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Nexus among Energy Consumption, Economic Growth, Urbanization and Carbon Emissions: Heterogeneous Panel Evidence Considering China's Regional Differences

Jingqi Sun [1,2], Jing Shi [1,*], Boyang Shen [3] , Shuqing Li [1,2] and Yuwei Wang [1]

[1] School of Economics and Management, North China Electric Power University, Beijing 102206, China; sjq@ncepu.edu.cn (J.S.); 50600934@ncepu.edu.cn (S.L.); wangyuwei2017666@gmail.com (Y.W.)

[2] Beijing Key Laboratory of New Energy and Low-Carbon Development, North China Electric Power University, Changping District, Beijing 102206, China

[3] Electrical Engineering Division, Department of Engineering, University of Cambridge, Cambridge CB3 0FA, UK; bs506@cam.ac.uk

* Correspondence: shijing0421@hotmail.com

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Abstract: This article examines the relation among carbon emissions, energy consumption, economic growth and urbanization in four panels: national level, developed areas, medium developed areas, and underdeveloped areas, which fully considers the differences across Chinese provinces. Due to the heterogeneity among Chinese provincial panels, the heterogeneous panel analysis technique is used, which includes heterogeneous panel estimation based on dynamic ordinary least squares (DOLS) and fully modified least squares (FMOLS), and the heterogeneous panel Granger test based on Dumitrescu and Hurlin is also used. The empirical results indicate that there are long-term equilibrium relationships between carbon emissions, GDP, energy consumption structure and urbanization rate in the four panels. GDP and energy consumption structure had obvious impacts on carbon emissions in all panels, but the urbanization rate significantly affected carbon emissions only in the national and medium developed areas. The heterogeneous Granger causality test reveals that the relationship between carbon emissions and various influencing factors in different regions varies. Finally, according to the empirical research results, policy implications of reducing carbon emissions in different regions were proposed.

Keywords: urbanization level; carbon emissions; energy consumption structure; heterogeneous panel analysis; regional differences

1. Introduction

In recent years, with the remarkable development of China's economy and the advancement of urbanization, large-scale industrialization has started in most parts of China. Large amounts of greenhouse gas emissions are emitted through the use of fossil fuels such as coal and petroleum. The emission of greenhouse gases, especially CO_2, has been doing significant harm to the atmosphere. As a result, the "greenhouse effect" has become more serious.

As it approaches 2020, China has entered the final lap in the race to build a well-off society. China's economy has entered the new normal, which has led to a better quality of economic development, a more rational social division of labor, more stable economic growth and more optimized industrial structure. Meanwhile, the mode of economic development in China is shifting from extensive growth focusing on scales and speed to intensive growth emphasizing quality and efficiency. The economic

structure is transforming from incremental expansion to the adjustment of stocks, and the momentum of economic development is shifting from the traditional growth point to a new growth perspective. An extensive economic development mode at the expense of environmental resources is difficult to sustain, which is the reason why the current economic development mode in China is unsustainable.

However, in the process of China's economic development and urbanization, high energy consumption has played a key role, causing continuous raising carbon emissions. Simultaneously, due to an obvious discrepancy in the standard of technical conditions and economic development in different areas, the carbon emissions caused by economic development and energy consumption vary a lot in different regions. Furthermore, as the evolution of urbanization in China continues, levels of carbon emissions in different regions will be affected. Therefore, considering the regional differences, inspecting the relations among carbon emissions, energy consumption, economic growth and urbanization levels is of theoretical and practical significance for China in order to formulate corresponding carbon emission policies that are consistent with China's regional development reality.

Since the United States economists Grossman and Krueger [1] proposed the famous Environmental Kuznets Curve (EKC) hypothesis in 1991, lots of scholars have used various environmental pollution indicators and time series and panel data to explore the environmental issues involving economic development, but consistent conclusions have not been reached. For instance, Laureti T et al. examined the factors influencing the NO_x emissions in the community of Madrid in Spain, finding that developing public transport can help to reduce the emissions of NO_x [2]. Castellano R et al. investigated the effect of road transportation on the emissions of three air pollutants in Organization for Economic Cooperation and Development (OECD) countries, showing that the condition of transport infrastructure construction and the choice of vehicles will have a significant impact on air quality [3]. However, most early research involved bivariate empirical models. The results of Roberts and Grimes' study showed that GDP and CO_2 emissions comply with the EKC assumption [4]. Lu H found that the output and CO_2 emissions are not simply inverse U-shaped relationships in China [5]. Azomahou and van Phu used non-parametric research methods showing that CO_2 emissions and GDP exist in a more complex relation than the EKC curve [6]. At the same time, more scholars chose multiple countries or divided a country into multiple regions for comparative research [7–9]. Galeotti and Lanza used panel data to reckon the relation between CO_2 emissions and GDP in order to predict the CO_2 emissions, and found that the empirical relationship between the two variables was a non-linear form rather than a linear or logarithmic function which was commonly considered [10]. Li F, Dong S, Li X, et al. employed the empirical analysis of panel data showing that there was a cointegration relation between actual per capita GDP and energy consumption. Moreover, the income elasticity of energy consumption in eastern China is more than twice that of the western region [11].

However, as the studies continue deepening, more and more scholars have found that the bivariate model has obvious deficiencies in the description of economy–environment linkages. Therefore, researchers gradually added various factors to explore the relations between GDP and CO_2 emissions from multiple perspectives [12,13]. Lean and Smyth used a panel vector error correction model (VECM) to estimate the relation between CO_2 emissions and GDP in the five Association of Southeast Asian Nations (ASEAN) countries, finding that there was a long-term non-linearity among energy consumption, carbon emissions and actual outputs [14]. Wu Z and Xie X empirically studied the impact of China's GDP and industrial structure on CO_2 emissions based on panel data in 30 provinces in China, finding that a long-term equilibrium nexus exists among the three variables [15].

Furthermore, when investigating the relationship between GDP and CO_2 emissions, urbanization has been turned into an important factor in the analysis framework and many outcomes appeared [16,17]. For instance, York examined the relationship between population, economy and energy consumption using the panel data of 14 EU countries during the period 1960–2000, finding that the population size, age structure, urbanization level and economic growth all significantly affect energy consumption levels [18]. Zarzoso and Maruoti found that urbanization and carbon emissions were in line with the EKC curve [19], while an opposite conclusion was obtained by Dong X and Yuan G [20]. Poumanyvong

and Shinji selected data from 99 countries over the past 30 years to study the relations among CO_2 emissions, energy consumption, and urbanization, revealing that the impacts of the three variables were different in different times [21]. Hossain analyzed the dynamic causality among carbon emissions, trade liberalization, GDP and energy consumption in recently industrialized countries, finding that high energy consumption would cause CO_2 emissions [22], and similar conclusions were also obtained by Solarin et al. [23].

In line with the above discussion, it can be inferred that most scholars adopted different methods to study the nexus between GDP and CO_2 emissions, which provides many references for our research. However, there are still some aspects that can be improved. Firstly, China is at an accelerated stage of industrialization, making the amounts of carbon emissions and total energy consumption quite different from developed countries, so it is essential to take into account China's characteristics when exploring the relations between GDP and CO_2 emissions, like considering urbanization. Secondly, much previous research on the nexus of China's carbon emissions and GDP adopted the whole national-level data, without considering regional differences, which is not helpful for developing carbon emission reduction policies according to local conditions. Besides, Chinese provincial panels have significant heterogeneity [11,24], which causes conventional panel analysis techniques based on homogeneous panel data to be biased, so the heterogeneous panel analysis approach should be applied when exploring these issues. Therefore, this paper takes the GDP, urbanization rate, carbon emission and energy consumption of 30 provinces in China as the research objects, and discusses the nexus among the examined variables in four regions named the whole country (Nation), developed areas (DA), medium developed areas (MDA) and underdeveloped areas (UDA), using the heterogeneous panel analysis methods. In general, the novelty and contributions of this paper include:

(1)　According to the World Bank's standard line for per capita GDP of developed countries, this paper divided China's 30 provinces into developed areas, medium developed areas and underdeveloped regions. Furthermore, the relationship between GDP, CO_2 emissions, urbanization rate and the energy consumption structure of provinces in different areas is examined to compensate for the gaps in previous research, which can help formulate appropriate carbon reduction policies based on regional development characteristics.

(2)　Taking into account the heterogeneity among Chinese provincial panels, this paper adopted heterogeneous panel analysis techniques, including heterogeneous panel estimation based on dynamic ordinary least squares (DOLS) and fully modified least squares (FMOLS) analysis, and the heterogeneous panel Granger test based on Dumitrescu and Hurlin, which overcomes the deficiencies of conventional panel analysis techniques, ensuring the validity of parameter estimation results and the reliability of the Granger causality test.

The rest of the article is organized as follows: the data resource, descriptive statistics of variables and the model adopted in this paper are presented in Section 2. In Section 3 the major econometric methodologies are presented. In Section 4, the empirical findings and the interpretations of results are displayed. Finally, in Section 5 the conclusions are summarized and some related policy remarks made.

2. Model, Data and Descriptive Statistics

2.1. Model and Data

As suggested by some previous studies [15,20,25], urbanization, energy consumption structure and economic growth have significant effects on CO_2 emissions. To explore the interrelationships among CO_2 emissions, urbanization, energy consumption structure and economic development level from a deeper perspective, this paper proposes an expanded model where four representative variables are involved, shown as Equation (1).

$$CE_{at} = f(UR_{at},\ ECS_{at},\ GDP_{at}) \tag{1}$$

where *a* and *t* represent regions and time period separately. *CE* means CO_2 emissions (million tons), *UR* is the urbanization rate counted by proportion of urban population to the total population, *ECS* means energy consumption structure revealing energy use structure, and *GDP* signifies the gross domestic product (billion yuan) reflecting the economic development level. The data of province-level CO_2 emissions are obtained from the China Emission Accounts and Datasets (CEADS, http://www.ceads.net/), and other data are collected from the National Statistics Bureau (NSB, http://www.statas.gov.cn). To reduce data fluctuations and eliminate the heteroscedasticity that may exist in the panel, the variables *CE* and *GDP* are converted in their natural logarithmic series, expressed as *LCE* and *LGDP*. Since *UR* and *ECS* are percentage-typed variables, their coefficient can stand for the elasticity directly. According to previous related researches [26–28], the logarithmic linear function is constructed as below:

$$LCE_{at} = \beta_{1a}UR_{at} + \beta_{2a}ECS_{at} + \beta_{3a}LGDP_{at} + \mu_{at} \qquad (2)$$

where β_{1a}, β_{2a} and β_{3a} are elasticities of *CE* with pertain to *UR*, *ECS* and *GDP* per capita, respectively. μ_{at} is error with a mean of 0 and a variance of σ^2. We use a balanced panel of 30 provinces in China, namely, Tianjin (TJ), Beijing (BJ), Shanghai (SH), Inner Mongolia (IM), Shandong (SD), Chongqing (CQ), Hubei (HuB), Jiangsu (JS), Jilin (JL), Shaanxi (S'X), Liaoning (LN), Ningxia (NX), Hunan (HuN), Guangdong (GD), Hainan (HaiN), Qinghai (QH), Hebei (HeB), Henan (HeN), Xinjiang (XJ), Zhejiang (ZJ), Heilongjiang (HLJ), Jiangxi (JX), Sichuang (SC), Anhui (AH), Guangxi (GX), Shanxi (SX), Guizhou (GZ), Yunnan (YN) and Gansu (GS), Fujian (FJ), covering the period from 1995 to 2015. According to the World Bank's standard line for per capita GDP of developed countries, this paper divided China's 30 provinces into developed areas (DA), medium developed areas (MDA) and underdeveloped areas (UDA), as shows in Table 1.

Table 1. The provinces in different areas.

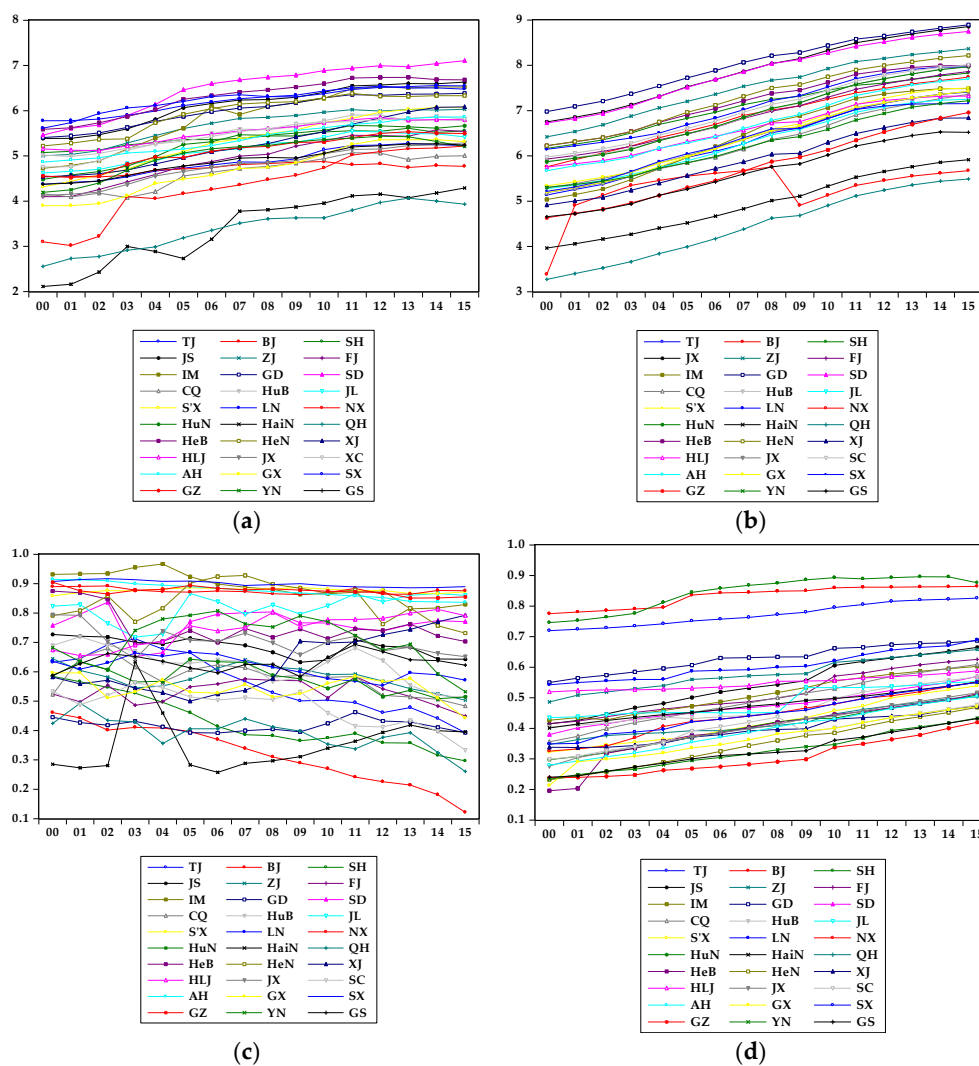| Panel	Provinces
Developed areas (DA)	TJ, BJ, SH, ZJ, FJ, IM, GD, SD, JS
Medium developed areas (MDA)	CQ, HuB, S'X, JL, LN, NX, HuN, HaiN, QH, HeB, HeN, XJ, HLJ, JX
Underdeveloped areas (UDA)	SC, AH, YN, GX, GZ, GS, SX

2.2. Descriptive Statistics of Variables

Table 2 shows the descriptive statistics for all variables in the national panel and the three sub-panels, and Figure 1 presents the trends of all variables in every province. It can be inferred that the heterogeneity across regions for the variables is confirmed, because in different provinces, there is a significant difference in the value of the same variable in the same period.

Table 3 presents the correlations among the analyzed variables for national level, which indicates that *CE* has significant positive correlations with *UR*, *ECS* and *GDP*. These findings reveal that energy-dependent development mode played a significant role in promoting high carbon development across the areas, and economic growth can help to promote urbanization. Besides, the results also show that *GDP* has negative correlations with *ECS* and positive correlations with *CE* and *UR*, indicating that low fossil energy consumption is harmful to economic development, and urbanization is still a significant element promoting *GDP*.

Table 2. Descriptive statistics for all variables in panel and cross-sections.

Objects	Variables	Mean	Median	Max.	Min.	Std. Dev.	Skewness	Kurtosis
Nation	*LCE*	9.6709	9.7599	11.709	6.3969	0.9208	−0.6400	0.9171
	UR	0.4513	0.4380	0.8961	0.1352	0.1682	0.5393	0.0432
	ECS	0.6609	0.6842	0.9671	0.1215	0.1756	−0.3236	0.6389
	LGDP	8.5446	8.5377	11.195	5.1227	1.1782	−0.2399	−0.1363
DA	*LCE*	9.9795	9.9043	11.709	8.4118	0.7533	0.2434	−0.6009
	UR	0.5859	0.5828	0.8961	0.1827	0.1899	−0.2780	−0.6840
	ECS	0.5867	0.5908	0.9671	0.1215	0.1761	−0.0326	−0.4116
	LGDP	9.1691	9.1840	11.195	6.7535	1.0577	−0.1567	−0.6143
MDA	*LCE*	9.4672	9.6541	11.432	6.3969	1.0634	−0.6840	0.1826
	UR	0.4229	0.4350	0.6894	0.1683	0.1134	−0.2760	−0.4710
	ECS	0.6717	0.6928	0.9282	0.2579	0.1684	−0.5998	−0.3879
	LGDP	8.2654	8.2638	10.518	5.1227	1.2085	−0.3922	−0.1641
UDA	*LCE*	9.6817	9.7333	11.162	8.5034	0.6679	0.1228	−0.4433
	UR	0.3350	0.3356	0.5622	0.1352	0.1038	−0.0800	−0.7620
	ECS	0.7218	0.6953	0.9241	0.3336	0.1625	−0.2125	−1.3756
	LGDP	8.2999	8.2719	10.311	6.3239	0.9419	0.0888	−0.8095

Figure 1. *LCE*, *LGDP*, energy consumption structure (*ECS*) and urbanization rate (*UR*) in 30 provinces from 2000 to 2015. (**a**) presents the trend of *LCE*, (**b**) is the trend of *LGDP*, (**c**) is that of *ECS* and (**d**) is that of *UR*.

Table 3. Correlations for the panel data set (*p* values in parentheses).

	LCE	*LGDP*	*UR*	*ECS*
LCE	1.0000			
LGDP	0.833248 (0.0000) ***	1.0000		
UR	0.231509 (0.0000) ***	0.466737 (0.0000) ***	1.0000	
ECS	0.335314 (0.0000) ***	−0.351735 (0.0000) ***	−0.466566 (0.0000) ***	1.0000

Note: *** Denotes statistical significance at 1% level.

3. Econometric Methodologies

3.1. Cross-Sectional Dependence Test

It is worth noting that due to the macroeconomic strategy at the provincial level such as the policy of reform and opening, the western development strategy and strategy of the rise of central plains area, cross-sectional dependence across provinces could exist. It is important to verify whether cross-sectional correlation exists before conducting a series of empirical analyses. According to existing studies [29,30], this paper assumes that the standard model with panel data can be represented as:

$$Y_{at} = \alpha_a + \beta_{at} X_{at} + \mu_{at}, \ a = 1, 2, \dots, A, \ t = 1, 2, \dots, T \tag{3}$$

The null hypothesis without cross-sectional dependence is: $H_0 : \rho_{ab} = \rho_{ba} = cor(\mu_{at}, \mu_{bt}) = 0$ for any $a \neq b$, and the alternative hypothesis is H_1 : exist $a \neq b$ making $\rho_{ab} = \rho_{ba} = cor(\mu_{at}, \mu_{bt}) \neq 0$, where ρ_{ab} is calculated as follows:

$$\rho_{ab} = \sum_{t=1}^{T} \mu_{at} \mu_{bt} / \sqrt{\sum_{t=1}^{T} \mu_{at}^2 \sum_{t=1}^{T} \mu_{bt}^2} \tag{4}$$

Pesaran's cross-sectional dependence test statistic can be displayed as follow:

$$CD = \sqrt{\frac{2T}{A(A-1)}} \sum_{a=1}^{A-1} \sum_{b=a+1}^{A} \hat{\rho}_{ab} \to N(0, 1) \tag{5}$$

3.2. Panel Unit Root Test

Before further empirical analysis, it is essential to perform a unit root test, which can determine the stability of variables to prevent false regression. According to existing studies [31–33], some models are widely used for panel unit root tests. However, for panels with cross-sectional dependencies, the first-generation unit root test tends to over-reject the null hypothesis [29,34]. Thence, Pesaran [35] developed a panel root *t*-statistic using average individual statistics that is expressed as follows:

$$\Delta z_{at} = \alpha_a + \beta_a^* z_{a,t-1} + c_0 \bar{z}_{t-1} + c_1 \Delta \bar{z}_t + \mu_{at} \tag{6}$$

where $\bar{z}_t = A^{-1} \sum_{a=1}^{A} z_{at}$ and Δ represents the difference operator. Thinking about the serial correlation in the data, the extended model can be:

$$\Delta z_{at} = \alpha_a + \beta_a^* z_{a,t-1} + c_0 \bar{z}_{a-1} + \sum_{m=0}^{r} c_{m+1} \Delta \bar{z}_{t-m} + \sum_{n=1}^{r} d_n \Delta z_{a,t-n} + \mu_{at} \tag{7}$$

where *r* is the lagged order determined by Akaike information criterion (AIC) and Schwarz information criterion (SIC). For each *a*, the extended cross-sectional augmented Dickey-Fuller (CADF) regression is performed according to the Formula (7), and then the *t*-statistic of β_a^* is obtained, called $CADF_a$. Based on this, the *CIPS* statistic is constructed by:

$$CIPS = A^{-1} \sum_{a=1}^{A} CADF_a \tag{8}$$

3.3. Panel Co-Integration Test

For integrating the relations among variables whose data have the same order sequence in the panel, Pedroni [36,37] put forward a panel co-integration test technique to test a long-run equilibrium relation. Consider the following model:

$$LCE_{at} = \alpha_{at} + \beta_a t + \gamma_{1a} UR_{at} + \gamma_{2a} ECS_{at} + \gamma_{3a} LGDP_{at} + \varepsilon_{at} \tag{9}$$

where *a* and *t* reveal regions and time period separately. α_{at} and β_a are the region-fixed and time-fixed effects. Bias from long-run equilibrium is the estimated residual reflected by ε_{at}. γ_{1a}, γ_{2a} and γ_{3a} are the elasticities of CE_{at} regarding UR_{at}, ECS_{at} and GDP_{at}, separately. The equilibrium relation among the analyzed variables is explored by inspecting the stability of ε_{at}. Normally, the unit root test of ε_{at} is constructed as follows:

$$\varepsilon_{at} = \rho_a \varepsilon_{a,t-1} + v_{at} \tag{10}$$

The null hypothesis is $H_0 : \rho_a = 1$, indicating that ε_{at} is non-stationary and there is no co-integration relation among examined variables.

3.4. Panel Data Model Estimation

When the studied variables are co-integrated, it is necessary to estimate the long-term relationships among *LCE*, *UR*, *ECS* and *LGDP*. There are many techniques that can be used to perform the estimation of the panel model, like the ordinary least squares (OLS) technique, fully modified OLS (FMOLS) technique [38] and dynamic OLS (DOLS) technique [39,40].

According to [39], the statistics obtained by OLS, FMOLS, and DOLS have asymptotically normal distributions in the panel co-integration regression model. Specifically, the asymptotic distributions of FMOLS and DOLS statistics are the same, while that of OLS statistic is not a consistent estimator of the parameters and there is a bias that cannot be ignored. Besides, the DOLS statistic is more effective than the FMOLS statistic and the OLS statistic.

3.5. Heterogeneous Panel Causality Test

It is necessary to examine the causality and its direction after the long-term nexus among the examined variables is discovered. Normally, when the conditional distribution of variable *y* which is defined by the past value of *y* equal to that which is defined by the past values of variables *y* and *x*, it shows that the Granger causality from *x* to *y* emerges [41–43]. The baseline for the standard Granger causality test is that the past value of *x* can affect the future trend of *y* with a statistical significance for more than one individual [41]. However, the heterogeneity between cross-sectional samples may result in the obtained Granger causalities varying in each cross-section, although the whole panel supports the existence of Granger causality [41]. Thence, Dumitrescu and Hurlin [44] developed a pairwise panel causality test (D–H causality test) to examine the heterogeneous panel causality between cross-section units. Suppose in a panel, *x* and *y* are two stationary sequences. For the *a*-th individual at *t*-th period, the following liner model can be expressed:

$$y_{at} = \alpha_a + \sum_{l=1}^{L} \beta_{al} y_{a,t-l} + \sum_{l=1}^{L} \delta_{al} x_{a,t-l} + \mu_{at} \tag{11}$$

The null hypothesis of homogeneous non-causality (HNC) can be defined as $H_0 : \delta_{al} = 0$ for any a, while the alternative hypothesis can be $H_1 : \delta_{al} = 0$ for any $a = 1, 2, \ldots, A_1$ while $\delta_{al} \neq 0$ for any $a = A_1 + 1, A_1 + 2, \ldots, A$.

The statistics of the D–H panel causality test is based on the average of cross-sectional units of Granger non-causality for a single Wald statistic, converging to the standard normal distribution. The specific calculation process of the test statistic is described in detail in [40]. In addition, this test requires that the variables be stationary. If not, the differential data of the variables should be used.

4. Empirical Findings and Interpretations

4.1. Cross-Sectional Dependence Test

Table 4 presents the results of cross-sectional dependence test. From Table 4, four variables, *LCE*, *LGDP*, *UR* and *ECS,* strongly reject the null hypothesis in all panels, indicating that cross-sectional dependence exists. Therefore, more advanced methods should be used, such as the second-generation panel unit root examination technique.

Table 4. Pesaran cross-sectional dependence test results.

Region	Variable	*LCE*	*LGDP*	*UR*	*ECS*	Overall
Nation	Pesaran CD test	80.573	80.507	79.978	15.362	22.134
	Prob.	0.0000 ***	0.0000 ***	0.0000 ***	0.0000 ***	0.0000 ***
DA	Pesaran CD test	23.104	23.934	22.914	8.310	4.872
	Prob.	0.0000 ***	0.0000 ***	0.0000 ***	0.0000 ***	0.0000 ***
MDA	Pesaran CD test	37.022	35.442	36.735	10.061	10.803
	Prob.	0.0000 ***	0.0000 ***	0.0000 ***	0.0000 ***	0.0000 ***
UDA	Pesaran CD test	17.634	18.255	17.677	5.391	82.73
	Prob.	0.0000 ***	0.0000 ***	0.0000 ***	0.0000 ***	0.0000 ***

Notes: *** Denotes the rejection of null hypothesis at 1% significance level.

4.2. Panel Unit Root Test

As described above, because the existence of cross-sectional dependence makes the results of first generation panel unit root test methods biased, the recently developed second-generation panel unit root test technique named the CIPS test is adopted in this section to inspect the stationarity of *LCE*, *LGDP*, *UR* and *ECS*. Table 5 reports the results of the panel unit root test, revealing that all variables are non-stationary at level but is stable at their first difference, that is, all variables are integrated at the first order, named I(1).

Table 5. Panel unit roots results.

Region	CIPS Test	Variable				Criterion		
		LCE	*LGPD*	*UR*	*ECS*	10% Level	5% Level	1% Level
Nation	Level	−2.007	−2.028	−2.076	−1.697	−2.11	−2.2	−2.38
	1st diff.	−3.376 ***	−2.612 ***	−2.977 ***	−3.286 ***	−2.14	−2.25	−2.45
DA	Level	−1.680	−1.867	−1.419	−1.394	−2.18	−2.33	−2.64
	1st diff.	−4.542 ***	−3.116 ***	−2.596 **	−2.627 **	−2.22	−2.4	−2.76
MDA	Level	−2.063	−1.831	−2.006	−1.880	−2.11	−2.22	−2.45
	1st diff.	−3.280 ***	−3.522 ***	−3.492 ***	−3.631 ***	−2.16	−2.28	−2.52
UDA	Level	−2.099	−1.847	−1.614	−1.166	−2.18	−2.33	−2.64
	1st diff.	−2.483 **	−2.252 *	−4.069 ***	−3.019 ***	−2.22	−2.4	−2.76

Notes: * CIPS test is estimated applying constant and trend with 1 lag. ** *** Denotes the rejection of null hypothesis at 5% and 1% levels of significance.

4.3. Panel Co-Integration Test

Table 6 lists the results of panel co-integration test in four panels. Among the seven statistics of the Pedroni residual co-integration test [37,38], there are four statistics supporting the long-term equilibrium relationships among the explored variables in DA and MDA, and five supporting that in nation and UDA. Therefore, it can be deduced that *LCE*, *UR*, *ECS* and *LGDP* share a long-run equilibrium nexus in four panels. For robustness, another two panel cointegration techniques like the Kao co-integration test [45] and the Fisher-type Johansen co-integration test [33] were also employed to examine the long-run relation among the variables, and the results of these two co-integration tests are also listed in Table 6, which confirm that a co-integration relationship exists among the variables in each panel.

Table 6. Panel co-integration test results.

Pedroni Residual Cointegration Test				
Test Statistics	**Nation**	**DA**	**MDA**	**UDA**
Panel v-Statistic	−1.641530 *	−2.153581 **	−3.457571 ***	−1.110789
Panel rho-Statistic	1.955698	1.943861	3.886977 **	2.509975 *
Panel PP-Statistic	5.265526 **	−1.057682	2.208866 *	2.076040 *
Panel ADF-Statistic	−4.228109 ***	−1.791574 **	−0.444975	−2.241201 **
Group rho-Statistic	−0.092068	3.028955	4.445418	3.641918
Group PP-Statistic	6.455908 ***	−2.219356 **	2.208195 **	2.611854 **
Group ADF-Statistic	−2.414394 **	−2.526311 ***	−0.303020	−1.707920 **

Kao Cointegration Test				
Test Statistics	**Nation**	**DA**	**MDA**	**UDA**
ADF	−3.673287 ***	−4.634771 ***	−4.130794 ***	−2.320584 **

Fisher-Type Johansen Cointegration Test								
Hypothesized No. of CE(s)	**Trace test**				**Max-Eigen Test**			
	Nation	**DA**	**MDA**	**UDA**	**Nation**	**DA**	**MDA**	**UDA**
None	852.6 ***	259.1 ***	370.3 ***	223.5 ***	626.4 ***	194.8 ***	276.4 ***	156.1 ***
At most 1	370.4 ***	102.6 ***	157.5 ***	109.9 ***	234.5 ***	61.24 ***	99.99 ***	72.97 ***
At most 2	209.5 ***	60.34 ***	91.93 ***	57.15 ***	143.9 ***	44.18 ***	61.24 ***	38.37 ***
At most 3	179.1 ***	47.74 ***	84.67 ***	46.72 ***	179.1 ***	47.74 ***	84.67 ***	46.72 ***

Notes: * ** *** Reveal the significance of 10%, 5% and 1%.

4.4. Panel Data Model Estimation

Considering the serial correlation and endogeneity that may exist in the panel, the DOLS and FMOLS techniques are employed in this section to estimate the elasticities of *CE* with respect to *UR*, *ECS* and *GDP*. The estimation results of DOLS and FMOLS are shown in Table 7. The results of every variable in terms of symbol and importance are similar to the two models, but there is little difference in terms of magnitude.

The results of DOLS and FMOLS indicate that *GDP* and *ECS* have obvious effect on *CE*, both at national and regional level. From the point of view of national analysis, UR has the most significant influence on *CE*, followed by *ECS*. From the perspective of developed regions, *ECS* and *GDP* have an obvious effect on *CE*, while *UR* have much less effect on *CE*. This is due to high urbanization in developed regions that are more inclined to rationalize the energy structure and promote low-carbon development. Judging from the medium developed areas, *UR* has a very significant impact on *CE*, which is the same as the national level results, revealing that most of China is still in the process of urbanization which will greatly promote *CE*. From the perspective of the underdeveloped areas, *ECS* has an obvious effect on the *CE*, but the impact of *UR* is not significant. This is due to the lagging economic development in underdeveloped areas and relatively low urbanization rate. Guided by the development experience in developed regions and medium developed regions, underdeveloped

regions tend to adopt low-carbon development modes from the very beginning, changing their energy structure and thus affecting carbon emissions.

Table 7. Estimation results of dynamic ordinary least squares (DOLS) and fully modified least squares (FMOLS) models for panel (dependent variable: *LCE*).

Region	Variable	DOLS		FMOLS	
		Coefficient	*t*-Statistic	Coefficient	*t*-Statistic
Nation	*LGDP*	0.326027	7.678835 ***	0.359891	7.156279 ***
	UR	3.520260	7.146156 ***	3.088734	5.385906 ***
	ECS	1.359559	6.331141 ***	1.556592	7.077251 ***
	R-squared	0.980714		0.965530	
DA	*LGDP*	0.626879	12.18511 ***	0.659694	9.420428 ***
	UR	0.919203	1.622341	0.488946	0.5354
	ECS	2.039462	8.543109 ***	2.366439	8.299984 ***
	R-squared	0.988573		0.975810	
MDA	*LGDP*	0.232068	3.699689 ***	0.245420	3.183068 ***
	UR	4.907433	6.727691 ***	4.528544	5.248588 ***
	ECS	1.380554	4.071370 ***	1.529320	4.200622 ***
	R-squared	0.980030		0.963835	
UDA	*LGDP*	0.506100	5.491478 ***	0.521565	6.112268 ***
	UR	0.486777	0.467970	0.303345	0.316176
	ECS	1.645008	3.805031 ***	1.648253	5.197572 ***
	R-squared	0.982220		0.969150	

Notes: *** Indicate the significance level of 10%, 5% and 1%.

4.5. Heterogeneous Panel Causality Test

Table 8 reports the results of the D–H causality test used for the heterogeneous panel causality test, from which several findings are discovered:

(1)　At national stage, there exists unidirectional causal relationships from *CE* to *UR*, from *GDP* to *UR*, from *GDP* to *ECS* and from *UR* to *ECS*, and a bidirectional causal nexus between *GDP* and *CE* and between *CE* and *ECS*. The results show that at the national level, *CE* will affect the evolution of *GDP* and *UR*, and economic development will also accelerate the process of urbanization and promote energy restructuring. In addition, with the further development of *UR*, *ECS* will be adjusted. Meanwhile, for *CE* and *GDP*, *ECS* has a feedback relationship, and that is the reason why *CE* will affect *GDP* and *ECS*, and *GDP* and *ECS* also have obvious consequent on *CE*. This shows that the processes of national *GDP* and *UR* still mainly rely on using large amounts of fossil fuels, and urbanization and adjustment of energy consumption structure are driven by continuous development of the economy. Therefore, at a national stage, under the premise of taking economic development as the primary task, we must speed up the energy consumption structural adjustment, and change the economic development mode of energy-dependence to an innovation-driven mode, which is low carbon and high quality. Besides, green urbanization is also important for the realization of a low-carbon and high-quality economy.

(2)　The results of developed regions show that there are unidirectional causal relationships from *CE* to *ECS*, from *GDP* to *UR*, from *GDP* to *ECS* and from *UR* to *ECS*, and a bidirectional causal relation between *GDP* and *CE*. This shows that both *CE* and *UR* in developed regions have an impact on the *ECS*, and *GDP* will have effect on the *UR* and *ECS*. Besides, in developed regions, economic development has matured and the rate of urbanization has not changed much. Therefore, under the premise of maintaining stable economic growth, we must attach importance to optimizing *ECS* and reducing *CE*. Hence, in developed regions, the experience of

foreign developed cities can be learned from in order to speed up the mainstreaming of *ECS* and industrial upgrading, so as to achieve low-carbon development and a green economy in parallel.

(3) In the medium developed regions, the unidirectional causal relationships from *GDP* to *CE*, from *UR* to *CE*, from *GDP* to *UR* and from *GDP* to *ECS* are supported and the bidirectional causal relationships between *ECS* and *CE*, and between *ECS* and *UR* are proven, revealing that the *GDP* of medium developed regions have impacts on *CE*, *UR* and *ECS*, and *UR* will affect *CE*. Furthermore, *ECS* and *CE*, *ECS* and *UR* have feedback effects, similar to that of the national level, showing that the medium developed regions are at a high-speed stage of *GDP* and *UR*, and *GDP* is the center of all things, driving the transformation of *UR* and *ECS*. The results also show that the medium-developed regions are still in an energy-dependent development mode and require a large amount of fossil fuels to support their development. Therefore, against the background of taking economic development as the core to promote urbanization, it is essential to speed up the optimization of *ECS*, change the development mode from energy-dependent to innovation-driven, and advocate the low-carbon and green road in the process of urbanization, which can be helpful for achieving the high-quality development of economy and urbanization.

(4) In underdeveloped regions, there are unidirectional causalities from *GDP* to *CE*, from *CE* to *ECS*, from *GDP* to *UR* and from *UR* to *ECS*, and a bidirectional causal nexus between *ECS* and *GDP*. The results express the fact that the stage of economic development in underdeveloped areas will affect the level of local urbanization, while *CE* will promote the adjustment of *ECS*. Furthermore, the feedback effect exists between *ECS* and *GDP* in the underdeveloped regions, that is, *ECS* will affect *GDP*, and *GDP* will also advance adjustment of ECS. Moreover, *GDP* will also promote the adjustment of *ECS*, showing that current economic development in underdeveloped areas is still an extensive economic development mode heavily depending on energy, which is unsustainable. Therefore, in order to promote carbon reduction in underdeveloped regions, it is necessary to change the economic development mode of energy-dependent to innovation-driven, according to the experience of developed regions and medium developed regions. At the same time, it is important to optimize *ECS*, which can reduce *CE*.

In general, the causal nexus between *CE* and various influencing factors in different regions differs. Firstly, regarding the relationship between *GDP* and *CE*, a bidirectional causal relation exists in both national and developed regions, while in medium developed and underdeveloped regions, a unidirectional causal relation exists from *GDP* to *CE*. These results show that in all regions, *GDP* growth will lead *CE* increase, indicating that China has not yet achieved a complete low-carbon development path. Meanwhile, in the whole country and developed regions, *CE* will affect *GDP*, and that is the reason why China has begun to pay attention to green development and has no longer only pursued *GDP* growth. However, economic development is still a major task in medium developed regions and underdeveloped regions, and will not be affected by *CE*.

Secondly, regarding the relationship between *UR* and *CE*, the unidirectional causality exists from *UR* to *CE* in the national and medium developed regions, but there is no significant causality in developed and underdeveloped regions. That means from a national point of view, the process of *UR* will inevitably lead to *CE*, but in spite of this, China's urbanization process will not be affected. This is determined by China's basic national conditions as the largest developing country, that is, the developing economy is the center of all work in China. Therefore, *CE* will not according to Granger cause *UR* in developed regions, medium developed regions and underdeveloped regions. In developed and underdeveloped regions, the former has a high urbanization, while the latter has a lower urbanization rate, which causes the current level of urbanization to have no significant effect on *CE* in these areas. In medium developed regions, urbanization is rapidly advancing, which has greater effect on *CE*.

Table 8. Results of heterogeneous panel causality test (*p*-values in parentheses).

Null Hypothesis	Nation	DA	MDA	UDA
LGDP does not homogeneously cause *LCE*	3.10338 (0.0020) ***	2.12600 (0.0339) **	2.54247 (0.0112) **	3.13033 (0.0019) ***
LCE does not homogeneously cause *LGDP*	2.50263 (0.0123) **	1.93272 (0.0533) *	1.27842 (0.2011)	1.18148 (0.2374)
UR does not homogeneously cause *LCE*	3.59742 (0.0003) ***	−0.25600 (0.7980)	4.15303 (0.0001) ***	0.47575 (0.6343)
LCE does not homogeneously cause *UR*	0.31890 (0.7498)	0.66250 (0.5077)	0.34312 (0.7315)	0.83167 (0.4056)
ECS does not homogeneously cause *LCE*	2.73181 (0.0063) ***	0.29076 (0.7712)	3.85200 (0.0001) ***	−0.12187 (0.9030)
LCE does not homogeneously cause *ECS*	5.04663 (0.0000) ***	1.69990 (0.0891) *	4.45963 (0.0000) ***	2.21315 (0.0269) **
UR does not homogeneously cause *LGDP*	1.22444 (0.2208)	−0.09315 (0.9258)	1.23966 (0.2151)	0.89106 (0.3729)
LGDP does not homogeneously cause *UR*	16.4150 (0.0000) ***	5.00276 (0.0000) ***	16.2335 (0.0000) ***	5.37282 (0.0000) ***
ECS does not homogeneously cause *LGDP*	1.40445 (0.1602)	−0.50073 (0.6166)	0.45791 (0.6470)	2.82768 (0.0047) ***
LGDP does not homogeneously cause *ECS*	7.66748 (0.0000) ***	3.57335 (0.0004) ***	4.59099 (0.0000) ***	5.32876 (0.0000) ***
ECS does not homogeneously cause *UR*	1.29042 (0.1969)	−0.46360 (0.6429)	2.64362 (0.0082) ***	−0.51684 (0.6053)
UR does not homogeneously cause *ECS*	5.41728 (0.0000) ***	2.08701 (0.0369) **	4.37912 (0.0000) ***	2.64840 (0.0081) ***

Notes: * ** *** Denote the rejections of null hypothesis at 10%, 5% and 1% significance levels, respectively.

Finally, regarding the nexus between *ECS* and *CE*, the bidirectional causal relationship in national and medium developed regions is held, while unidirectional causality from *CE* to *ECS* is supported in developed regions and underdeveloped regions. These results show that in national and medium-developed regions, the economic development mode is energy-dependent, resulting in a large amount of CO_2 emissions, and excessive carbon emissions will in turn pressurize the structural adjustment of energy consumption. In developed regions, the economic development mode is mainly driven by innovation, so fossil fuels (especially coal) account for a relatively small percentage of total energy consumption and do not have an obvious effect on *CE*. In underdeveloped regions, the stages of economic development and industrialization are low, resulting in the overall consumption of fossil energy being relatively small. Hence, the effect of *ECS* on *CE* is not significant. In addition, the industrial structure in the underdeveloped regions is unstable and there is a large adjustable space. Hence, it is possible to learn from the experiences of developed regions and focus on the development of low-energy and low-carbon industries, that is, implementing low-carbon development strategies when developing the economy. It is worth mentioning that in developed and underdeveloped regions, *CE* has an impact on *ECS*, indicating that *CE* plays a significant role in promoting the optimization of *ECS* in the two regions.

It is worth noting that in 2003, Granger emphasized in the Nobel Prize-winning address that Granger causality is essentially a kind of prediction of stationary time series data, and therefore it is only applicable to econometric variable prediction and cannot be used as a criterion to test true causality. In other words, Granger causality does not equal actual causation. In this section, the causal relationship which was obtained by the D–H heterogeneous panel causality test method is Granger causality essentially too; that is, analyzing the Granger causality between different variables in this section aims at exploring whether these macroeconomic variables will statistically influence each other

and the direction of the influence, rather than examining the true "actual causation" between these macro variables, which is very complicated.

5. Conclusions and Policy Implications

With remarkable economic development, lots of fossil energy consumption has produced considerable CO_2, exacerbating the global greenhouse effect. As the largest emitter of CO_2, China has made solemn promises to reduce global carbon emissions. However, China is still a developing country, and abundant energy resources determine that the development of China's economy requires consumption of large amounts of fossil energy, so the task of carbon reduction is arduous. It should be noted that the different levels and modes of economic development in different regions of China make it difficult to implement a unified *CE* reduction policy. In addition, accelerating urbanization evolution in China also has an impact on *CE*, which also varies in different regions, making it theoretically and practically important to explore the factors that affect *CE* in different areas of China under this background of accelerating urban evolution. Based on this, this paper divided 30 provinces in China into three areas according to the relevant standards of the World Bank, and adopted heterogeneous panel analysis techniques to inspect the nexus between *CE*, *GDP*, *ECS* and *UR*, considering regional differences. The acquired results used a more objective way to reveal the factors influencing carbon emissions in China's current social and economic context, which can provide a theoretical basis and empirical support for the formulation of corresponding carbon emission reduction policies.

The heterogeneous panel techniques were applied in this paper to investigate China's regional carbon emission-influencing factors, and several useful findings were discovered: (1) a long-term equilibrium nexus exists between *CE*, *GDP*, *ECS* and *UR* in the four panels named nation, DA, MDA and UDA, which is partly consistent with some previous research results [11,22,25,27]. (2) DOLS and FMOLS results indicated that *GDP* and *ECS* had obvious impacts on *CE* both at national and regional level, and *UR* significantly affected *CE* in the national and medium developed areas, but had no significant effect on *CE* in developed regions and underdeveloped regions. Furthermore, at the national and medium developed levels, *UR* contributed most to *CE*, followed by *ECS* and *GDP*, showing that most of China was still in the process of urbanization which will greatly promote carbon emissions. In developed and underdeveloped regions, *ECS* contributed most to *CE*, and *UR* had a much less significant effect, which was because the high or low urbanization rate made the areas no longer vigorously develop urbanization, or use low-carbon development modes from the very beginning. (3) The results of the Granger causality test for heterogeneous panels revealed that the causal relation between *CE* and various influencing factors in unequal regions was not same. Specifically, there was a bidirectional causal nexus between *GDP* and *CE* in the whole country and developed regions, but a unidirectional causal relation from *GDP* to *CE* in medium-developed and underdeveloped regions, revealing that China did not achieve a complete low-carbon development path. In addition, a unidirectional causal relation exists from *UR* to *CE* in national and medium developed regions, but less significant causality in developed and underdeveloped regions, indicating that China's urbanization process will not be affected by increased carbon emissions. Finally, there was a bidirectional causal nexus between *ECS* and *CE* in national and medium developed regions, but a unidirectional causality from *CE* to *ECS* in developed and under-developed regions, indicating that the economic development mode was energy-dependent in the national and medium developed regions, and innovation-driven in developed regions. In the underdeveloped regions, the total consumption of fossil energy was relatively small, so the impact of *ECS* on *CE* was not significant. It should be noted that in developed and underdeveloped regions, *CE* had an effect on *ECS*, indicating that *CE* played an important role in promoting the optimization of *ECS* in these two regions.

From the national panel, the results obtained in this paper seem to be little different to previous studies. However, the difference between this article and some previous ones is that according to the level of economic development instead of the geographical location, China's 30 provinces are divided into three sub-panels named developed areas, medium developed areas and underdeveloped

areas. The empirical results show that the results of different sub-panels vary from each other and are different from those of the national panel. It can be concluded that the results fully take into account China's regional differences and can more fully reflect the relationships among carbon emissions, economic growth, energy consumption and urbanization in the regions with different economic levels in China, which can provide some empirical references for formulating energy, economic, and environmental policies that are more in line with the actual conditions in each region. This is also the practical value of this paper.

According to the above empirical findings, several policy recommendations can be put forward as follows:

(1)	For developed regions, the empirical results showed that both *CE* and *UR* had impacts on *ECS*, while *GDP* had an impact on *UR* and *ECS*, and feedback exists on *CE* and *GDP*. Therefore, the economic development of developed regions tends to be mature. Under the premise of maintaining stable economic growth, optimizing *ECS* and reducing *CE* are more essential in these areas. Specifically, we can learn from the experiences of developed cities in global countries to quicken the mainstreaming of *ECS* and industrial upgrading, which can realize low-carbon development and the green economy in parallel.

(2)	For medium developed regions, the empirical results showed that *GDP* had impacts on *CE*, *UR* and *ECS*, and *UR* would affect *CE*. There were feedback effects between *ECS* and *CE*, and between *ECS* and *UR*, showing that the medium developed regions were still in the development mode of energy-dependence. Therefore, taking economic development as the core role to promote urbanization, we should speed up the optimization of *ECS* and realize the innovation-driven *GDP* mode. Meanwhile, in the process of urbanization, we should promote low-carbon green ways to achieve high-quality economic and urban development.

(3)	For underdeveloped regions, *GDP* would affect *UR*, while *CE* would advance adjustment of *ECS*, revealing that the current economic development in underdeveloped regions is still an energy-dependent mode, which is extensive and unsustainable. Therefore, in order to promote carbon reduction in underdeveloped regions, we must change the mode of economic development via drawing on the experience of developed areas and medium developed areas, and finally achieve innovation-driven development. Moreover, it is important to optimize *ECS*, and reduce the level of *CE*.

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