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Impacts of Income Inequality and Economic Growth on CO_2 Emissions: Comparing the Gini Coefficient and the Top Income Share in OECD Countries

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Abstract: This study investigates the nexus of income inequality, economic growth, and CO_2 emissions based on the environmental Kuznets curve (EKC) hypothesis for 38 OECD countries during 1990–2015. The indices of income inequality include the Gini coefficient and the top income share. The main objective of this study is to re-examine the effects of income inequality and economic growth on CO_2 emissions based on the Environmental Kuznets Curve (EKC) hypothesis. The panel analysis for OECD countries is examined using country fixed effects and Granger causality including pre-tests for unit root, cointegration, and stationarity. The main findings of this study are as follows. First, the effects of economic growth on CO_2 emissions have an inverted U-shaped relationship, and the effects of income inequality on CO_2 emission also have an inverted U-shaped relationship. Second, the Gini coefficient and the top income share represented by the income inequality index are well-defined tools for analyzing the relationship between income inequality and environmental degradation. Third, the increase in trade dependency and renewable energy consumption has contributed to the decrease in CO_2 emissions, but the increase in energy use has led to an increase in CO_2 emissions. Finally, economic growth and income inequality have Granger causality for CO_2 emissions, and economic growth bi-directionally causes Granger causality for income inequality. Therefore, this study suggests that resolving income inequality is crucial and another important environmental policy that affects CO_2 emissions.

Keywords: income inequality; CO_2 emissions; economic growth; top income share

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1. Introduction

Since the beginning of the industrialization era, economic growth and lower income inequality due to increasing average income have been considered the main causes of increased CO_2 emissions and global warming [1]. Thus, there is a trade-off between economic growth and CO_2 emissions, as well as between social equality and environmental mitigation; fairness among the three pillars is a source of sustainable development [2].

The nexus of income inequality, economic growth, and environmental degradation was well described by Kuznets [3] and the environmental Kuznets curve (EKC), described in [4]. Kuznets [3] noted that income inequality increases in the initial stages of economic growth, but decreases after the income turning point. Similarly, the EKC hypothesizes an inverted U-shaped relationship between the level of environmental degradation and income per capita. These two hypotheses have been widely utilized to demonstrate the relationship between environmental issues and economic aspects, but the results based on empirical analysis are somewhat mixed according to the different analysis methods and the different targeted countries (or groups).

Nevertheless, the Kuznets (or EKC) hypothesis has been considered a powerful tool in that it provides the empirical results of environmental consequences (or income inequality) on economic growth. Numerous studies have attempted to investigate the validity of these hypotheses. To illustrate the relationships among the three aspects in more detail, Figure 1 conceptualizes the nexus of income inequality, economic growth, and CO_2 emissions based on the Kuznets and EKC hypotheses [4–6]. Direction A indicates the direct effects of economic growth on CO_2 emissions, and direction B shows the direct effects of income inequality on CO_2 emissions. Direction C also illustrates the indirect and interactive effects of income inequality on CO_2 emissions, and combines the effects of income inequality on economic growth.

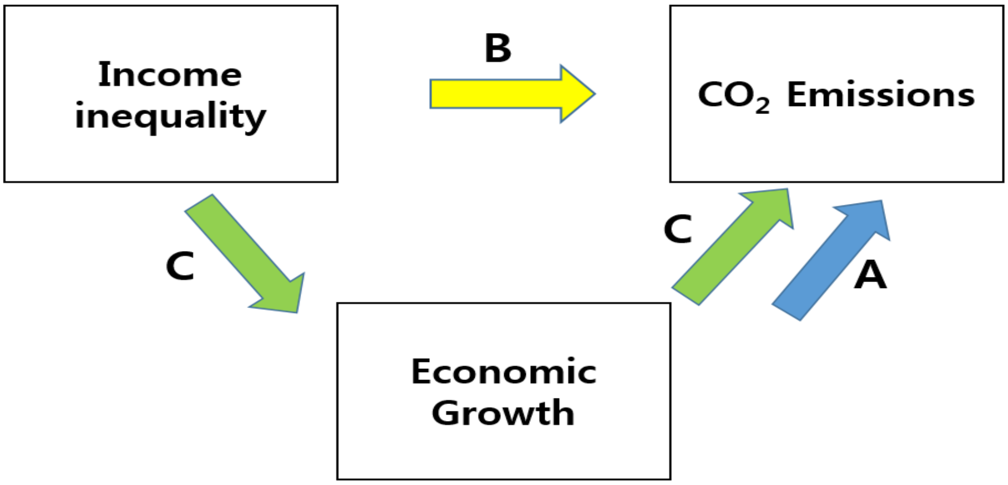


Figure 1. The relationship of income inequality, economic growth, and CO_2 emissions. Source: Author's own elaboration based on Bae (2018) [5].

Extant literature has analyzed the impacts of economic growth on CO_2 emissions. For example, Kasperowicz [7] shows the directly positive relationship between economic growth and CO_2 emissions within 18 EU member countries from 1995 to 2012. This period was chosen because extensive economic growth increases the use of energy and results in growing CO_2 emissions. Similarly, Bengochea-Morancho et al. [8] re-examined the relationship between economic growth and CO_2 emissions in the 10 EU member countries from 1981 to 1995, but they argued that the relationship between the two variables was determined according to the average income level. Kang [9] analyzed the relationship between CO_2 emissions involved in international trade and economic growth for OECD and non-OECD countries from 2005 to 2015, and emphasized the importance of CO_2 emissions embodied in trade balance in terms of increasing international trade. However, Baek and Gweisah [10] reported that unlike the simple relationship between economic growth and CO_2 emissions, recent studies have tried to analyze the effects of environmental degradation on other relevant variables. For example, Yang et al. [11] mentioned that the increase in income inequality combined with financial instability contributed to the increased environmental pollution for emerging countries.

Among the relationships with other factors affecting environmental quality, the impact of income inequality on CO_2 emissions is considered another crucial theme, even if the theoretical linkage between inequality and environmental impact is ambiguous [9,10]. Boyce [12] mentioned that income distribution or inequality affects the social demand for environmental quality and, subsequently, influences environmental policy because inequality can reduce the ability of cooperative solutions to environmental problems. In other words, this connection between income inequality and environmental quality is known as the preservation of environmental public goods [12]. Ravallion et al. [1] highlighted that the differences in income inequality on CO_2 emissions depend on the properties of the income function. If the derived demand for environmental pollutants rises with income and the marginal propensity to emit (MPE) falls in terms of rising income, a 'trade-off' exists between inequality and CO_2 emissions because any inequality reducing redistribution of income can increase the aggregate rate of emissions [1]. However, if the derived demand for emissions also rises with income but the MPE rises with income, there can be a 'win–win' relationship because lower inequality can induce a decrease in CO_2

emissions. Moreover, Mittmann and Mattos [13] investigated that income inequality affects CO_2 emissions, but income levels in Latin American countries are an important factor in determining the direction between income inequality and CO_2 emission.

In addition, there are several kinds of environmental sustainability factors such as international trade and renewable energy consumption. Du et al. [14] explained that international trade contributes to the increase in CO_2 emissions due to the increase in income growth and technology spillover, but the impact of trade on CO_2 emission depends on different income levels. Zakari et al. [15] mentioned that renewable energy consumption can achieve sustainable consumption and production patterns, and therefore we have sustainable development without environmental degradations.

Therefore, in Figure 1, we must not only look at directions A and B but also at the interaction relationship between income inequality and economic growth with regard to CO_2 emissions in terms of 'trade-off' and 'win–win' effects. Ravallion et al. [1] mentioned that economic growth improves the trade-off with equality and that lower inequality enhances the trade-off with growth. Through the interaction effects of income inequality and economic growth, global warming tends to accelerate when there is a positive relationship between economic growth and income equality. In addition, Bae [5] showed that high income inequality directly improves CO_2 emissions, while indirectly reducing the impact on economic growth. However, considering the effect of CO_2 emissions on different climate change mitigation policies, the relationship between income inequality and CO_2 emissions cannot be confirmed, because various climate policies and factors do not substantially mitigate CO_2 emissions. For example, Pata and Caglar [6] mentioned that income level can be the important factor in environmental pollution while increasing human capital-induced income can reduce the ecological footprint in the long run. Moreover, Wan et al. [16] argued that increasing income inequality can decrease CO_2 emissions with respect to decreasing energy consumption and prompting R&D expenditures.

The main purpose of this study is to re-examine the effects of income inequality and economic growth on CO_2 emissions based on the Kuznets and EKC hypotheses in the context of OECD countries' panel data from 1990 to 2015. However, most previous studies have analyzed the impact of income inequality on environmental pollution using the Gini coefficient index [5,7,10]. The Gini coefficient simplifies income distribution status as a number, allowing us to easily understand the level of income inequality. However, this coefficient has the disadvantage that the income distribution of the entire income class is represented by a single number, which does not indicate the income distribution of a specific income class. Specifically, Piketty [17] argued that the top income share is also a useful income distribution index by providing a long-term time series that can be compared between countries; there is a limit to considering the proportion of income of the top class. Moreover, Jorgenson et al. [18] investigated the relationship between the top 10% income share and CO_2 emissions within the U.S. state level, and they found that the effect of the Gini coefficient was not significant but the top 10% income share was related with political economy and Veblen effects. Therefore, another purpose of this study is to compare the Gini index with the top income shares of CO_2 emissions. As a result, this study analyzes the impacts of income inequality and economic growth on the environment, and suggests that the easing of income inequality is an important policy for green growth. For these purposes, this study employs pooled OLS (ordinary least squares), panel analysis with a country fixed model, dynamic panel data (DPD) model estimations, and Granger causality for independent variables on CO_2 emissions.

2. Materials and Methods

The basic model is constructed at the nexus of income inequality and economic growth on CO_2 emissions based on the Kuznets and EKC hypotheses following the previous literature [1,10,18,19] and Figure 1 as follows:

$$\mathrm{CO_2} = f(GDP,\ IIE,\ Z)$$

where CO_2 is the log of CO_2 emission per capita, *GDP* is the log of *GDP* per capita, *IIE* is the log of the income inequality index, and *Z* is the log of the explanatory variables related to CO_2 emissions. This basic model represents three parts of the relationship. First, the nexus of economic growth and CO_2 emission is based on the traditional EKC hypothesis. Second, the relationship between income inequality and CO_2 emission is applied in the works of Ravallion et al. [1] and Mittmann and Mattos [13] which generated the dependence of income distribution on CO_2 emission. Third, the *Z* variable comprises trade dependency, energy use, and renewable energy consumption. For example, Hailemariam et al. [20] used the control variables of *Z* including population size and share of agricultural value added, which represented economic development. However, Baek and Gweisah [10] noted that previous studies were typically considered to suffer from omitted variable bias, which could be an important factor in environmental outcomes. Therefore, this study included other relevant variables that can be symbolized by globalization, increasing energy use owing to industrialization, and energy mix [8,14,15,21].

Using the basic model, this study formulated more detailed econometric models as follows: First, to examine the EKC hypothesis, this study constructed squared forms using Equations (1) and (2).

$$CO_{2_{it}} = \alpha_0 + \alpha_1 GDP_{it} + \alpha_2 (GDP_{it})^2 + \delta_i + \varepsilon_{it} \tag{1}$$

$$CO_{2_{it}} = \alpha_0 + \alpha_1 GDP_{it} + \alpha_2 (GDP_{it})^2 + \alpha_{3k} Z_{ikt} + \delta_i + \varepsilon_{it} \tag{2}$$

where i $(i = 1,\ 2, \cdots, N)$ indicates the country, t $(t = 1,\ 2, \cdots, T)$ indicates the period, l $(l = 1,\ 2,\ 3)$ indicates three types of income inequality indices, k $(k = 1,\ 2,\ 3)$ indicates the explanatory variables related to CO_2 emissions, δ indicates the individual fixed country effects, and ε denotes the error term. In Equations (1) and (2), $\alpha_1 > 0$ and $\alpha_2 < 0$ show an inverted U-shaped relationship between GDP and CO_2 emissions, respectively.

Second, to identify the effects of income inequality on CO_2 emissions and the interaction effects of income inequality and economic growth on CO_2 emissions, this study obtains Equations (3) and (4), respectively.

$$CO_{2_{it}} = \beta_0 + \beta_{1l} IE_{ilt} + \beta_{2l} (IIE_{ilt})^2 + \delta_i + \varepsilon_{it} \tag{3}$$

$$CO_{2_{it}} = \beta_0 + \beta_{1l} IE_{ilt} + \beta_{2l} (IIE_{ilt})^2 + \beta_{3k} Z_{ikt} + \beta_{4l} [GDP_{it} \times IIE_{ilt}] + \delta_i + \varepsilon_{it} \tag{4}$$

Similarly, in Equations (3) and (4), $\beta_{1l} > 0$ and $\beta_{2l} < 0$ show an inverted U-shaped relationship between income inequality and CO_2 emissions, implying that the early stage of rising income inequality contributes to an increase in CO_2 emissions, but beyond the turning point, tends to reduce CO_2 emissions. In addition, if $\beta_{4l} > 0$, the interaction effects of GDP and income inequality on CO_2 emissions are positive, implying that the combination of economic growth and rising CO_2 emissions depends on the difference in the level of income inequality.

This study primarily focused on the comparisons between the Gini coefficient and the top income share of CO_2 emissions by using a proxy for income inequality. Although the Gini coefficient and the top income share have merits and demerits, the Gini coefficient shows an extremely strong and statistically significant correlation with the top income share. That is, we can determine that as the Gini coefficient rises, income distribution tends to deteriorate as the top income share rises, and both the Gini coefficient and the top income share can be used complementarily to examine the income distribution situation. In addition, this study utilized panel data of 38 OECD countries from 1990 to 2015, and we need to examine the Hausman test, in which the preferred model is fixed or random effects. Subsequently, cross-sectional dependence can be observed in macro panel data with long time series. This study utilized the Pesaran [22] test to determine whether the residuals are correlated across entities.

To fulfill the purpose of this study investigating the panel Granger causality test with variables affecting CO_2 emissions, especially the nexus between income inequality, GDP, and CO_2 emissions, this study employed the CADF (cross-sectionally augment Dickey–Fuller) unit root and panel cointegration tests. Shariff and Hamzah [23] mentioned that the CADF can express the ADF statistics using the t-value results' ratio for the *i*th cross sectional unit. The cointegration test needs to identify the presence of a long-run relationship among variables with both time-series and cross sectional dimensions [24]. Westerlund [25] introduced a structural panel cointegration test based on an error-correction model, including the null hypothesis that the series are not cointegrated.

This study used the panel data sample and adopted the three kinds of econometric procedures, pooled OLS (POLS), fixed effects (FE), and random effects (RE). The POLS allows to identify changes over time by combining for each data, but it has some disadvantages in terms of omitted variable bias and heterogeneity problems. The FE is useful for only involving the impact of variables which vary over time, and is constructed by the causes of changes within an entity. The RE allows for time-invariant variables including the assumption that the error terms are not correlated with predictors [25].

Moreover, this study adopted the DPD model from the work of Arellano and Bond [26], which contains one lagged dependent variable to remove unobserved heterogeneity and endogeneity. Basically, the DPD model of Arellano and Bond [26] was applied by the difference generalized method of moments (GMM) estimator, which included the system equations for each time period.

Finally, this study estimated the causality between GDP and income inequality on CO_2 emissions by following Granger [27] and Dumitrescu and Hurlin [28]. In particular, Dumitrescu and Hurlin [28] emphasized the detection of causality at the panel level, including the null hypothesis that there is no Granger causality between two variables, and constructed an extended Granger causality relation by providing panel levels (W-bar and Z-bars).

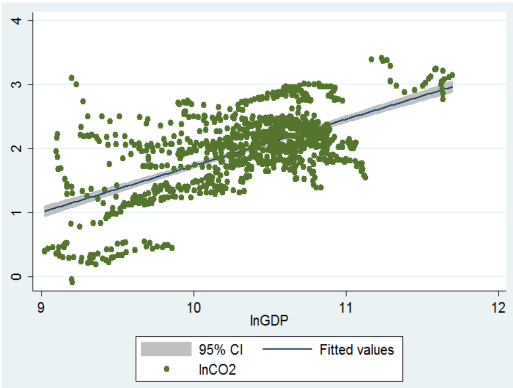
Table 1 shows the estimated variables, definitions, and descriptive statistics for each variable. For panel data from 38 OECD countries from 1990 to 2015, due to the data limitations, CO_2 emissions, GDP per capita, trade dependency, energy use, and renewable energy consumption were obtained from the World Development Indicators (WDI) of the World Bank [29]. Income inequality variables consist of Gini coefficients, the top 1% income share, and the top 10% income share provided by the World Inequality Database (WID) [30]. All estimated variables are transformed into natural logarithms, to avoid the bias of different units for each variable.

Table 1. Data descriptive, annual data (1990–2015, N = 988, n = 38, T = 26).

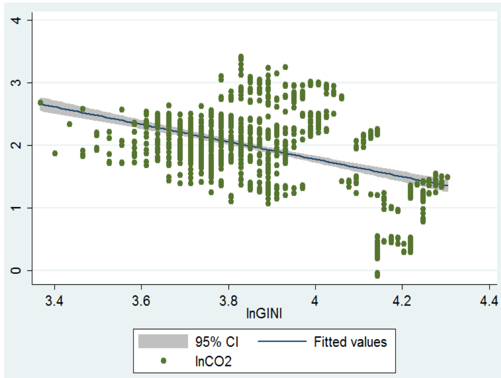
Variable (Definition, Unit, Source)	Mean	Std. Dev.	Min	Max
CO_2 (CO_2 emissions, Metric tons per capita, WDI)	8.4	4.6	0.9	30.4
GDP (GDP per capita, PPP, constant 2017 international $, WDI)	34,789.3	17,368.5	8307.3	120,647.8
TD (Trade dependency, % of GDP, WDI)	82.1	46.8	15.8	351.1
EU (Energy use, kg oil equivalent per capita, WDI)	3950.6	2354.8	537.7	18,178.1
RENEW (Renewable energy consumption, % of total final energy consumption, WDI)	17.9	15.4	0.4	77.3
GINI (Gini coefficient, %, WID)	48.2	9.2	29	74
TIS99 (Total 1% income share, %, WID)	12.4	5.0	3.7	31.5
TIS90 (Total 10% income share, %, WID)	37.1	9.2	20.9	66.3

Source: Author's own elaboration based on World Bank (2022) WDI [29] and WID (2022) [30].

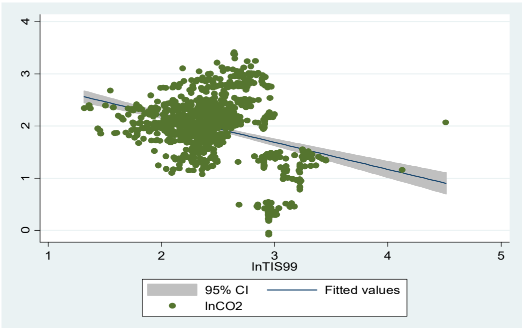
Figure 2 shows the simple linear relation between GDP and inequality indexes for CO_2 emissions, excluding the other relevant variables (e.g., *TD*, *EU*, and *RENEW*). Within 38 OECD countries from 1990 to 2015, the effect of GDP on CO_2 emissions is positive, but the effects of income inequality indexes on CO_2 emissions are negative. This implies that economic growth tends to increase CO_2 emissions, but rising income inequality contributes to falling CO_2 emissions. Similarly, Figure 3 denotes the simple linear relation between income inequality indexes for GDP without the other relevant variables, and economic growth spurs the relief in income inequality.



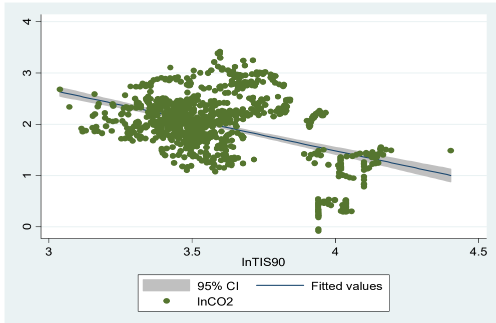
(**a**) *GDP* vs. *CO*2



(**b**) *GINI* vs. *CO*2

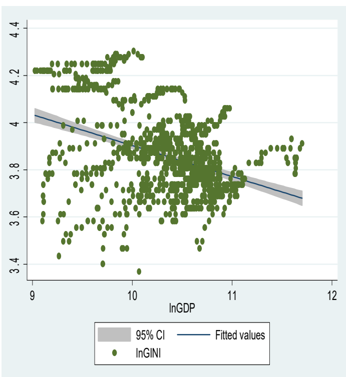


(**c**) *TIS99* vs. *CO*2

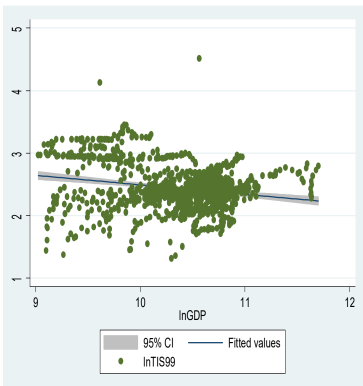


(**d**) *TIS90* vs. *CO*2

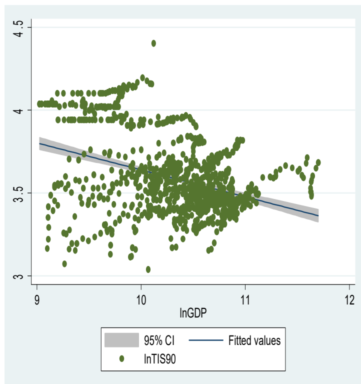
Figure 2. The simple relationships of income inequality indexes and GDP for CO_2 emissions. Note: All variables are taken in the logarithmic form. Source: Author's own elaboration based World Bank (2022) WDI [29] and WID (2022) [30].



(**a**) *GDP* vs. *GINI*



(**b**) *GDP* vs. *TIS99*



(**c**) *GDP* vs. *TIS90*

Figure 3. The simple relationships of income inequality indexes and GDP. Note: All variables are taken in the logarithmic form. Source: Author's own elaboration based World Bank (2022) WDI [29] and WID (2022) [30].

3. Results and Discussions

Table 2 shows the results of the CADF unit root test, and the optimal lag length is 1, chosen according to Schwarz's criteria. The results of the level for each variable are not statistically significant, but the first difference for each variable is statistically significant at the 1% level, implying that all variables can be stationary after the first difference.

Table 2. Results of CADF unit root test.

	Level		First Difference	
	I	II	I	II
ln(CO_2)	−1.87 (0.23)	−2.40 (0.26)	−3.48 (0.00)	−3.81 (0.00)
ln(GDP)	−1.95 (0.10)	−2.35 (0.39)	−3.03 (0.00)	−3.16 (0.00)
ln(TD)	−1.88 (0.20)	−2.15 (0.84)	−2.27 (0.00)	−3.20 (0.00)
ln(EU)	−1.79 (0.42)	−2.38 (0.32)	−3.56 (0.00)	−4.02 (0.00)
ln($RENEW$)	−1.95 (0.10)	−2.28 (0.55)	−3.62 (0.00)	−3.81 (0.00)
ln($GINI$)	−1.78 (0.43)	−1.91 (0.99)	−2.23 (0.00)	−3.10 (0.00)
ln($TIS99$)	−1.43 (0.98)	−1.83 (0.99)	−2.33 (0.00)	−2.97 (0.00)
ln($TIS90$)	−1.65 (0.74)	−1.75 (0.99)	−2.49 (0.00)	−2.90 (0.00)

Note: I and II indicate 'with constant' and 'with constant and trend', respectively. Test results indicate the standardized Z (t-bar) statistics and p-value in parentheses. Source: Author's own elaboration based on World Bank (2022) WDI [29] and WID (2022) [30].

Table 3 shows the results of the Westerlund panel cointegration test with constant and trend. Westerlund [25] proposed four cointegration tests: G_t, G_a, P_t, and P_a. The results of Gt and G_a show evidence for cointegration of at least one of the cross-sectional data, while the results of P_a and P_t indicate evidence for cointegration for the panel as a whole. Considering the results of P_t and P_a, the null hypothesis is rejected at 1% significance level, except for models 6 and 8; we concluded that there can be no concern about spurious regression using OLS with long-run estimation.

Table 3. Results of Westerlund panel cointegration test (with constant and trend).

Model	G_t		G_a		P_t		P_a	
	value	z-value (*p*-value)	value	z-value (*p*-value)	value	z-value (*p*-value)	value	z-value (*p*-value)
1	−1.44	−0.37 (0.35)	−4.06	1.98 (0.97)	−9.40	−2.72 (0.00)	−4.86	−2.98 (0.00)
2	−2.45	−1.52 (0.06)	−6.11	4.50 (1.00)	−16.69	−4.16 (0.00)	−19.81	−2.65 (0.00)
3	−1.45	−0.43 (0.33)	−4.91	1.02 (0.84)	−10.12	−3.27 (0.00)	−4.91	−3.07 (0.00)
4	−2.29	−0.55 (0.29)	−7.00	3.79 (1.00)	−14.05	−2.01 (0.02)	−12.44	−4.03 (0.00)
5	−1.38	0.01 (0.50)	−4.34	1.66 (0.95)	−10.04	−3.21 (0.00)	−4.66	−2.72 (0.00)
6	−2.05	0.84 (0.80)	−5.51	4.98 (1.00)	−13.01	−3.25 (0.00)	−6.28	1.35 (0.91)
7	−1.41	−0.18 (0.42)	−4.16	1.86 (0.96)	−9.42	−2.74 (0.00)	−4.44	−2.44 (0.00)
8	−2.17	0.15 (0.56)	−7.13	3.68 (1.00)	−13.01	−1.15 (0.12)	−6.81	0.94 (0.82)

Note: *p*-value in parentheses. Source: Author's own elaboration based on World Bank (2022) WDI [29] and WID (2022) [30].

Tables 4–7 indicate the estimated results of Equations (1)–(4) with respect to the pooled OLS, country fixed panel analysis, and DPD models. First, to decide between fixed or random effects for panel analysis, this study adopted the Hausman test. The null hypothesis for all results is rejected at the 1% significance level, implying that a fixed effect is preferred. To identify cross-sectional independence, this study used the Pesaran test. The null hypothesis of all the results is also rejected at the 1% significance level, which indicates the presence of cross-sectional dependence under fixed effects. In particular, Hoeschel [31] argued that ignoring the cross-sectional correlation of panel models can lead to biased statistical results. Therefore, this study identified the significance of estimators for all models using the Driscoll–Kraay standard errors, which included covariance matrix estimators that do not consider cross-sectional dependence. The Sargan test can identify the overidentifying moment conditions for DPD models, and includes the null hypothesis that overidentifying restrictions are valid. All results of the Sargan test fail to reject the null hypothesis, and this implies that DPD models are valid. Moreover, the DPD model's estimators are valid if there is no serial correlation in error terms, and Arellano and Bond tests include the AR(1) and AR(2). All result showed that no autocorrelation of order 1 (AR(1)) can be rejected with significance at 1% but no autocorrelation of order 2 AR(2) cannot be rejected with significance at 10%, and this implied that the DPD models of Arellano and Bond are corrected.

Table 4 indicates the effects for economic growth on CO_2 emissions based on the traditional EKC hypothesis, which is represented by direction A in Figure 1. In model 1, the estimated coefficients of GDP square and GDP have positive and negative signs with at least 10% statistical significance, respectively, indicating an inverted U-shaped relationship between economic growth and CO_2 emissions. In model 2, which included the other relevant variables for CO_2 emissions, the result of fixed effects only has an inverted U-shaped relationship between GDP and CO_2 emissions. In addition, the coefficients of TD and RENEW have negative signs, but the coefficient of EU has a positive sign with 5% statistical significance. This implies that the increase in international trade and renewable energy consumption has contributed to the decrease in CO_2 emissions; however, the increase in energy use tends to increase CO_2 emissions.

Table 4. The effect of economic growth on CO_2 emissions.

	POLS	FE	DPD	POLS	FE	DPD
		Model 1			**Model 2**	
$\ln(CO_2)$t-1			0.85 *** (38.12)			0.51 *** (23.23)
$\ln(GDP)$	3.53 ** (2.28)	1.14 ** (2.45)	2.46 *** (7.40)	0.24 (0.71)	1.04 *** (3.67)	2.40 *** (9.12)
$[\ln(GDP)]^2$	−0.14 * (−1.88)	−0.06 ** (−2.48)	−0.13 *** (−7.43)	−0.01 (−0.52)	−0.05 *** (−3.69)	−0.12 *** (−9.09)
$\ln(TD)$				−0.06 *** (−17.49)	−0.03 ** (−2.35)	−0.10 *** (−5.82)
$\ln(EU)$				0.76 *** (20.17)	0.71 *** (27.13)	0.42 *** (16.45)
$\ln(RENEW)$				−0.18 *** (−12.08)	−0.13 *** (−14.42)	−0.10 *** (−12.48)
Constant	−19.81 ** (−2.42)	−3.73 (−1.57)	−12.14 *** (−7.21)	−5.15 *** (−3.12)	−8.43 *** (−5.81)	−14.51 *** (−10.48)
R-squared	0.41	0.14		0.82	0.79	
Hausman		39.92 ***			42.56 ***	

Table 4. *Cont.*

	POLS	FE	DPD	POLS	FE	DPD
		Model 1			**Model 2**	
Pesaran		20.69 ***			4.24 ***	
Sargan			$\chi^2 = 3.01$ p-value = 0.22			$\chi^2 = 8.45$ p-value = 0.13
AR(1)			−4.58 p-value = 0.00			−3.57 p-value = 0.00
AR(2)			−0.71 p-value = 0.47			−0.79 p-value = 0.42

Notes: Values in parentheses indicate the t-value, which are based on the Driscoll–Kraay standard errors. R-squared of fixed effect is based on the overall value. *, **, and *** refer to the 10%, 5%, and 1% significance levels. Source: Author's own elaboration based on World Bank (2022) WDI [29] and WID (2022) [30].

Tables 5–7 shows the results of the effects of income inequality on CO_2 emissions with respect to the Gini coefficient and the top income share, represented by direction B in Figure 1. First, the coefficients of *TD*, *EU*, and *RENEW* in Tables 3–5 showed the same results as in Table 2, and this meant that the increase in international trade and renewable energy use decreased CO_2 emissions, but the increase in energy use increased CO_2 emissions, even if we consider the relationship between income inequality and CO_2 emissions.

In the results of Table 5, the coefficients of *GDP* and *GDP* squared have positive and negative signs, with the same results as model 1, at 1% statistical significance. This indicates that there is an inverted U-shaped relationship between the Gini coefficient and CO_2 emissions and implies that the early stage of income inequality tends to increase CO_2 emissions, but beyond the turning point, it decreases CO_2 emissions. Thus, if we use the Gini coefficients characterized by income inequality, there exits the mixed situations for 'trade-off' and 'win–win' relationships between income inequality and CO_2 emissions.

In model 4 of Table 5, the coefficients of the interaction effect for GDP and the Gini coefficient are positive and statistically significant, and this shows that an increase in the interaction between economic growth and income inequality can induce an increase in CO_2 emissions. This implies that the combination of economic growth and CO_2 emissions varies at different levels of income inequality (measured by the Gini coefficient), and that the association of income inequality (measured by the Gini coefficient) and CO_2 emissions also varies at different levels of economic growth.

Table 5. The effect of income inequality (measured by Gini coefficient) on CO_2 emissions.

	POLS	FE	DPD	POLS	FE	DPD
		Model 3			**Model 4**	
ln(*CO2*)t-1			0.87 *** (38.06)			0.51 *** (22.59)
ln(*GINI*)	40.33 *** (8.54)	7.29 *** (3.64)	6.02 *** (4.03)	7.61 ** (2.27)	2.33 ** (1.96)	0.58 *** (3.46)
$[\ln(GINI)]^2$	−5.33 *** (−8.97)	−0.92 *** (−3.44)	−0.71 *** (−3.03)	−0.95 ** (−2.24)	−0.31 ** (−1.99)	−0.62 *** (4.27)
ln(*GDP*×*GINI*)				0.05 **(2.08)	0.01 **(2.39)	0.04 **(2.14)
ln(*TD*)				−0.04 *** (−5.15)	−0.05 ** (−2.60)	−0.02 (−1.54)
ln(*EU*)				0.82 *** (32.97)	0.69 *** (29.37)	0.37 *** (14.72)

Table 5. *Cont.*

	POLS	FE	DPD	POLS	FE	DPD
		Model 3			Model 4	
ln(*RENEW*)				−0.18 *** (−13.70)	−0.14 *** (−15.88)	−0.11 *** (−14.24)
Constant	−74.07 *** (−7.92)	−16.42 *** (−4.37)	0.36 (0.11)	−19.31 *** (−2.97)	−1.20 (−0.53)	−3.23 (−1.34)
R-squared	0.31	0.01		0.81	0.79	
Hausman		19.99 ***			17.99 ***	
Pesaran		24.59 ***			4.14 ***	
Sargan			χ^2 = 4.22 *p*-value = 0.12			χ^2 = 9.11 *p*-value = 0.10
AR(1)			−4.62 *p*-value = 0.00			−3.68 *p*-value = 0.00
AR(2)			−0.78 *p*-value = 0.43			−0.77 *p*-value = 0.43

Notes: Values in parentheses indicate the t-value, which are based on the Driscoll–Kraay standard errors. R-squared of fixed effect is based on the overall value. **, and *** refer to the 5%, and 1% significance levels. Source: Author's own elaboration based on World Bank (2022) WDI [29] and WID (2022) [30].

Tables 6 and 7 show the results for the effects of the top 1% and 10% income shares on CO_2 emissions, respectively. An inverted U-shaped relationship exists between *TIS99* (or *TIS90*) and CO_2 emissions, except for the case of fixed effects for models 6 and 8. This implies that an increase in the top 1% (or 10%) income share initially tends to an increase in CO_2 emissions, but beyond the turning point, an inverse relation exists between top income share and CO_2 emissions. That is, in analyzing the relationship between income inequality and environmental deterioration, both the Gini coefficient and top income share have high explanatory power and correlation. Moreover, the interaction effect of the top 10% income share and economic growth has a positive sign with statistical significance, but the top 1% income share does not have a statistically significant coefficient.

Table 6. The effect of income inequality (measured by top 1% income share) on CO_2 emissions.

	POLS	FE	DPD	POLS	FE	DPD
		Model 5			Model 6	
ln(*CO2*)t-1			0.88 *** (39.02)			0.50 *** (22.23)
ln(*TIS99*)	1.75 * (1.86)	0.36 *** (3.36)	0.07 ** (2.08)	0.68 ** (2.06)	0.02 (0.26)	0.24 *** (4.26)
[ln(*TIS99*)]^2	−0.45 ** (−2.27)	−0.05 *** (−2.72)	−0.01 *** (−2.99)	−0.10 * (−1.73)	−0.01 (−0.75)	−0.03 *** (−3.69)
ln(*GDP*×*TIS99*)				0.04 (1.38)	0.01 (0.66)	0.01 (0.92)
ln(*TD*)				−0.05 *** (−4.95)	−0.06 *** (−3.02)	−0.14 *** (−2.87)
ln(*EU*)				0.84 *** (41.33)	0.69 *** (29.62)	0.38 *** (15.30)
ln(*RENEW*)				−0.19 *** (−14.38)	−0.14 *** (−15.97)	−0.11 *** (−13.98)
Constant	0.43 (0.40)	2.51 *** (18.14)	0.12 (1.22)	−5.27 *** (−12.04)	−3.11 *** (−15.99)	−2.21 *** (−12.90)

Table 6. *Cont.*

	POLS	FE	DPD	POLS	FE	DPD
		Model 5			**Model 6**	
R-squared	0.14	0.03		0.81	0.80	
Hausman		10.10 ***			12.88 ***	
Pesaran		22.61 ***			3.04 ***	
Sargan			χ^2 = 3.88 *p*-value = 0.14			χ^2 = 7.99 *p*-value = 0.15
AR(1)			−4.63 *p*-value = 0.00			−3.76 *p*-value = 0.00
AR(2)			−0.81 *p*-value = 0.42			−0.91 *p*-value = 0.35

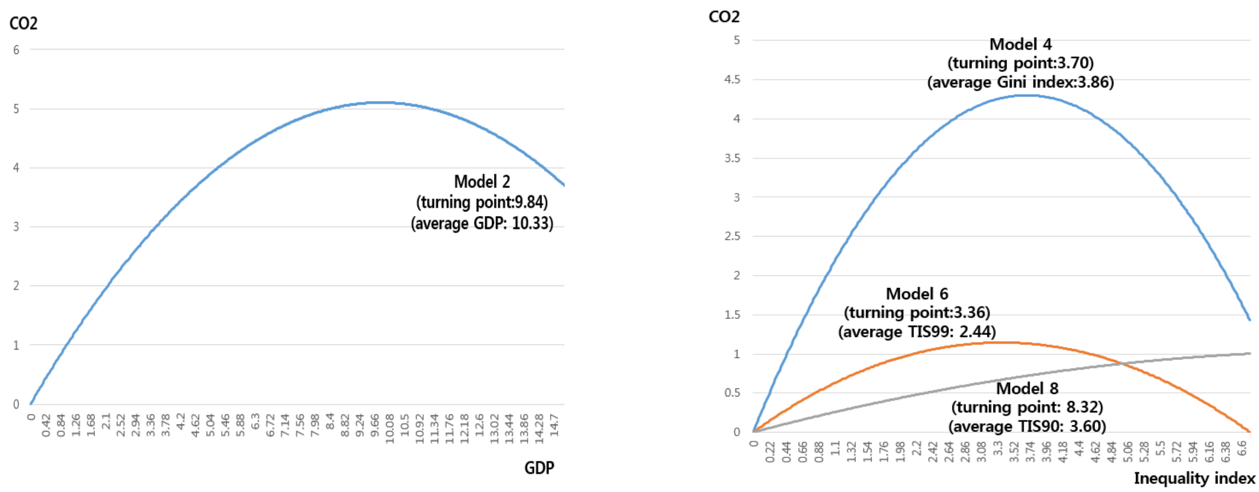
Notes: Values in parentheses indicate the t-value, which are based on the Driscoll–Kraay standard errors. R-squared of fixed effect is based on the overall value. *, **, and *** refer to the 10%, 5%, and 1% significance levels. Source: Author's own elaboration based on World Bank (2022) WDI [29] and WID (2022) [30].

Table 7. The effect of income inequality (measured by top 10% income share) on CO_2 emissions.

	POLS	FE	DPD	POLS	FE	DPD
		Model 7			**Model 8**	
ln(CO_2)t-1			0.83 *** (38.96)			0.51 *** (22.68)
ln(*TIS90*)	2.14 *** (18.35)	0.36 *** (3.51)	0.04 ** (2.14)	0.25 *** (4.42)	0.11 (1.52)	0.94 ** (2.52)
[ln(*TIS90*)]^2	−0.13 *** (−17.98)	−0.02 *** (−3.35)	−0.01 ** (2.15)	−0.02 *** (−4.22)	−0.01 (−1.59)	−0.11 ** (−2.30)
ln(*GDP*×*TIS90*)				0.07 ** (2.25)	0.01 *** (2.70)	0.01 ** (2.20)
ln(*TD*)				−0.05 *** (−7.39)	−0.06 *** (−3.03)	−0.03 ** (−2.07)
ln(*EU*)				0.84 *** (38.93)	0.69 *** (29.52)	0.38 *** (16.13)
ln(*RENEW*)				−0.18 *** (−13.11)	−0.14 *** (−15.98)	−0.11 *** (−14.48)
Constant	7.95 *** (24.13)	2.99 *** (10.47)	0.29 (0.58)	−4.89 *** (−18.20)	−3.37 *** (−13.80)	−3.77 *** (−5.25)
R-squared	0.19	0.19		0.80	0.79	
Hausman		9.85 ***			15.23 ***	
Pesaran		22.17 ***			3.29 ***	
Sargan			χ^2 = 4.38 *p*-value = 0.11			χ^2 = 7.45 *p*-value = 0.18
AR(1)			−4.63 *p*-value = 0.00			−3.73 *p*-value = 0.00
AR(2)			−0.78 *p*-value = 0.43			−0.82 *p*-value = 0.41

Notes: Values in parentheses indicate the t-value, which are based on the Driscoll–Kraay standard errors. R-squared of fixed effect is based on the overall value. ** and *** refer to the 5%, and 1% significance levels. Source: Author's own elaboration based on World Bank (2022) WDI [29] and WID (2022) [30].

Figure 4 shows the estimated results for the two related variables; (a) shows the relationship between GDP and CO_2 emissions based on model 2, and (b) illustrates the relationship between income inequality and CO_2 emissions with respect to models 4, 6, and 8. In Figure 4a, this indicates an inverted U-shaped relationship in which the average GDP per capita from 1990 to 2015 within OECD countries exceeds the turning point. This implies that in OECD countries, CO_2 emissions are already declining due to economic growth.



(**a**) *GDP* vs. *CO*2 (**b**) Income inequality index vs. *CO*2

Figure 4. The relationship of income inequality and GDP for CO_2 emissions. Source: Author's own elaboration based on World Bank (2022) WDI [29] and WID (2022) [30].

In addition, Figure 4b shows an inverted U-shaped relationship, in which the average income inequality from 1990 to 2015 within OECD countries does not exceed the turning point. This indicates that rising income inequality tends to increase CO_2 emissions within OECD countries. However, although both the Gini coefficient and top share income have an inverted U-shaped relationship with environmental degradation, the height of the graph varies according to the index of income inequality, indicating that the further away from the horizontal axis, the greater the degree of inequality. Thus, while the Gini coefficient indicates the degree of inequality in the income distribution of the entire society, the top income share reflects the aspect that can determine the level of income concentration of a very specific income class (especially, the top 1% or 10%).

Table 8 is consisted of three results; W-bar, Z-bar, and Z-bar tilde of panel Granger causality. The W-bar is based on the linear hypotheses which include the average Wald statistic for the coefficients of independent variables for the Granger causality. The Z-bar indicates the standardized statistics under the Wald test's assumption that they are independently and identically distributed across individuals. Moreover, the Z-bar tilde shows the approximated standardized statistic with a normal distribution. Therefore, the testing procedure of the null hypothesis is based on Z-bar and Z-bar tilde, and we conclude that Granger causality exists if the null hypothesis can be rejected. Again, in Figure 1, there are three different directions for the effects of GDP and income inequality on CO_2 emissions. Direction A is from economic growth to CO_2 emissions, and the results of Granger causality can be rejected at a 1% statistically significant level. Direction B is from income inequality to CO_2 emissions, and the results can also be rejected. Specifically, direction C is from income inequality to GDP (or from GDP to income inequality), and it can be rejected at a 1% significant level with bi-directionally for each variable. Finally, *TD*, *EU*, and *RENEW* also demonstrate Granger causality by rejecting the null hypothesis.

Table 8. Results of granger causality.

Direction	Granger Cause	W-Bar	Z-Bar	Z-Bar Tilde
A	$GDP \Rightarrow CO_2$	3.45	10.69 (0.00)	8.63 (0.00)
B	$GINI \Rightarrow CO_2$	2.27	5.56 (0.00)	4.31 (0.00)
	$TIS99 \Rightarrow CO_2$	1.80	3.50 (0.00)	2.58 (0.00)
	$TIS90 \Rightarrow CO_2$	1.85	3.71 (0.00)	2.76 (0.00)
C	$GINI \Rightarrow GDP$	4.26	14.22 (0.00)	11.60 (0.00)
	$TIS99 \Rightarrow GDP$	4.72	16.22 (0.00)	13.28 (0.00)
	$TIS90 \Rightarrow GDP$	4.68	16.05 (0.00)	13.14 (0.00)
	$GDP \Rightarrow GINI$	3.22	9.68 (0.00)	7.78 (0.00)
	$GDP \Rightarrow TIS99$	3.83	12.36 (0.00)	10.04 (0.00)
	$GDP \Rightarrow TIS90$	3.14	9.32 (0.00)	7.48 (0.00)
Others	$TD \Rightarrow CO_2$	2.70	7.42 (0.00)	5.58 (0.00)
	$EU \Rightarrow CO_2$	2.86	8.11 (0.00)	6.46 (0.00)
	$RENEW \Rightarrow CO_2$	5.28	18.65 (0.00)	15.33 (0.00)

Note: The optimal lag length is 1 and is chosen according to Schwarz's criteria "A ⇒ B" indicates "A causes Granger causality, producing B for at least one country". All variables are taken in the first difference. Directions are based on Figure 1. Source: Author's own elaboration based on World Bank (2022) WDI [29] and WID (2022) [30].

4. Conclusions

There are numerous factors affecting environmental equality, but most of the literature proves the relationship between economic growth and CO_2 emissions based on the EKC hypothesis. However, an increase in income inequality by individuals and countries owing to economic growth can be considered another social problem that can influence environmental issues [31–34]. Therefore, this study aimed to investigate the effects of economic growth and income inequality on CO_2 emissions in 38 OECD countries from 1990 to 2015. In addition, this study utilized the Gini coefficient and the top income share, which represent income inequality, and adopted econometric methods for panel regressions and Granger causality. The main findings of this study are as follows:

First, in the non-linear form based on the EKC hypothesis, the relationship between economic growth and CO_2 emissions is inverted U-shaped, in which the average GDP per capita exceeds the income turning point. Similarly, the nexus between income inequality and CO_2 emissions also has an inverted U-shaped relationship, but average income inequality does not exceed the turning point. This implies that within OECD countries, economic growth has already achieved the stage for relief of environmental quality, but increasing income inequality leads to environmental degradation. Therefore, according to the progress of economic growth and/or low income inequality, environmental pollution tends to decline.

Second, the relationship between income inequality and CO_2 emissions (or economic growth) is explained well not only in terms of the Gini coefficients but also concerning the top income share, and it maintains an inverted U-shape between the two income inequality indexes and CO_2 emissions. Therefore, the top income share can also be considered a well defined index to investigate the EKC hypothesis.

Third, increasing trade dependency and renewable energy use tends to decrease CO_2 emissions, but energy use contributes to increasing CO_2 emissions. In particular, according to the inverse relationship between trade dependency and CO_2 emissions, we infer that CO_2 emissions in the process of production have decreased because of pollution prevention facilities and the outflow of foreign direct investment in OECD countries. In addition, the interaction between economic growth and income inequality concerning CO_2 emissions is estimated to be positive, which means that the impacts of economic growth and income inequality have contributed to the increase in CO_2 emissions.

Finally, economic growth and income inequality have Granger causality for CO_2 emissions, but not vice versa. However, income inequality has a bidirectional Granger causality for economic growth. This implies that an interaction between economic growth and income inequality exists in the long term.

We have pursued economic growth to reduce poverty, but the gap between the rich and the poor has widened. In addition, the climate crisis through CO_2 emissions and income inequality are deeply involved. Thus, how we can get out of the climate crisis is a matter of how we can overcome income inequality. Consequently, this study provides suggestions for policy implications. We consider that the virtuous circles concerning the relationships among economic growth, income inequality, and CO_2 emissions related to the results of this study are as follows: (i) improvements in quality life and resolution of income inequality through economic growth; (ii) increasing society's demand for environmental quality; and (iii) achieving sustainable development through green growth. Although low-carbon policies related to the expansion of environmental pollutant reduction facilities in the production process are crucial, this study shows that the policies could be key to reducing CO_2 emissions by resolving the problems of income inequality. Boyce [12] emphasized that increasing inequality leads to more environmental degradation and that the equity of our society is important not only as an end, but also as a means of environmental protection.

If we will suffer from the climate crisis, the loss of income and assets of the poor will be generally greater than that of the rich because the poor do not have a means of avoiding the risk of climate change, and this leads to a vicious cycle that leads to greater poverty. Therefore, while a society might accomplish economic growth at a certain level, we need to consider that the mitigation of income inequality helps improve environmental quality. Moreover, to solve environmental problems, policy makers must not only focus on the fruits of economic performance but also make more continuous efforts to alleviate income inequality. In terms of environmental policy, it is important to consider the effect of distribution, and green growth policy cannot be an exception.

However, this study has some limitations such as that the recent situation has not been addressed due to the period restrictions of datasets; this remains the work of further research.

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