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Coal Consumption and Economic Growth: Panel Cointegration and Causality Evidence from OECD and Non-OECD Countries

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Abstract: This paper examines the relationship between coal consumption and economic growth for 30 OECD (Organisation for Economic Co-operation and Development) countries and 32 non-OECD countries for 1990–2013 using a multivariate dependent panel analysis. For the analysis, we conducted the common factor defactorization process, unit root test, cointegration test, long-run cointegrating vector, and Granger causality test. Our results suggest the following: First, there is no long-run relationship between coal consumption and economic growth in OECD countries; however, in non-OECD countries, the relationship does exist. Second, excessive coal usage may hinder economic growth in the long run. Lastly, the growth hypothesis (coal consumption affects economic growth positively) is supported in the short run for non-OECD countries. As coal consumption has a positive effect on economic growth in the short run and a negative effect in the long run, energy conservation policies may have adverse effects only in the short run. Thus, non-OECD countries should gradually switch their energy mix to become less coal-dependent as they consider climate change. Moreover, a transfer of technology and financial resources from developed to developing countries must be encouraged at a global level.

Keywords: coal consumption; economic growth; nexus; panel analysis; dependent panel

1. Introduction

Climate change is a significant problem that has led to several efforts to reduce greenhouse gas emissions. Developed countries in the Kyoto Protocol should have reduced their emissions. However, the United States, which emits about 30% of global greenhouse gas emissions, pulled out in 2001 and, thus, the Kyoto Protocol cannot be said to be totally successful [1]. The Protocol's first commitment period ended in 2012. The second commitment period started but several major countries, which together emit more than 50% of global greenhouse gas emissions, indicated that they would not ratify the treaty. Furthermore, the Copenhagen Climate Change Conference in 2009 failed to achieve a binding accord. This is a serious problem as there are no longer strong and binding restraints to greenhouse gas emissions. Therefore, as the Paris Agreement has come to be a successor of the Kyoto Protocol, new policies that can control greenhouse gas emissions are needed after the 2015 Paris Climate Change Conference [2].

Although coal is economical and relatively abundant, it can cause considerable environmental problems through, among other things, increasing greenhouse gas emissions [3]. For these reasons, it can be a good subject for implementing resource policies. Practically, a reduction in coal consumption can reduce greenhouse gas emissions [4]. Each country or intergovernmental organization should make a decision about coal usage because coal is a double-sided energy source. If coal is revealed

as absolutely useful in economic aspects, decision-makers may decide to use more coal and reduce carbon in other sectors given that carbon dioxide is considered an environmental cost [5,6].

Some countries need to grow their economy above all, which is the representative case of the preservation after development even though the international trend indicates carbon reduction. Thus, we formulated a hypothesis that developing countries will have a more powerful relationship between coal consumption and economic growth than developed countries since developing countries tend to focus more on economic growth than ecological conservation. Although coal is an interesting and important energy source, as we mentioned above, relatively few nexus studies about coal have been published.

Two different approaches are used in energy consumption and economic growth nexus studies: supply-side and demand-side approaches [7]. The supply-side approach consists of a type of Cobb−Douglas production function that includes coal as an independent variable. On the other hand, the demand-side approach is based on a trivariate framework consisting of coal consumption, coal price, and income. We constructed a production function by adopting the supply-side approach to remove an omitted variable problem, which has been used recently in the field according to Westerlund et al. [8]. We conducted this study to examine the causal relationship between coal consumption and economic growth for OECD (Organisation for Economic Co-operation and Development) and non-OECD countries. This research will give insight for environmental and climate policymakers since each country's economic growth tends to have a different impact on carbon mitigation.

This study contributes to the existing literature on the energy nexus, especially on coal, from several perspectives. First, this study handles cross-sectional dependence caused by international trends. To remove the cross-sectional dependence, we adopted a common factor structure, which is calculated by principal component analysis. For a residual-based cointegration test, there is a potential problem known as "common factor restriction" [9,10]. Although the methods used in this analysis are also residual based, our process is not affected by that restriction from the results of the common factor defactorization process.

Second, we divided countries into two groups: OECD and non-OECD. By using these two groups, the policy implications could be more powerful. As far as we know, this is the first approach of a causal relationship investigation utilizing panel data of two groups, especially for the comparison of OECD and non-OECD. Furthermore, this research has the following strong points for the empirical aspect. We utilized a panel data approach to consider the unobserved heterogeneity of each cross-section. According to Harris and Tzavalis [11], panel analysis performs better than a single time series. An econometric model has low statistical power if the analysis is conducted with a short time series in the case of a time-series analysis [12]. However, a panel approach gives high explanatory power to the model through the use of extensive data. In addition, considering volatile international energy indicators, we used a model that can allow a structural break. This helps us to describe a more realistic behavior of the international resource state. Finally, we constructed a multivariate model by adding two variables to the model: total labor force and total fixed capital formation. According to Westerlund et al. [8], the cointegration relationship can be misrecognized because of omitted variables and unobserved common factors. This study supplemented those limits.

The rest of this paper proceeds as follows. Section 2 introduces the existing literature on the nexus between coal consumption and economic growth. Section 3 explains the methodology used in this study. Section 4 presents the data and results. The policy implications and conclusion are included in Section 5.

2. Literature Survey

The energy–growth nexus is an interesting subject in energy economics on which numerous papers have been published and studies conducted [13–25]. There are four testable hypotheses about the relationship between coal consumption and economic growth, each of which may hold in different countries. First, there is unidirectional causality from coal consumption to economic growth

(the growth hypothesis): if coal consumption increases, economic production will grow. Thus, coal is essential for a nation's economic growth [26]. Under this hypothesis, energy conservation policies reducing coal consumption can hinder economic growth [27].

Second, according to the conservation hypothesis, economic growth is the driving factor behind coal consumption. This indicates that there is unidirectional causality from economic growth to coal consumption. In this case, energy conservation policies have no impact on economic growth. However, since an increase in economic growth may actually reduce coal consumption, an economy would be less coal dependent [13]. According to Li and Li [26], it is possible that gradually switching coal to another energy source—that is, renewable energy sources and natural gas—gives countries with this relationship freedom from coal consumption.

Third, coal consumption and economic growth affect each other. This means there is bidirectional causality (the feedback hypothesis). In this scenario, energy conservation negatively impacts economic growth and economic prosperity may require further coal consumption [25].

Fourth, the neutrality hypothesis addresses a weak relationship between coal consumption and economic growth. This hypothesis is adopted when there is no causal relationship between coal consumption and economic growth. Under the neutrality hypothesis, coal consumption has no direct influence on economic growth and vice versa. Countries in which the neutrality hypothesis holds may be able to implement sustainable development strategies with lower levels of carbon emissions.

Yang [28] found a unidirectional causal relationship from gross national product (GNP) to coal consumption in Taiwan. Thereafter, Yang [29] showed bidirectional causality between coal consumption and economic growth using the same data period. For China, Jinke et al. [18], Wolde-Rufael [24], and Li and Li [26] suggested evidence of unidirectional causality from economic growth to coal consumption, and Chandran Govindaraju and Tang [30] provided results supporting the neutrality hypothesis. For India, Chandran Govindaraju and Tang [30], Jinke et al. [18] and Bhattacharya et al. [31], and Li and Li [26] produced different analytical results that supported the neutrality, growth, and conservation hypotheses, respectively. In the case of Japan, Jinke et al. [18] found unidirectional causality from economic growth to coal consumption but Wolde-Rufael [24] showed unidirectional causality in the opposite direction.

Analyses for Korea also produced various results. Yoo [25] concluded there is bidirectional causality, Jinke et al. [18] supported the neutrality hypothesis, and Wolde-Rufael [24] supported the conservation hypothesis. In Nigeria, Nasiru [20] revealed unidirectional causality from economic growth to coal consumption. With respect to South Africa, Jinke et al. [18] provided results supporting the neutrality hypothesis while Wolde-Rufael [24] found evidence of bidirectional causality. The United States was found to have a bidirectional causal relationship between coal consumption and economic growth [24]. Ocal et al. [21] found an absence of causality in Turkey.

Apergis and Payne [13,16] employed a panel structure to analyze 14 emerging markets and 25 OECD countries and found evidence for the feedback hypothesis in both groups. Finally, Li and Leung [32] adopted panel methodology to analyze regional effects within China and revealed some differences between regions. Table 1 summarizes the existing cross-country literature on studies about the coal consumption–economic growth nexus.

Table 1. Summary of existing cross-country literature on the relationship between coal consumption and economic growth.

Author(s)	Countries (Sample Period)	Methods	Variables	Adopted Hypothesis
Group A (cross-country analysis with time series method)				
Jinke et al. [18]	China India Japan South Africa Korea (1980–2005A)	Engle-Granger VECM	Coal consumption Real GDP	China: conservation India: neutrality Japan: conservation South Africa: neutrality Korea: neutrality
Jinke et al. [33]	China India South Africa United States Japan (1980–2005A)	Engle-Granger VECM	Coal consumption Real GDP	China: conservation India: neutrality South Africa: neutrality United States: not related Japan: conservation
Wolde-Rufael [24]	China India Japan Korea South Africa United States (1965–2005A)	Toda-Yamamoto Granger causality	Coal consumption Real GDP	China: conservation India: growth Japan: growth Korea: conservation South Africa: feedback United States: feedback
Li and Li [26]	China India (1965–2006A)	Engle-Granger VECM	Coal consumption Real GDP	China: conservation India: growth
Chandran Govindaraju and Tang [30]	China India (1965–2009A)	Engle-Granger VECM	Coal consumption Real GDP Carbon emissions Squared GDP	China: neutrality India: conservation
Bildirici and Bakirtas [34]	BRICTS countries (1980–2011A)	ARDL cointegration ECM	Coal consumption Real GDP	Brazil: growth Russia: not related India: growth China: feedback Turkey: not related South Africa: not related
Lei et al. [35]	Six biggest coal consuming countries (2000–2010A)	Engle-Granger VECM	Coal consumption Real GDP Coal price	China: conservation India: neutrality Germany: feedback Russia: feedback Japan: feedback United States: neutrality
Group B (panel data analysis)				
Apergis and Payne [16]	15 emerging markets (1980–2006A)	Pedroni [36] cointegration VECM	Coal consumption Real GDP Capital Labor	Feedback
Apergis and Payne [13]	25 OECD Countries (1980–2005A)	Larsson et al. [37] cointegration VECM	Coal consumption Real GDP Capital Labor	Feedback
Anoruo [38]	15 African countries (1980–2012A)	Bootstrap Granger causality	Coal consumption Real GDP	Conservation

Note: We extended the literature survey from Jin and Kim [39]. VECM: vector error correction model. GDP: gross domestic product. ECM: error correction model. BRICTS: a group of countries including Brazil, Russia, India, China, Turkey, and South Africa. "Not related" denotes "not cointegrated".

There are various well-known methods to analyze nexus studies. In fact, the development of methods has been remarkable. As recently as a few years ago, most published studies were conducted using either independent panel analysis or time-series models [13,14,16,18–21,24–27,33–35,38,40,41]. Thereafter, studies considering structural breaks but not cross-sectional dependence were published [42]. Recently, most studies have been conducted using dependent panel analysis [17,22,23,43–45]. Some have considered cross-sectional dependence and structural breaks simultaneously [22,23]. In particular, Apergis and Payne [15] used a panel smooth transition vector error correction model (VECM), which can handle structural breaks. However, with a few exceptions, these studies all focus on nuclear energy, electricity, and renewable energy—and not coal. Furthermore, there are only a few studies using panel analysis, as shown in Table 1. To the best of our knowledge, this analysis is the first attempt to use advanced methods to study the coal–economic growth relationship. In addition, this paper achieves partial methodological development by handling cross-sectional dependence by extracting common factors from raw data.

3. Data and Methodology

We collected annual data from 1990 to 2013 for 30 OECD countries (which consisted of Australia, Austria, Belgium, Canada, Chile, the Czech Republic, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Japan, Luxembourg, Mexico, the Netherlands, New Zealand, Norway, Poland, Portugal, Slovenia, South Korea, Spain, Sweden, Switzerland, Turkey, the United Kingdom, and the United States) and 32 non-OECD countries (which consisted of Argentina, Bangladesh, Belarus, Botswana, Brazil, Bulgaria, China, Cuba, the Dominican Republic, Egypt, Honduras, Hong Kong, India, Indonesia, Kazakhstan, Kenya, Kyrgyzstan, Malaysia, Mauritius, Morocco, Nigeria, Pakistan, Peru, the Philippines, the Republic of Macedonia, Russia, South Africa, Sri Lanka, Tajikistan, Thailand, Ukraine, and Uzbekistan.). We used data for the total primary energy supply per capita in the form of coal consumption (C) in kiloton of oil equivalent and defined real gross domestic product (GDP) in 2005 USD millions using purchasing power parity (PPP) as a proxy for economic growth (Y). Coal consumption and economic growth data were derived from the International Energy Agency [46]. The gross fixed capital formation data (*K*) used as a capital variable (in constant 2005 USD) and labor force data (*L*) were derived from the World Bank [47]. All variables were divided by the population of each country to remove the impact of a country size. Table 2 presents the descriptive statistics of each variable.

Table 2. Descriptive statistics of each variable.

Group	Variables	Mean	Standard Deviation	Observations
OECD	Coal consumption (C)	704.40	612.31	N = 30
	Real GDP (Y)	28,149.75	10,886.89	T = 24
	Capital (K)	6,742,162,584.98	3,546,619,324.85	N * T = 720
	Labor (L)	483,899.29	54,071.87	
Non-OECD	Coal consumption (C)	331.82	528.57	N = 32
	Real GDP (Y)	7,452.38	6,222.90	T = 24
	Capital (K)	723,662,062.66	1,031,929,414,88	N * T = 768
	Labor (L)	431,255,97	68,659.83	

Note: OECD: Organisation for Economic Co-operation and Development.

As mentioned in the introduction, we constructed a function based on the Cobb–Douglas production function with a supply-side approach, as follows:

$$Y_{it} = A C_{it}^{\alpha} K_{it}^{\beta} L_{it}^{\chi} \varepsilon_{it}, \tag{1}$$

where Y_{it}, C_{it}, K_{it}, and L_{it} represent economic growth (economic output), coal consumption, capital, and labor force, respectively. A is the technological parameter. To estimate this equation in linear form, we transformed all variables to natural logarithm.

3.1. Data Preprocessing

When handling panel data, researchers should take into account the effect across cross-sections because panel data consist of cross-sections and time series. However, most panel analysis methods assume cross-sectional independence. This can distort panel results [48]. Therefore, we adopted a common factor structure suggested by Bai and Ng [48] to handle cross-sectional dependence.

$$Y_{it} = \xi_i F_t + E_{it}, \tag{2}$$

where $i = 1, \ldots, N$ for each cross-sectional unit and $t = 1, \ldots, T$ for each time-series unit in the panel. F_t, ξ_i, and E_{it} denote the common factors, factor loadings, and idiosyncratic components, respectively. To decompose data into common factors and idiosyncratic components, we used principal component analysis. Because the common factors and idiosyncratic components represent international trends and movement within the domestic situation, respectively, the common factors and idiosyncratic components were analyzed separately. If the original series is I(1) and common factors and idiosyncratic components are I(1) and I(0), respectively, then the non-stationarity of the original series is driven only by international trends [17]. All four variables in this study each have one common factor series. Thus, we extracted a common factor from all series.

3.2. Unit Root Tests

Before investigating the relationship between variables, we should understand the trend properties of each variable, known as stationarity, to avoid spurious regression. In this analysis, we used three different unit root tests: Breitung and Das [49] (Breitung), Im et al. [50] (IPS), and Levin et al. [51] (LLC). LLC and IPS are panel-version augmented Dickey–Fuller tests. There are two representative differences between both tests: homogeneity and test statistic. The LLC test and the IPS test assume cross-sectional homogeneity in the autoregressive (AR) process and heterogeneity of all cross-sections, respectively. For the test statistic, the t-statistic and t-bar are used to examine the stationary property. The Breitung test suggested a robust ordinary least squares (OLS) t-statistic and generalized least squares t-statistic based on the AR(1) process. While the former two unit root tests assumed cross-sectional independence, the latter one allowed cross-sectional dependence. In our analysis, all tests were conducted including intercept and deterministic trends.

3.3. Panel Cointegration

As the I(1) process of data was confirmed, a long-run equilibrium relationship should be established to investigate the relationships between the variables. As we mentioned in Section 3.1, cross-sectional dependence can disturb panel results. In addition, the time-series part of the analysis might be shocked by a specific impact. Therefore, we used the cointegration analysis proposed by Westerlund and Edgerton [52], which is able to consider cross-sectional dependence and structural breaks simultaneously. This test is based on the following model:

$$y_{it} = \alpha_i + \eta_i t + \delta_i D_{it} + x'_{it}\beta_i + (D_{it}x_{it})'\gamma_i + z_{it}, \tag{3}$$

$$x_{it} = x_{it-1} + w_{it}, \tag{4}$$

where $i = 1, \ldots, N$ and $t = 1, \ldots, T$ represent the cross-section and time series, respectively, and D_{it} is a time dummy taking into account structural breaks. It makes it possible to investigate the volatile international market by giving flexibility to the model. α_i and β_i denote the intercept and slope before the break, respectively, and δ_i and γ_i the intercept and slope after the break, respectively. Thereafter,

to remove the effect from cross-sectional dependence, z_{it} is decomposed into common factor and idiosyncratic components using the singular value decomposition.

The basic concept of this model is to conduct unit root tests using residuals, separated with common factor and taking into account structural breaks. Westerlund and Edgerton [52] proposed using the breakpoint estimator for determining the structural breakpoint of each cross-section. In estimating the number of common factors, this method followed the suggestion of Bai and Ng [48] for the information criterion. In this method, two test statistics exist: Z_φ and Z_τ. The coefficient of the first lag variable from the augmented Dickey–Fuller (ADF) equation made by the residual term of Equation (3) are used to obtain both test statistics. While Z_φ is constructed with the coefficient of AR(1) and standard error, which is estimated from the ADF process, Z_τ uses the t-ratio of the ADF equation. Z_φ usually has higher power than Z_τ, especially when the number of time series is relatively larger than the cross-section number.

3.4. Long-Run Estimation

After confirming the long-run equilibrium relationship using the cointegration test, we could proceed to estimate the cointegrating vector using the fully modified OLS (FMOLS) method suggested by Pedroni [53]. This method allows us to not only remove bias caused by serial correlation and endogeneity but also to consider cross-sectional heterogeneity. The estimated models are as follows:

Model 1:

$$Y_{it} = \alpha_i + \eta_i t + + C'_{it}\beta_{1i} + K'_{it}\beta_{2i} + L'_{it}\beta_{3i} + ECT_{1it} \tag{5a}$$

Model 2:

$$C_{it} = \alpha_i + \eta_i t + + Y'_{it}\beta_{1i} + K'_{it}\beta_{2i} + L'_{it}\beta_{3i} + ECT_{2it} \tag{5b}$$

For Model 1, real GDP per capita is used as the dependent variable and coal consumption per capita, gross fixed capital formation, and labor force are employed as explanatory variables. Model 2 includes coal consumption and economic growth as the dependent variable and explanatory variable, respectively.

3.5. Panel Granger Causality

Using the estimated cointegrating equation, we could estimate Granger causality using the two-step procedure suggested by Engle and Granger [54]. We constructed a panel error correction model based on the dynamic panel approach proposed by Holtz-Eakin [55]:

$$\Delta Y_{it} = \alpha_{1i} + \sum_{k=1}^{h} \varphi_{11ik}\Delta C_{it-k} + \sum_{k=1}^{h} \varphi_{12ik}\Delta K_{it-k} + \sum_{k=1}^{h} \varphi_{13ik}\Delta L_{it-k} + \lambda_{1i}ECT_{1it-1} + \varepsilon_{1it}, \tag{6a}$$

$$\Delta C_{it} = \alpha_{2i} + \sum_{k=1}^{h} \varphi_{21ik}\Delta C_{it-k} + \sum_{k=1}^{h} \varphi_{22ik}\Delta K_{it-k} + \sum_{k=1}^{h} \varphi_{23ik}\Delta L_{it-k} + \lambda_{2i}ECT_{2it-1} + \varepsilon_{2it}, \tag{6b}$$

where ECT_{it-1} represents the error correction term (ECT) derived from the cointegrating equation, λ_i is the adjustment speed, k is lag length, and ε_{it} is the serially uncorrelated residual with mean zero. Since these equations have differenced form, we can handle correlation between country-specific effects and explanatory variables. However, the differenced form can lead to different problems in which lagged dependent variables are correlated with the differenced residual and heteroscedasticity in the residual. To handle these problems, a generalized method of moments (GMM) estimator for panel analysis, which was proposed by Arellano and Bond [56], is generally used.

Causality is shown by testing the statistical significance of the coefficient in each error correction model. For short-run causality, φ_{ik} can provide evidence. For example, if the Wald statistic of $H_0 : \varphi_{11ik} = 0$ is rejected, then there is short-run causality from coal consumption to economic growth. For long-run causality, the adjustment speed determines whether there is causality. When the test

statistic of $H_0 : \lambda_i = 0$ is significant and the value is negative, it supports the evidence of long-run causality. Lastly, we can test strong causality through joint testing of each explanatory variable and ECT. The results of the causality test imply the hypotheses of the energy consumption–economy nexus (growth, conservation, feedback, and neutrality).

4. Empirical Results

4.1. Unit Root Test Results

We used three unit root tests: Breitung, IPS, and LLC. As shown in Tables 3 and 4, all variables are represented as an I(1) process. This means that we should proceed to cointegration analysis. The lag selections of all tests were based on the Akaike information criterion. For the LLC test, we used the Bartlett kernel proposed by Newey and West [57]. The null hypothesis of all tests is that all panels are non-stationary.

Table 3. Results of panel unit root test for the OECD group.

Variables	Method	Level Statistic (*p*-Value)	1st Difference Statistic (*p*-Value)
Coal consumption per capita (C)	LLC	−1.4066(0.0798) *	−16.4942(0.0000) ***
	IPS	−0.9472(0.1718)	−16.0198(0.0000) ***
	Breitung	1.6476(0.9503)	−7.0365(0.0000) ***
Real GDP per capita (Y)	LLC	−0.0388(0.4845)	−8.8890(0.0000) ***
	IPS	−0.5729(0.2834)	−9.6856(0.0000) ***
	Breitung	3.7438(0.9999)	−5.9634(0.0000) ***
Total fixed capital formation (K)	LLC	1.8879(0.9705)	−9.6178(0.0000) ***
	IPS	−1.1129(0.1329)	−11.7364(0.0000) ***
	Breitung	2.7806(0.9973)	−5.3423(0.0000) ***
Labor force (L)	LLC	0.0573(0.5228)	−11.6065(0.0000) ***
	IPS	0.5321(0.7207)	−9.4481(0.0000) ***
	Breitung	2.4608(0.9931)	−3.7664(0.0000) ***

Note: * denotes rejection of the null hypothesis at the 10% significance level, ** at the 5% significance level, and *** at the 1% significance level.

Table 4. Results of panel unit root test for the non-OECD group.

Variables	Method	Level Statistic (*p*-Value)	1st Difference Statistic (*p*-Value)
Coal consumption per capita (C)	LLC	−2.180(0.0175) **	−12.7589(0.0000) ***
	IPS	−0.3784(0.3526)	−10.2460(0.0000) ***
	Breitung	2.2614(0.9881)	−5.1778(0.0000) ***
Real GDP per capita (Y)	LLC	1.4956(0.9326)	−10.3656(0.0000) ***
	IPS	1.3600(0.9131)	−8.0241(0.0000) ***
	Breitung	−0.6304(0.2642)	−5.1770(0.0000) ***
Total fixed capital formation (K)	LLC	−2.4744(0.0066) ***	−11.3142(0.0000) ***
	IPS	−1.2221(0.1108)	−8.7737(0.0000) ***
	Breitung	−0.0346(0.4862)	−4.5735(0.0000) ***
Labor force (L)	LLC	−2.5090(0.0061) ***	−4.8868(0.0000) ***
	IPS	2.1025(0.9822)	−3.7145(0.0001) ***
	Breitung	1.6470(0.9502)	−3.6697(0.0001) ***

Note: * denotes rejection of the null hypothesis at the 10% significance level, ** at the 5% significance level, and *** at the 1% significance level.

4.2. Panel Cointegration Test Results

We used a method that can handle structural breaks and cross-sectional dependence for panel cointegration. This model also considers a common factor for cross-sectional dependence but we have already extracted the common factor from each variable in the data preprocessing. Thus, we assumed there is no common factor in the cointegration test. For structural breaks, we assumed a regime shift from two options: level shift and regime shift. Those two options help to examine the real relationship between variables by providing flexibility to the cointegration model. All analyses from unit root test to Granger causality were conducted with modified data, which is without the common factor.

Table 5 presents the cointegration test results. There are opposite results between the OECD and non-OECD groups. Only the non-OECD group has a long-run equilibrium relationship between coal consumption, economic growth, gross fixed capital formation, and labor force. Thus, our hypothesis that developing countries have a stronger relationship between coal consumption and economic growth is supported. These results differ from those of Apergis and Payne [13] and Jin and Kim [39], possibly as a result of our consideration of structural breaks and cross-sectional dependence.

Table 5. Results of panel cointegration test.

Group	Test Statistic	Statistic Value (*p*-Value)
OECD	Z_φ	−1.4221(0.0775) *
	Z_τ	−0.4509(0.3260)
Non-OECD	Z_φ	−3.4844(0.0002) ***
	Z_τ	−3.1297(0.0009) ***

Note: * denotes rejection of the null hypothesis at the 10% significance level, ** at the 5% significance level, and *** at the 1% significance level.

Based on these results, we moved to the cointegrating equation and dynamic error correction for only the non-OECD group in order to describe the role of coal in economic growth for the non-OECD group, which has been established to have a long-run relationship.

4.3. Long-Run Estimator

Table 6 shows the results of cointegrating vector estimation based on FMOLS. Adjusted R-squared values indicate that both models have high explanatory power.

Table 6. Fully modified ordinary least squares (FMOLS) long-run estimators of the non-OECD group.

Explanatory Variables	Model 1	Model 2
Real GDP per capita (Y)	-	−0.754(−26.563) ***
Coal consumption per capita (C)	−0.159 (−5.288) ***	-
Gross fixed capital formation (K)	0.234(7.739) ***	0.442(15.020) ***
Labor force (L)	−0.038(−1.861) *	1.099(55.593) ***
Adjusted R-squared	0.996	0.970

Note: * denotes rejection of the null hypothesis at the 10% significance level, ** at the 5% significance level, and *** at the 1% significance level.

Since we analyzed data in natural logarithm, the long-run coefficients are interpreted as elasticities. For Model 1, the coefficient of the gross fixed capital formation variable is positive and statistically significant at the 1% significance level. However, for coal consumption and labor force, the coefficients are negative and statistically significant at the 1% and 10% levels, respectively. The results indicate that increases of 1% in coal consumption and labor force decrease economic growth by 0.038% and 0.159%, respectively, and a 1% increase in gross fixed capital formation results in a 0.234% increase in economic growth. As far as we are aware, there is no study that has produced negative impact results

from coal consumption and labor force on economic growth, simultaneously. As discussed by Soytas and Sari [58], the negative impact may indicate excessive and inefficient inputs of coal consumption and labor force. In Model 2, the coefficient of the economic growth variable is negative and statistically significant at the 1% level. On the other hand, the gross fixed capital formation and labor force variables have coefficients that are positive and statistically significant at the 1% level. The coefficients show that a 1% increase of real GDP per capita results in a 0.754% decrease in coal consumption, and 1% increases of gross fixed capital formation and labor force increase coal consumption by 0.442% and 1.099%, respectively.

4.4. Panel Granger Causality Results

We used a dynamic error correction model to estimate causal relationships. Various methods estimate Granger causality. Two kinds of approaches exist. A representative method for the first approach was proposed by Kónya [59]. However, this method does not consider long-run causality. The second approach, which includes a GMM estimator, pooled mean group estimator, was developed by Pesaran et al. [60] and was used in the present study. In addition, the second approach includes a short-run non-causality test suggested by Dumitrescu and Hurlin [61]. Since we have already performed data preprocessing, our model does not suffer from a cross-sectional dependence problem. Thus, we selected the method that can estimates long-run causality and did not consider cross-sectional dependence. We selected a difference option since it performs better than orthogonal deviation when removing cross-sectional fixed effects, as discussed by Hayakawa [62].

Our empirical results on Granger causality indicate bidirectional causality between ΔY and ΔC in both short-run and long-run cases (Table 7).

Table 7. Results of panel Granger causality test for the non-OECD group.

| Dependent Variable | Source of Causation (Independent Variables) | | | | | | | | |
| | Short Run | | | | Long Run | Strong Causality | | | |
	ΔY	ΔC	ΔK	ΔL	ECT	$ECT, \Delta Y$	$ECT, \Delta C$	$ECT, \Delta K$	$ECT, \Delta L$
ΔY	-	35.19 *** (0.015)	3.76 * (0.008)	4.27 ** (−0.023)	355.51 *** (−0.091)	-	713.19 ***	622.43 ***	180.77 ***
ΔC	2.60 (0.145)	-	2.77 * (0.032)	32.77 *** (0.588)	73.05 *** (−0.039)	27.33 ***	-	75.59 ***	37.99 ***

Notes: We reported Wald F-test statistics of each coefficient. The numbers in brackets indicate the estimated coefficient value. * denotes rejection of the null hypothesis at the 10% significance level, ** at the 5% significance level, and *** at the 1% significance level.

The causality results on economic growth show that while coal consumption and gross fixed capital formation have positive impacts on economic growth in the short run, labor force has a negative impact. The coefficient of ECT is statistically significant at the 1% level with an appropriate speed of adjustment. In terms of causality on coal consumption, economic growth is statistically insignificant. On the other hand, gross fixed capital formation and labor force are positive and statistically significant at the 10% and 1% levels, respectively. In addition, long-run causality exists since the coefficient of ECT is negative and statistically significant. Consequently, the overall results support the growth hypothesis of unidirectional causality from coal consumption to economic growth.

4.5. Discussion of the Results

From the entire analysis procedure, we derived the following results. First, the cointegration test suggested by Westerlund and Edgerton [52] indicates a long-run equilibrium relationship between economic growth, coal consumption, gross fixed capital formation, and labor force for only the non-OECD group. This result differs to that of Jin and Kim [39]. The reason for the different results is that the method adopted in this research has greater flexibility than that of Jin and Kim's [39] approach for analyzing the realistic behavior of volatile international indicators since it considers

structural breaks and cross-sectional dependence in view of the panel framework. Second, the long-run estimation proposed by Pedroni [53] suggests that both models have high explanatory power and that coal consumption and labor force have negative impacts on economic growth with statistical significance, which may be influenced by excessive and inefficient usage. Third, the results of the panel causality test using a GMM estimator support the growth hypothesis for the non-OECD group of unidirectional causality from coal consumption to economic growth.

The empirical results can be summarized as follows: (1) OECD countries have no long-run equilibrium relationship between coal consumption and economic growth but non-OECD countries do have. (2) Coal consumption and economic growth are negatively related for non-OECD countries in the long run. (3) The growth hypothesis is supported in the non-OECD countries, which represent developing countries in this analysis. In other words, the hypothesis we established is empirically proven.

5. Conclusions

As we mentioned in Section 2, there are four nexus hypotheses: growth, conservation, feedback, and neutrality. Although these hypotheses are useful for explaining the relationship between energy source as a factor of production and economic growth, there may be some risk of misunderstanding. These nexus hypotheses indicate the direction of causality from one to another but do not specify the sign of the relationship. For example, if a study adopted the conservation hypothesis for a specific country or group, we do not know whether economic growth impacts energy consumption positively or negatively, but just the direction. For a sophisticated policy implication, we must not only report the hypothesis but also specify the sign of relationship. We certainly reported both sign and direction of causality in this study since a misunderstanding can be caused by the opposite signs of long-run and the short-run.

In some countries where the growth hypothesis is supported, economic growth can be discouraged by energy conservation policies in general. However, our empirical results indicate that the increase in coal consumption has a positive impact on economic growth in the short run but a negative impact in the long run, which may be caused by the fact that these countries have been undergoing technological transition. In other words, policies that increase coal consumption could be an attractive choice in the short term but a poor option in the long term. Given that the two biggest coal consuming countries among the non-OECD countries—China and India—have also decreased their share of global coal consumption according to IEA [63], it seems that they have noticed a way to go further and that the empirical results of this research narrow the gap between empirical study and reality.

Furthermore, economically developed countries may restrain coal usage to prevent environmental degradation (carbon emissions), but developing countries may not, in terms of the EKC (Environmental Kuznets Curve), which assumes an inverted U-shaped curve relationship between economic growth and environmental contamination.

To the best of our knowledge, coal is the cheapest energy source. An increase in coal usage is natural and intuitive from the view of the economy, excluding other views. However, our empirical analysis showed that coal consumption adversely affects economic growth in the long run. Therefore, policymakers should consider reducing coal dependency in the long run through alternative energy sources, while maintaining current levels of coal consumption. Even though coal has a negative impact on economic growth in the long run, it occupies a significant proportion of energy in the iron and steel industry and electricity generation sector. Coke is essential to smelt iron and coal electricity generation cannot be eliminated since this takes charge of the base load in terms of cheap operating expenses. Considering that the contribution of nuclear power, which is an abundant and economical source of base-load power, to the global energy supply is shrinking after the Fukushima accident, it is extremely difficult to reduce coal-fired power plants. However, even a part of coal power generation needs to be substituted with natural gas, considering the environment. If there is an externality—such as carbon tax from emissions—in the future, this substitution seems to be natural.

In addition, as climate change is a problem pertaining to not just a specific country but the entire world, carbon emission reduction requires a global effort. For example, transfer of technology and financial resources from developed to developing countries, which have been proposed in the COP (Conference of the Parties), must be encouraged. According to Li and Wang [64], technology change reduces carbon emissions in reality. For discussing Korea in detail, the new government plans to phase out coal and nuclear power plants in the long term. Since Korea is included in the OECD and OECD are proven empirically to have no relationship between coal and economy by our research, this may be the right path to follow. However, phasing out coal without countermeasures considering the electricity capacity will be a dead end. Korea is undergoing a sudden change. They are making an effort to cost-down renewable energy sources and are gradually dismantling coal-fired power plants to achieve economic and environmental development.

This study has several contributions as follows. We attempted to investigate the exact relationship between coal consumption and economic growth and the difference between two groups of countries, the OECD and non-OECD countries. To accomplish this, our panel framework included as many countries as possible. We adopted the dependent panel analysis through a defactorization process to prevent problems caused by cross-sectional dependence. The cointegration test results showed opposing results by group, which provides some evidence to help policymakers explain the role of coal for each group.

Although it is well known that coal is an abundant and economical energy source, its role remains debatable because of its environmental disadvantages. There has been much effort to regulate carbon emissions, which are driven mainly by coal consumption. However, there are not as many studies as there could be on this topic. According to Li and Li [26], the use of coal is a double-edged sword for developing countries, which is why we divided our study into two groups of developed and developing countries. We formulated the hypothesis that there is a stronger relationship between coal consumption and economic growth in developing countries since we assumed that developing countries might focus on economic advantage rather than on environmental disadvantage. Accordingly, we carried out this study to investigate the relationship between coal consumption and economic growth for OECD and non-OECD countries over 1990–2013 using a multivariate panel approach.

There are several directions for further research. First, we could apply this framework to another subject group. For instance, the difference between countries with high and low coal consumption implies different influences from the perspective of economic growth. This implied efficiency of coal consumption compared to other energy sources should be examined using countries with high coal mixes. Second, the demand-side approach suggested by Bloch et al. [7] and other variables, such as electricity consumption and carbon emissions, could be considered with respect to the model. Finally, non-linear panel methodology that takes account of structural shift should be considered.

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