Adjusted-R^2	0.814
F-statistics (Wald-statistics)	4.480		*F*-statistics (prob-value)	19.325 (0.000) ***
Significant level	Critical values (T = 47)		Durbin–Watson	0.963
	Lower bounds, I(0)	Lower bounds, I(1)	J–B normality test	0.341 (0.926)
1%	3.74	5.06	Breusch-Godfrey LM test	1.593 (0.375)
5%	2.86	4.01	ARCH LM test	1.476 (0.348)
10%	2.45	3.52	Ramsey RESET	0.387 (0.982)

Note: Stars indicate statistical significance. *** 1% level.

Table 4. Long-run coefficient estimates.

Variable	Coefficient	Standard Error	*t*-Statistic	Prob.
$\ln nf_t$	−0.051 **	0.123	−1.233	0.002
$\ln y_t$	−0.145	0.126	−1.186	0.243
$\ln en_t$	0.560 ***	0.077	7.283	0.000
$\ln t_t$	1.203 ***	0.194	6.22	0.000
Constant	3.447 ***	0.695	4.961	0.000

Note: Stars indicate statistical significance. *** 1% level; ** 5% level.

Trade openness positively correlates with CO_2 emissions and it is statistically significant at the 1% level. A 1% increase in trade openness causes a 1.203% increase in CO_2 emissions. This is in agreement with previous work form Tao and Song [41], but it contradicts Shahbaz et al. [42] for the case of Tunisia and Shahbaz et al. [43] for Indonesia, which showed that trade openness allows developing economies access to advanced technologies, resulting in a reduction of CO_2 emissions.

The error correction model is estimated on the base of SIC (Table 5). The elasticity of CO_2 emissions for non-fossil energy usage was positive in the short run and statistically insignificant at conventional levels. This finding provides little evidence on the beneficial role of non-fossil energy usage on CO_2 emissions in the short term. However, non-fossil energy usage has a positive impact on the environment in the long term, likely because non-fossil energy usage reaches a level that affects CO_2 emissions.

Table 5. Error correction representation of the autoregressive distributed lag (ARDL) model.

Dependent Variable is Δco_2			
Variable	**Coefficient**	**Standard Error**	***T*-Ratio [Prob]**
$\Delta\ln(co_2)_{t-2}$	0.264 ***	0.132	3.852 [0.000]
$\Delta\ln nf_t$	0.026	0.334	0.793 [0.432]
$\Delta\ln y_t$	0.356 **	0.110	3.234 [0.003]
$\Delta\ln en_t$	0.424 ***	0. 049	3.599 [0.000]
$\Delta\ln t_t$	0.316 ***	0.057	5.543 [0.000]
$\mathrm{Ecm}_{(t-1)}$	−0.273 ***	0.063	−4.372 [0.000]

Note: Stars indicate statistical significance. *** 1% level; ** 5% level.

Economic growth has a positive and statistically significant effect on CO_2 emissions at the 1% level in the short run, implying that a GDP per capita increase of 1% raises CO_2 emissions by 0.356%. The short-run elasticity of energy usage for CO_2 emissions is 0.424, indicating that a 1% increase in per capita energy usage is related with a 0.424% increase in CO_2 emissions. Thus, energy usage seems to be an important factor in environmental degradation after economic growth in the short run.

The result suggests that a positive relationship between trade openness and CO_2 emissions exists in the short term at the 1% level. For example, a 1% increase in trade openness causes a 0.316% increase in CO_2 emissions in the short run. This is similar to the findings in Shahbaz et al. [44] for the case of Bangladesh. The error-correction term reveals the CO_2 adjustment rate back to its long-run equilibrium level after a shock. The error-correction term is statistically significant and negative. The estimated coefficient of $\text{Ecm}_{(t-1)}$ is -0.273, which suggests that the deviation from the long-run balanced level of CO_2 emissions in one year is adjusted by 27.3% over the next year.

3.3. The VECM Granger Causality Results

Table 6 displays the results of the Granger causality analysis. In the short run, there is a unidirectional relationship from non-fossil energy use to energy consumption and CO_2 emissions, suggesting a Granger-causality relationship with non-fossil energy use causing energy consumption and CO_2 emissions in the short term. These findings imply that the construction and maintenance of non-fossil energy generation facilities may result in energy consumption and additional emissions. A unidirectional relationship from GDP per capita to CO_2 emissions exists, too, indicating that GDP per capita causes CO_2 emissions in the short run. This result is in agreement with Shafiei and Salim [45] for the case of OECD countries but contrasts with Salim and Rafiq [46] for India, which indicates unidirectional causality from CO_2 emissions to income. It also differs from Xue et al. [47] for nine European countries and Peng et al. [48] for China. In addition, there is a unidirectional relationship from GDP per capita to energy consumption and from CO_2 emissions to trade openness. This implies that emission mitigation policies would influence trade openness in the short term.

Table 6. Granger causality test.

	Short-Run *F*-Statistics (Probability)					Long Run
Dependent Variable	$\Delta\ln(co_2)_t$	$\Delta\ln nf_t$	$\Delta\ln y_t$	$\Delta\ln en_t$	$\Delta\ln t_t$	Ect_{t-1} (*t*-Statistics)
$\Delta\ln(co_2)_t$	—	7.378 ** (0.025)	13.471 *** (0.001)	11.213 *** (0.004)	3.989 (0.136)	−0.61(3.28) **
$\Delta\ln nf_t$	0.520 (0.770)	—	2.695 (0.259)	0.845 (0.655)	1.054 (0.590)	
$\Delta\ln y_t$	0.871 (0.647)	2.334 (0.311)	—	1.435 (0.487)	0.020 (0.989)	—
$\Delta\ln en_t$	16.870 *** (0.000)	13.610 *** (0.001)	8.370 ** (0.015)	—	2.191 (0.334)	—
$\Delta\ln t_t$	5.924 * (0.052)	1.709 (0.425)	1.104 (0.575)	4.055 (0.132)	—	

Note: Stars indicate statistical significance. *** 1% level; ** 5% level; * 10% level.

Carbon dioxide emissions have a significant influence on energy consumption and vice versa, suggesting a bidirectional relationship between them. These data are consistent with those of Halicioglu [49] for Turkey and Tang and Tan [50] for Vietnam, but they contradict Soytas and Sari [51], which suggests that there is only a one-way causal relationship from CO_2 emissions to energy use. Regarding long-run causality, the error correction term (ECT) coefficients are statistically significant and have the expected sign, which further confirms the previous bound test results.

3.4. Instability Tests Results

To avoid the instability caused by the parameter set leading to an unreliable model, this study employs CUSUM and CUSUMSQ to test the stability for the parameters used for the model. Every coefficient in the constructed error-correction model is stable and credible, with the plots of both tests well within the critical bounds at the 5% significance level (Figures 1 and 2). Thus, the chosen model can be applied to policy decision-making purposes, so that the effect of policy changes considering economic growth, energy consumption, trade openness, and non-fossil energy consumption would not result in major distortions in the level of CO_2, as the parameters in this model follow a stable pattern over the period under examination.

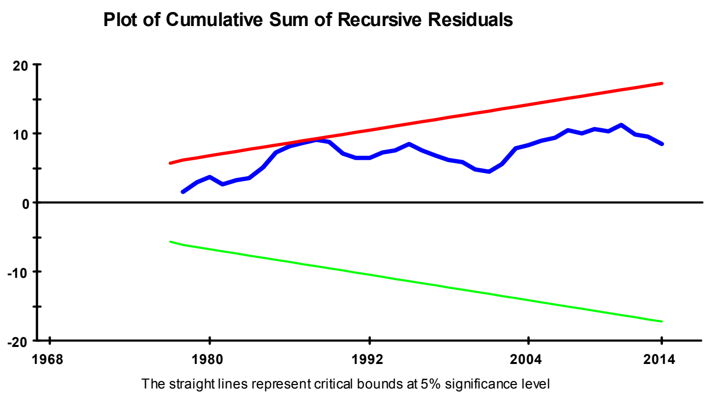

Figure 1. Recursive residuals and cumulative test results.

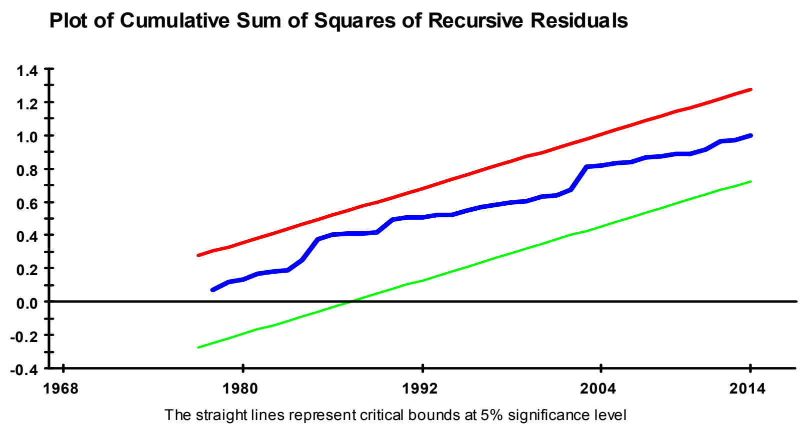

Figure 2. Recursive cumulative sum of squared residuals and test results.

4. Conclusions and Policy Implications

China is faced with the environmental challenge to reduce its dependency on fossil fuels in order to substantially diminish its CO_2 emissions. As alternatives to traditional energy, non-fossil energy usage is an effective means of mitigating climate change. This study investigates the long term relationship among CO_2 emissions, economic development, non-fossil energy usage, energy consumption, and trade openness by using an ARDL model. The short term relationship dynamics were examined using ECM.

The results confirmed that there is both a long- and short-run relationship between CO_2 emissions, non-fossil energy consumption, energy consumption, economic development, and trade openness. Non-fossil energy usage reduces CO_2 emissions with a significant effect in the long run. This study finds that non-fossil energy consumption has a major part to play in curbing CO_2 emissions in the long term in China. Trade openness and energy consumption cause a significant increase in carbon emissions both in the long and short term. However, GDP per capita does not have any remarkable impact on CO_2 emissions in the long term but increases them in the short term. Therefore, the results prove that CO_2 emissions are mainly determined by economic development, trade openness, and energy use in the short term. The Granger causality test shows one-way causal relationship from non-fossil energy usage to CO_2 emissions. Other one-way causal relationships from GDP per capita to energy use and from CO_2 emissions to trade openness were also confirmed. Moreover, there is bidirectional causality between CO_2 emissions and energy usage.

These results have important implications for policy making. Specifically, the results indicate that the country's energy usage and corresponding CO_2 emissions will continue to grow over the long term in the coming decades. To reduce pollution as well as achieve economic stability and sustainable growth, it is necessary to continue increasing the share of renewable energy and reduce dependency on fossil fuels. For example, the government should formulate and implement effective policies to promote technology innovation in renewable and nuclear energy. It should also devote more attention to the subsidy system for clean energy prices and improve the pricing mechanisms for solar and wind power, as well as power generated from other non-fossil sources. It would also be necessary to introduce tax policies that encourage investments in non-fossil power generation, transmission and storage. Furthermore, the government should pay more attention to the effects of environmental deterioration resulting from increased trading activities. It is necessary to encourage enterprises to introduce advanced foreign technologies and managerial experience in the fields of environmental protection and clean manufacturing. The administration should also enhance environmental supervision of foreign-funded enterprises.

Author Contributions: All the authors have been involved in the work of the paper. Deshan Li conceived and designed the experiments; Deshan Li composed the manuscript, while Degang Yang revised it. Both authors read the final version and agreed with its content.

Conflicts of Interest: The authors claim that there is no conflict of interest.

Appendix A

Table A1. Descriptive statistics for the variables.

Variable	Mean	Std. Dev.	Min	Max
co_2	3343.539	2788.524	476.772	9761.078
en	882.814	534.209	167.418	2230.150
nf	59.868	76.407	4.386	322.534
t	0.284	0.185	0.050	0.653
y	950.773	1044.298	109.384	3862.917

Table A2. Descriptive statistics for the growth rates of the variables.

Variable	Mean	Std. Dev.	Min	Max
co_2	0.065	0.064	−0.102	0.286
en	0.057	0.115	−0.123	0.695
nf	0.092	0.087	−0.138	0.297
t	0.046	0.136	−0.222	0.389
y	0.075	0.048	−0.081	0.162

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