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Decoupling Economic Growth from Carbon Emissions: A Cross-country Panel Analysis and Implications

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① Decoupling—achieving economic growth while reducing carbon emissions—requires combined efforts in industrial restructuring, technological innovation, and financial development. This study analyzes panel data from 59 countries to estimate the income turning point, defined as the level of per capita GDP at which carbon emissions begin to decline, and to examine the structural factors that influence its trajectory.

② The estimated average turning point is USD 23,000 in per capita GDP, with most high-income countries already achieving stable decoupling. A greater share of globally competitive service industries consistently supports decoupling by driving structural change. Meanwhile, the effects of technological and financial development vary by context—reinforcing emissions in carbon-intensive economies but aiding decoupling where green systems are in place.

③ For Korea, the turning point is estimated at approximately USD 30,000 per capita GDP, significantly above the average. As its income level now exceeds this threshold, Korea stands at a pivotal stage in consolidating the transition toward sustained decoupling.

④ Korea's delayed decoupling stems largely from its industrial and energy structures. The expansion of labor-intensive, low value-added service sectors has a limited structural effect, while persistent reliance on carbon-intensive sectors—such as manufacturing and fossil fuel-based energy production—has resulted in that advances in technology and finance have often amplified emissions through scale effects.

⑤ To ensure sustained decoupling beyond these structural constraints, it is critical for the Korean economy to increase the share of low-carbon, high value-added industries and service sectors, accelerate the deployment of clean energy and green technologies, and implement practical policy tools to scale up green finance.

⑥ Additionally, adopting a transition finance framework tailored to Korea's industrial structure—as a complement to the existing green finance system—is worth considering. Such a framework could help close financing gaps in the phased decarbonization of hard-to-abate industries and support investment in bridge technologies, while also helping to safeguard the competitiveness of key industrial sectors during the transition.

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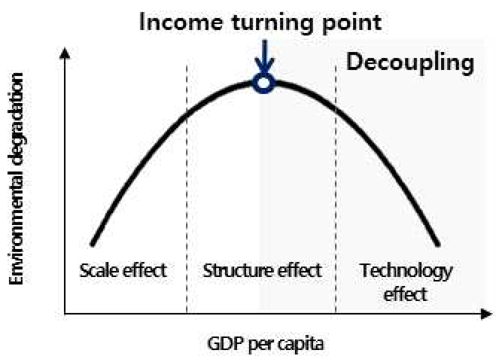
Ⅰ. Background

As global environmental standards tighten amid the unfolding climate crisis, countries around the world are placing growing emphasis on decoupling economic growth from CO_2 emissions—that is, achieving sustained economic expansion without a corresponding increase in environmental pressure. In the same vein, the current low-carbon transition strategies of major advanced economies go beyond merely mitigating the direct impacts of climate change, aiming instead to foster long-term sustainable economic structures and to develop new engines of future growth. Since decoupling entails reducing environmental degradation and prioritizing environmentally sustainable growth paths, the concept is closely linked to the environmental Kuznets curve (EKC). The EKC hypothesis posits that pollutant emissions, which contribute to environmental degradation, increase at low income levels but decline once income surpasses a certain threshold (the turning point). The term derives from the "Kuznets curve" (Kuznets, 1955), which illustrates a similar inverted U-shaped relationship between economic growth and income inequality (Panayotou, 1993).

The EKC framework explains the non-linear relationship between economic growth and environmental degradation across different stages of development (Dinda, 2004; Stern, 2004). In the first stage of economic development, known as the scale effect stage, rapid industrialization and urbanization increase production and consumption, driving up energy demand and resource use, which in turn leads to rising pollutant emissions. Once per capita income surpasses a certain threshold, a shift in industrial structure occurs—from emission-intensive manufacturing to service-oriented sectors—resulting in a gradual reduction of environmental pressure. This is referred to as the structure effect stage. In the final phase, known as the technology effect stage, rising environmental awareness, stricter regulations, and increased availability of clean technologies enable emissions to decline even as income levels continue to rise. This pattern—economic growth without a corresponding increase in emissions—is referred to as decoupled growth (see **Figure 1**).

[Figure 1] Environmental Kuznets Curve and the decoupling process



Notes: 1) Adapted by the author from Panayotou (2003).
2) The y-axis indicates measurable levels of environmental degradation or emissions of substances harmful to the environment.
3) The gray shaded region represents the decoupling phase.

Source: Author's own elaboration

Decoupling economic growth from environmental impact in line with the EKC pattern requires far more than a simple reduction in CO_2 emissions. For decoupling to take place, sweeping changes must be made to a country's economic structure to ensure long-term sustainable growth. As such, the success and trajectory of decoupling largely depend on, and vary significantly with, each country's unique economic and policy conditions (Lim & Cho, 2019). In fact, the global trend since 2000 shows that average per capita GDP has increased alongside per capita CO_2 emissions—driven mainly by middle-income countries such as India and China. In contrast, many advanced economies have experienced absolute decoupling, where CO_2 emissions have declined despite continued income growth (see **Figure 2**).

In Korea, recent signs of weak decoupling[1)]—including a decline in the income elasticity of CO_2 emissions—have been observed. However, to meet its 2030 Nationally Determined Contribution (NDC), Korea must further accelerate its annual emissions reduction rate (see **Figure 3**). It is also worth noting that Korea's per capita GDP and productivity remain below the OECD averages, while its energy intensity and per capita CO_2 emissions are well above.[2)] Therefore, achieving decoupling in Korea will require large-scale investments in globally competitive, high-efficiency production systems, low-carbon infrastructure, and environmentally friendly technologies.

Decoupling economic growth from CO_2 emissions is widely regarded as a process fraught with uncertainty. It requires a comprehensive consideration of multiple factors, including domestic and global conditions as well as the medium- to long-term ripple effects. Unlike localized environmental degradation with direct and immediate impacts—such as acid rain or water pollution—climate change caused by rising CO_2 emissions has widespread, global consequences and features a substantial time lag before its full economic costs become apparent (Shahbaz & Sinha, 2019). Moreover, because CO_2 emissions are closely tied to a country's long-established energy supply structure,[3)] they cannot be easily reduced or restructured in the short term

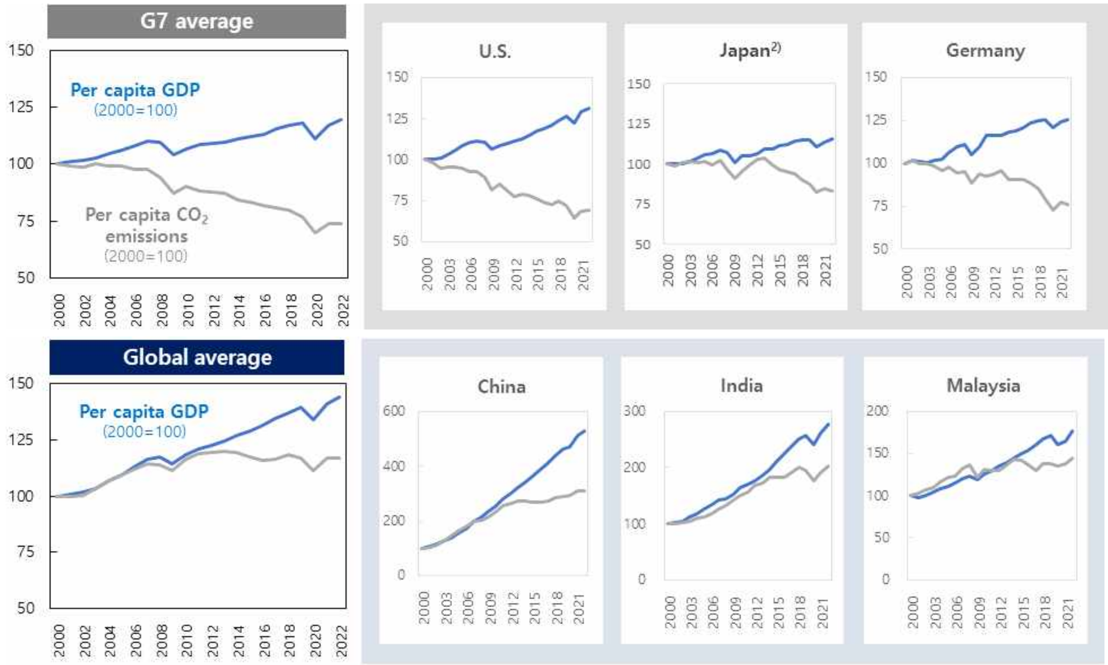
1) This phenomenon, in which the increase in CO_2 emissions slows even as income growth continues (i.e., the EKC slope becomes less steep before the turning point), is referred to as weak decoupling or relative decoupling. It is distinguished from absolute decoupling, where emissions decrease in absolute terms despite economic growth (Lim & Cho, 2019).

2) According to World Bank data (2022), Korea's per capita GDP and productivity stood at 86% and 82% of the OECD averages, respectively, while its energy intensity (energy use per USD 1,000 of GDP) and per capita CO_2 emissions were 1.5 times and 1.4 times higher.

3) Historically, industrialization-driven economic growth has led to increased energy demand, which has been predominantly met through fossil fuel consumption. This has contributed to the widespread perception that rising CO_2 emissions are an inevitable byproduct of economic expansion (Lee, 2017).

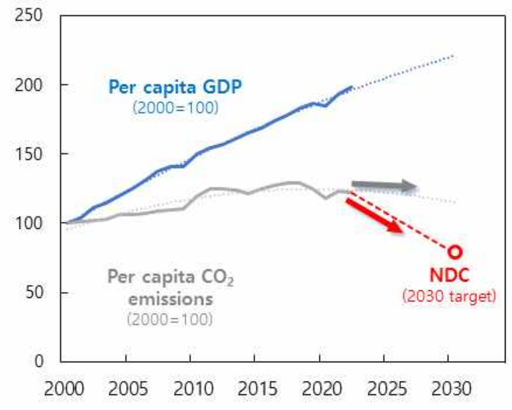
—even when there is sufficient awareness of their long-term impacts. Against this backdrop, this study analyzes the EKC pattern of CO_2 emissions both globally and in Korea, considering income levels and the structural characteristics of Korea's economic development. It further explores policy solutions to facilitate Korea's low-carbon transition and ensure long-term sustainable growth.

[Figure 2] Per capita GDP and per capita CO_2 emissions in major countries



Notes: 1) Per capita GDP is measured in constant 2015 USD; per capita CO_2 emissions are in metric tons.
2) Japan's per capita CO_2 emissions are based on data from the Greenhouse Gas Inventory Office (GIO).
Source: World Bank.

[Figure 3] Per capita GDP and per capita CO_2 emissions in Korea: Trends and targets



Notes: 1) GDP is measured in constant 2015 USD; CO_2 emissions are in metric tons.
2) The dotted line represents the quadratic polynomial trend.
3) The red circle indicates Korea's 2030 NDC (40% below 2018 level) converted to per capita terms using projected population data.

Source: World Bank.

The remainder of this study is organized as follows. **Section II** estimates the EKC patterns and income turning points of countries that have transitioned out of the low-income group, using regression analysis based on cross-country panel data. It also examines the magnitude and significance of structural factors—such as differences in economic structure, techno-logical advancement, and financial development—that contribute to decoupling beyond income effects. **Section III** evaluates Korea's decoupling progress based on the regression results, focusing on the key features of its trajectory and relevant policy options to support its low-carbon transition and sustainable growth. **Section IV** summarizes the key findings and recaps their policy implications.

Ⅱ. Decoupling Analysis Using a Panel Regression Model

This section presents an econometric analysis of average decoupling trends and patterns among middle- and high-income countries, with the aim of establishing a benchmark for evaluating Korea's decoupling strategy. It proceeds by (1) examining the key drivers of decoupling process, (2) introducing the analytical model—which incorporates income levels and structural determinants—along with the estimation methodology, and (3) discussing the results and their implications.

1. Decoupling Paths and Driving Factors

Understanding the EKC relationship and the emergence of decoupling begins with the role of income levels as a primary explanatory factor. In empirical studies from the 1990s, researchers primarily focused on whether the EKC was statistically significant and identifying the income turning point. Early studies commonly employed a simple analytical model that included only per capita GDP and indicators of environmental degradation, as proposed by Grossman and Krueger (1991) (Panayotou, 1993; Shafik, 1994; Cole et al., 1997). However, subsequent studies argued that accurately validating the EKC requires controlling for factors beyond income—such as population density, urbanization, and political freedom—that reflect important non-economic or structural characteristics (Selden & Song, 1994; Kaufmann et al., 1998; Torras & Boyce, 1998). At the same time, some researchers have cautioned that empirical EKC models are often subject to omitted variable bias (OVB)[4] or spurious regression. Moreover, whether decoupling is observed—and the estimated income turning point—can vary substantially across countries and time periods (Stern, 2004). To address these concerns, this study adopts an extended EKC model that incorporates additional structural variables expected to influence decoupling patterns.

The EKC and decoupling are phenomena that reflect dynamic changes in the relationship between economic growth and environmental sustainability. However, such a transition is not guaranteed to occur automatically upon reaching a particular income threshold. Rather, this transition is shaped by a range of underlying forces, implying that analytical models based solely on income are insufficient to explain the pathways toward decoupling or to identify its key driving factors (Kaika & Zervas, 2013). These considerations underscore the importance of moving beyond simple EKC verification through the analysis of models that reflect a country's structural characteristics and economic dynamics.

First, international trade plays a crucial role in shaping both the EKC and the decoupling process, as it affects how growth and emissions are distributed across countries. Suri and Chapman(1998) found that trade openness tends to shift the income turning point upward. This is because, while developed countries benefit from imports that lower domestic energy consumption and industrial emissions—thereby accelerating decoupling—developing countries experience increased exports that simultaneously raise income levels and intensify environmental pressure, ultimately delaying the onset of decoupling. This phenomenon, which is closely related to the so-called pollution haven hypothesis, suggests that shifts in trade structure and volume can both impede and promote a country's decoupling process.

Second, changes in economic structure (i.e., the composition of industrial production) and advancements in technology are widely recognized as two key drivers of decoupling within the EKC framework. Panayotou (2003) argued that pollution intensity varies by the type of economic activity, and that direct pollutant emissions tend to decline as economies develop and transition from manufacturing to services. Stern (2004) identified two main channels through which technological

4) For example, even when panel regression models include fixed effects to control for unobserved heterogeneity, EKC specifications with only a limited set of control variables—excluding key structural determinants—may still suffer from endogeneity. To address this issue, the present study adopts an extended EKC model that incorporates additional explanatory variables expected to influence decoupling dynamics.

innovation and economic growth jointly facilitate decoupling. In the first, environmental pressure is reduced through gains in productivity and efficiency, as cleaner technologies lower emissions per unit of output. In the second, the development of breakthrough technologies that directly reduce emissions contributes simultaneously to environmental improvement and sustained growth. This mechanism is consistent with innovation-led growth theories, which suggest that well-designed environmental regulations can induce firms to develop environmentally friendly technologies (Porter & van der Linde, 1995; Acemoglu et al., 2012).

Recently, a growing body of research has examined the effects of technological progress in digital transformation—particularly in areas such as data technology and artificial intelligence (AI)—on the EKC. Zhang et al. (2022) find that digital innovation contributes to lowering CO_2 emissions by accelerating the transition to a data-driven economy and enhancing emissions monitoring and management systems. In contrast, Wang et al. (2024) highlight that the effects of digital technologies on the EKC vary depending on a country's stage of economic development. For instance, in countries still in the early stages of decoupling, emissions may increase as AI and other digital technologies are developed and scaled up, owing to the high energy intensity embedded throughout their life cycle—particularly in economies still reliant on carbon-intensive energy systems.

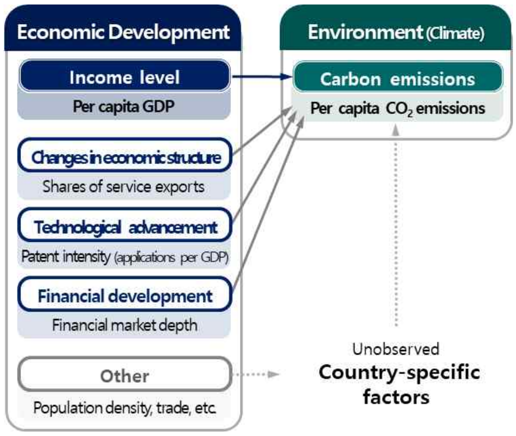
Dasgupta et al. (2001) identified the level of financial market development as another key determinant of the EKC pattern. This is especially relevant, as decoupling at any stage of economic development requires substantial investment and costly structural shifts. For instance, Nasreen et al. (2017) showed that in developing countries, the EKC pattern becomes evident only when financial markets are sufficiently developed and stable—providing capital access and financial resilience to support large-scale investment in sustainable development. Accordingly, they emphasized the critical role of well-functioning financial systems in steering capital flows toward low-carbon investments. Likewise, De Haas and Popov (2019), in a study of 48 countries, found that mature equity-based financial systems contribute to reducing CO_2 emissions by facilitating firm-level investment in green innovation.

On the other hand, Javid and Sharif (2016) noted that financial market development can exacerbate environmental degradation if it is not closely aligned with government climate policy objectives. This reflects the fact that finance does not directly reduce emissions per se; rather, it supports or incentivizes mitigation efforts in the real economy. The divergence in findings on the role of financial development further suggests that its estimated impact on decoupling may vary significantly depending on the choice of financial variables and the countries analyzed.

In this study, three core determinants of the Environmental Kuznets Curve (EKC) are identified based on the existing literature: ① the scale of production, ② the structure of the economy, and ③ technological advancement.[5] To reflect the institutional context that enables or constrains these structural processes, the study further introduces ④ financial development as a complementary institutional variable (see **Figure 4**).

The scale effect reflects the emissions associated with quantitative economic expansion, holding technology and input ratios constant. It is typically proxied by per capita GDP, which captures a country's level of economic development (Stern, 2004). The structure effect describes how changes in economic composition—particularly shifts from manufacturing to services—affect pollution intensity and shape emissions patterns around the income turning point. The technology effect captures the role of efficiency gains and innovation, such as endogenous productivity improvements or advancements in green technologies, in influencing the EKC trajectory. Financial development, meanwhile, serves as a proxy for a country's capacity to mobilize and allocate capital in ways that either facilitate or impede the decoupling process.

[Figure 4] Analytical framework: The impact of economic development on CO_2 emissions



Source: Author's own elaboration

2. Methodology

In this study, to investigate patterns of decoupling within the framework of the EKC, a basic model is specified in the form of a quadratic polynomial function, capturing the hypothesized inverted U-shaped relationship between income levels and CO_2 emissions (Stern, 2004; Kaika & Zervas, 2013):

equation (1)

$$\ln CO2pc_{c,t} = \beta_0 + \beta_1 \ln GDPpc_{c,t} + \beta_2 (\ln GDPpc_{c,t})^2 + \epsilon_{c,t}$$

Here, $\ln CO2pc_{c,t}$ and $\ln GDPpc_{c,t}$ represent the natural logarithms of per capita CO_2 emissions and per capita GDP for country

5) Although international trade is widely recognized in the literature as a key factor affecting the CO_2–growth relationship, it is treated in this study as an auxiliary control variable. This is because reliance on trade (e.g., emissions offshoring or import substitution) may not provide a structurally sustainable solution for long-term decoupling. The study instead focuses on identifying domestically actionable and institutionally grounded drivers of decoupling, consistent with global climate governance frameworks.

c in year t, respectively. If an inverted U-shaped relationship exists between these two variables, the coefficient on $\ln GDPpc_{c,t}$ is expected to be positive, while the coefficient on its squared term is expected to be negative. The income *turning point (TP)*, which indicates the level of income at which CO_2 emissions begin to decline, can be derived as follows:

equation (2)

$$TP = \exp(-\beta_1/(2\beta_2))$$

To better understand the drivers of decoupling beyond income level effects, two extended models are developed by incorporating additional explanatory variables($\ln x_{j,c,t-1}$) that are expected to influence the decoupling process:

(i) Indirect effect model

equation (3)

$$\ln CO2pc_{c,t} = \beta_0 + \beta_1 \ln GDPpc_{c,t} + \beta_2 (\ln GDPpc_{c,t})^2 + \sum_{j=1} \gamma_j \ln x_{j,c,t-1} + d.crisis_t + \mu_c + \epsilon_{c,t}$$

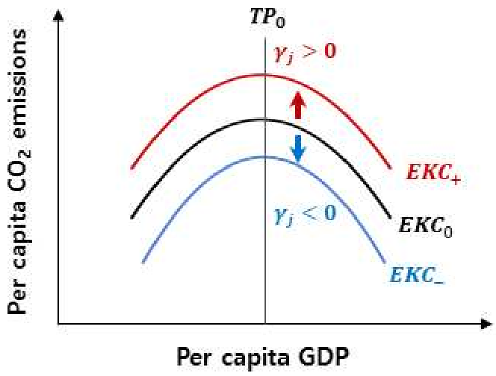
(ii) Direct effect model[6]

equation (4)

$$\ln CO2pc_{c,t} = \beta_0 + \beta_1 \ln GDPpc_{c,t} + (\beta_2 + \sum_{j=1} \gamma_j \ln x_{j,c,t-1})(\ln GDPpc_{c,t})^2 + d.crisis_t + \mu_c + \epsilon_{c,t}$$

First, **equation (3)** assumes that the variable $\ln x_{j,c,t-1}$ supports decoupling indirectly by contributing to the reduction of CO_2 emissions, independent of income. While $\ln x_{j,c,t-1}$ does not alter the location of the turning point (**Figure 5**, TP_0), it can still affect the overall level of emissions. Specifically, if the coefficient on $\ln x_{j,c,t-1}$ is statistically significant and negative, it indicates that the variable strengthens the decoupling trend by shifting the entire emissions curve downward (**Figure 5**, $EKC_0 \rightarrow EKC\_$).

[Figure 5] Estimation of the EKC pattern using equation (3)



Notes: 1) EKC_0 is the initial curve that does not incorporate the effect of $\ln x_{j,c,t-1}$. The curve shifts upward (EKC_+) or downward ($EKC\_$) depending on changes in the overall level of CO_2 emissions attributable to γ_j.
2) TP_0 is estimated using **equation (2)** and remains invariant to the inclusion of $\ln x_{j,c,t-1}$.

Source: Author's own elaboration

6) While an alternative specification that includes both the additional explanatory variable term $\sum \gamma_j \ln x_{j,c,t-1}$ independently and its interaction with income (i.e., GDP per capita) could be considered, this study focuses on identifying the impact of the additional variable on the curvature of the EKC through the interaction term. Equation (4) was adopted as the final specification, as it demonstrated superior goodness-of-fit and explanatory power relative to alternative models.

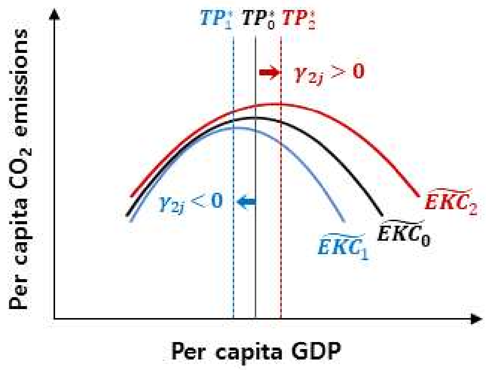
Equation (4) specifies a model in which the additional variable $\ln x_{j,c,t-1}$, along with the squared term of income level, directly influences the curvature of the EKC and, consequently, the location of the income turning point.7) For instance, if the estimated coefficient of the interaction term (γ_{2j}) is negative, an increase in $\ln x_{j,c,t-1}$ lowers the income turning point (**Figure 6**, $TP_0^* \rightarrow TP_1^*$) and steepens the EKC curve (**Figure 6**, $\overline{EKC_0} \rightarrow \overline{EKC_1}$), thereby accelerating the decoupling process. Under this specification, the income turning point is calculated as follows:

equation (5)

$$TP^* = \exp\left(-\frac{\beta_1}{2(\beta_2 + \sum \gamma_{2j} \ln x_{j,c,t-1})}\right).$$

In both **equations (3)** and **(4)**, the variable $\ln x_{j,c,t-1}$ is interpreted as a factor that promotes decoupling—either indirectly or directly—when its estimated coefficient (γ_j or γ_{2j}) is negative and statistically significant. Given that **equation (3)** closely resembles the empirical specifications commonly used in previous EKC studies, it serves as the primary model for the main analysis and interpretation of results in this study. **Equation (4)** is additionally employed to test the robustness of the key decoupling drivers by capturing their direct influence on the curvature of the EKC.

[Figure 6] Estimation of the EKC pattern using equation (4)



Notes: 1) $\widetilde{EKC_o}$ is the initial curve that does not incorporate the effect of $\ln x_{j,c,t-1}$. The shape of the curve changes ($\widetilde{EKC_1}$ or $\widetilde{EKC_2}$) depending on the coefficient of the interaction term (γ_{2j}) which alters the CO_2 emissions trajectory.
2) TP_0^* is estimated using **equation (5)** and shifts to a new turning point (TP_1^* or TP_2^*) with change in γ_{2j}.

Source: Author's own elaboration

Here, the log-transformed values of the variables corresponding to the three factors—structural change in the economy ($\ln ser_{c,t-1}$), technological advancements ($\ln tech_{c,t-1}$), and financial development ($\ln fmd_{c,t-1}$)—were used as explanatory variables. Based on existing studies, a one-year lag was applied to all three variables to reflect their delayed effects on emissions (De Haas & Popov, 2019). For $\ln ser_{c,t-1}$, the share of services in total exports was used to capture shifts in economic structure.8) For $\ln tech_{c,t-1}$, the number of patent applications per

7) In this study, $\ln x_{j,c,t-1}$ is assumed to shape the decoupling trend around the turning point by interacting with the second-order (quadratic) term of income, which determines the curvature of the EKC, rather than the first-order (linear) term, which primarily captures the early-stage relationship between emissions and income.

billion USD of GDP was selected as an indicator of a country's overall technology intensity.[9] In some model specifications, this was supplemented with a more targeted proxy—the number of international patent applications[10] related to clean energy per billion USD of GDP ($\ln c{\cdot}tech_{c,t-1}$)—to better reflect innovation relevant to the low-carbon transition. For $\ln fmd_{c,t-1}$, the Financial Market Depth Index (FMD),[11] published by the IMF, was employed to capture the level of financial development. To assess the role of green finance more directly, the green bond issuance-to-GDP ratio ($\ln g{\cdot}bond_{c,t-1}$) was also considered.[12] In addition, a dummy variable ($d{\cdot}crisis_t$) was included to control for global shocks such as the 2008–09 financial crisis and the COVID-19 pandemic, while a country fixed effect (μ_c) was included to account for time-invariant country-specific characteristics.[13]

The study covers the period from 2000 to 2020, during which the decoupling of economic growth from CO_2 emissions began to accelerate.[14] The sample consists of 59 countries classified as middle- or high-income according to the World Bank's income classification.[15] To address potential econometric issues such as spurious regression or inefficient estimation commonly associated with

8) The GDP share of services is commonly used as a proxy for structural change in growth studies, but its high correlation with per capita GDP (>0.6) raises concerns about multicollinearity. To address this, this study uses the share of services in total exports, which is less correlated with income (~0.3). This variable is interpreted not just as domestic service sector growth, but as a shift toward globally competitive service industries. Its average value was 25.2% across all 59 countries, with 21.9% in middle-income and 27.1% in high-income groups, suggesting its potential as a proxy for economic development stage.

9) Unlike other studies that use the number of patent applications per million inhabitants as a proxy for technological advancement, this study adopts the number of patent applications per billion USD of GDP to better represent the extent to which economic growth is driven by technological innovation while reducing the risk of multicollinearity.

10) This study uses patent family data by technology area, as reported in the IEA's international patent application statistics. These data capture valuable inventions for which two or more national or regional patent applications have been filed.

11) The Financial Market Depth (FMD) index, a subcomponent of the IMF's Financial Development Index, is a composite measure that captures the capacity of financial markets to support economic activity in the real sector. It incorporates a range of indicators—such as the stock market capitalization-to-GDP ratio, the volume of government debt securities, and corporate commercial paper issuance—that reflect market size and liquidity. Compared to single indicators (e.g., private credit-to-GDP ratio), the FMD provides a more comprehensive assessment of the diverse functions performed by financial markets.

12) This study uses data on sovereign and country-level green bond issuance from the IMF's green bond statistics.

13) The Hausman test strongly favored the fixed effects model ($p < 0.01$), indicating that it more effectively accounts for unobserved heterogeneity across countries.

14) Following Lim and Cho (2019), the year 2000 was selected as the starting point of the analysis, as it marks the beginning of a clearly observable global trend toward the decoupling of economic growth from CO_2 emissions.

15) Income groups are based on the World Bank's 2021 classification (nominal GNI per capita). The analysis includes 59 middle- and high-income countries for which sufficiently detailed and

panel data, panel unit root and heteroscedasticity tests were conducted using the Levin–Lin–Chu test and the modified Wald test, respectively. Based on the test results,[16] the Generalized Least Squares (GLS) estimator was employed to correct for heteroscedasticity.

3. Results and Discussion

3.1 EKC and Income Turning Point

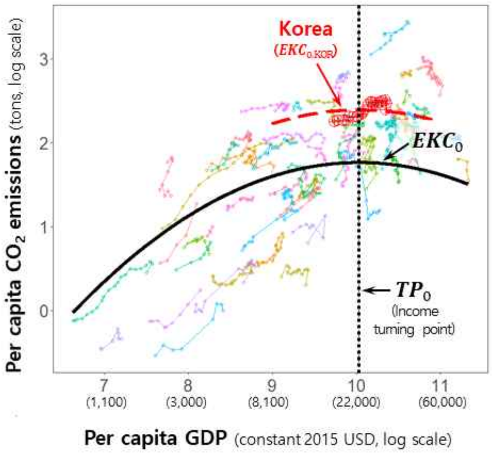
Table 1 presents the estimation results based on **equation (3)**. The coefficients of both the linear (β_1) and quadratic (β_2) terms of income were statistically significant across all model specifications, confirming the presence of an EKC relationship between per capita GDP and per capita CO_2 emissions within the sample. In all models, the income turning point lies at or above USD 23,000 in per capita GDP.[17] For instance, in model (D)—which includes all three explanatory variables representing structural change, technological advancement, and financial development—the relationship between per capita GDP and CO_2 emissions follows an EKC trajectory (**Figure 7**, EKC_0). Moreover, the results suggest that the decoupling phase, characterized by a decline in CO_2 emissions, begins once a country's per capita income surpasses USD 23,000 (**Figure 7**, TP_0).

consistent statistical data are available. Low-income countries were excluded due to data limitations, and because they are considered to be at an early stage of economic development, making a meaningful analysis of decoupling less feasible (Allard et al., 2018)

16) The Levin–Lin–Chu test (Levin et al., 2002) was applied to all variables, rejecting the null hypothesis of a unit root at the 1% significance level and confirming the stationarity of the panel data. In addition, the model was tested for homoscedasticity using the procedure proposed by Baum (2001), and the null hypothesis was likewise rejected at the 1% level. For detailed test results, see **<BOX 1>** 'Data and Descriptive Statistics.'

17) When the estimated coefficients β_1 and β_2 from models (A) through (E) in **Table 1** were applied to **equation (2),** the resulting income turning points ranged from USD 22,700 in model (B) to USD 27,900 in model (C), with an average of approximately USD 25,200.

[Figure 7] Relationship between per capita GDP and CO_2 emissions



Notes: 1) The solid black curve (EKC_0) represents the quadratic polynomial EKC estimated under model (D) in **Table 1**, while the vertical dotted black line indicates the corresponding income turning point (TP_0~USD 23,000).

2) The red dotted curve ($EKC_{0,KOR}$) depicts Korea's EKC path, derived by applying Korea's average observations ($\ln\overline{x}_{j,KOR}$) to the regression coefficients from model (D).

Source: Author's own estimations

Table 2 presents the results of the analysis conducted by splitting the sample into two groups based on income level. Both β_1 and β_2 were statistically significant in most model specifications. In the case of high-income countries, the estimation results under model (D) indicate an income turning point of approximately USD 20,000.[18] Given that the average per capita GDP (USD 30,000),[19] it is likely that the majority of countries in this group have already passed the turning point, with the decoupling process underway.

Meanwhile, the income turning point for middle-income countries, as estimated under model (D) in **Table 2**, exceeds USD 65,000—more than ten times the group's average per capita GDP of USD 6,400. This indicates that most middle-income countries remain in the early stage of the EKC. Absent structural changes and assuming all other conditions remain constant, economic growth in these countries is likely to continue to be accompanied by rising CO_2 emissions.

18) The results of the high-income subsample analysis in **Table 2** show that both the linear and quadratic terms of income were statistically significant only under models (A) through (D). Based on these estimates, the income turning points ranged from USD 18,000 to USD 28,700, with an average of approximately USD 21,300.

19) The average per capita GDP over the study period (2000–2020) was USD 22,400 for the full sample of 59 countries, USD 30,400 for the high-income group (36 countries), and USD 6,400 for the middle-income group (23 countries).

[Table 1] Inverted U-shaped relationship between economic growth and CO_2 emissions and panel regression results on key drivers of decoupling (Full sample)[1)2)]

	Dependent variable: $\ln CO2pc_{c,t}$				
Explanatory variable	(A)	(B)	(C)	(D)	(E)
Income level:					
$\ln GDPpc_{c,t}$	3.517***	3.089***	3.337***	3.091***	3.527***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
$(\ln GDPpc_{c,t})^2$	-0.173***	-0.154***	-0.163***	-0.154***	-0.173***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Changes in economic structure:					
$\ln mnf_{c,t-1}$ [3)]	0.291***				
	(0.000)				
$\ln ser_{c,t-1}$		-0.124***	-0.214***	-0.124***	-0.152***
		(0.000)	(0.000)	(0.000)	(0.002)
Technological advancements:					
$\ln tech_{c,t-1}$		0.0477***		0.0477***	0.0669***
		(0.000)		(0.000)	(0.000)
$\ln c.tech_{c,t-1}$			-0.0354***		
			(0.000)		
Financial development:					
$\ln fmd_{c,t-1}$				0.000549	
				(0.959)	
$\ln g.bond_{c,t-1}$					-0.00116
					(0.438)
Constant: β_0	-16.25***	-11.85***	-14.89***	-11.87***	-13.83***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Income turning point (TP)[4)] (per capita GDP, USD)	25,971	22,680	27,895	22,827	26,733
Fixed effects	Country	Country	Country	Country	Country
Number of observations	737	688	457	688	97
Number of countries	60	59	31	59	28
Chi-squared	98,398	108,738	36,722	106,113	670,556

Notes: 1) Results are based on the estimation of equation (3). *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively.
2) Values in parentheses indicate p-values.
3) This variable (log-transformed GDP share of manufacturing %) is included to cross-validate the effect and direction of structural changes, based on the hypothesis that a higher manufacturing share is associated with greater CO_2 emissions.
4) Turning points are calculated by applying the estimated coefficients (β_1 and β_2) to **equation (2).**

Source: Author's own estimations

[Table 2] Inverted U-shaped relationship between economic growth and CO_2 emissions and panel regression results on key drivers of decoupling (by income group)[1)2)]

Dependent variable: $\ln CO2pc_{c,t}$

Explanatory variable	(A)	(B)	(C)	(D)	(E)	(A)	(B)	(C)	(D)	(E)
	High-income group					**Middle-income group**				
Income level:										
$\ln GDPpc_{c,t}$	3.644***	2.751***	2.402***	2.792***	3.689	2.002***	2.296***	2.120***	2.328***	2.223**
	(0.000)	(0.000)	(0.000)	(0.000)	(0.108)	(0.000)	(0.000)	(0.000)	(0.000)	(0.012)
$(\ln GDPpc_{c,t})^2$	-0.186***	-0.140***	-0.117***	-0.141***	-0.177	-0.0823***	-0.102***	-0.0924***	-0.105***	-0.0918*
	(0.000)	(0.000)	(0.000)	(0.000)	(0.109)	(0.000)	(0.000)	(0.000)	(0.000)	(0.078)
Changes in economic structure:										
$\ln mnf_{c,t-1}$ [3)]	0.449***					-0.0612				
	(0.000)					(0.144)				
$\ln ser_{c,t-1}$		-0.143***	-0.204***	-0.145***	-0.146***		-0.0664***	-0.0747**	-0.0653***	0.0750
		(0.000)	(0.000)	(0.000)	(0.006)		(0.004)	(0.013)	(0.004)	(0.367)
Technological advancements:										
$\ln tech_{c,t-1}$		0.0493***		0.0491***	0.177***		0.0306***		0.0297***	0.00757
		(0.000)		(0.000)	(0.000)		(0.002)		(0.005)	(0.511)
$\ln c.tech_{c,t-1}$			-0.0552***					0.0325***		
			(0.000)					(0.001)		
Financial development:										
$\ln fmd_{c,t-1}$				-0.0478***					0.0277*	
				(0.003)					(0.086)	
$\ln g.bond_{c,t-1}$					-0.00237*					-0.00614
					(0.090)					(0.122)
Constant: β_0	-15.90***	-9.107***	-9.971***	-9.294***	-12.77	-8.970***	-9.417***	-8.378***	-9.571***	-10.46***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.286)	(0.000)	(0.000)	(0.000)	(0.000)	(0.006)
Income turning point (TP)[4)] (per capita GDP, USD)	17,956	18,490	28,709	19,945	-	191,534	77,258	95,977	65,233	181,288
Fixed effects	Country	Country	Country	Country	Country	Country	Country	Country	Country	Country
Number of observations	503	452	349	452	59	234	236	108	236	38
Number of countries	37	36	25	36	15	23	23	6	23	13
Chi-squared	16,813	16,010	8,555	16,208	12,935	44,734	51,629	27,871	51,434	126,009

Notes: 1) Results are based on the estimation of equation (3). *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively.
2) Values in parentheses indicate p-values.
3) This variable (log-transformed GDP share of manufacturing %) is included to cross-validate the effect and direction of structural changes, based on the hypothesis that a higher manufacturing share is associated with greater CO_2 emissions.
4) Turning points are calculated by applying the estimated coefficients (β_1 and β_2) to **equation (2).**

Source: Author's own estimations

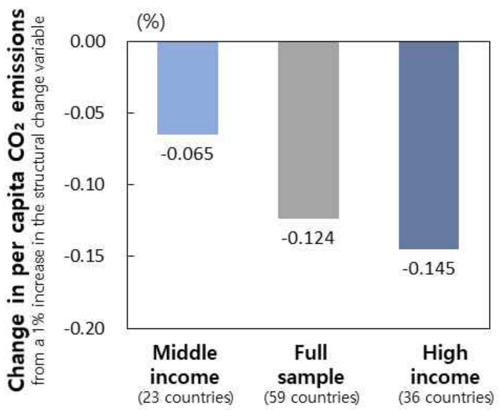
3.2 Effects of Changes in Economic Structure

Across all model specifications in **Table 1**, the regression coefficient for $\ln ser_{c,t-1}$ was statistically significant and negative. This result implies that a structural transition toward service industries, which are globally competitive, contributes positively to the decoupling of economic growth from CO_2 emissions. Specifically, estimation results from model (D) suggest that a 1% increase in the export share of services is associated with an average reduction of 0.12% in per capita CO_2 emissions.[20] Such structural changes appear to enhance the decoupling process by shifting the EKC downward (**Figure 5**, $EKC_0 \rightarrow EKC\_$).

The contribution of structural change to decoupling was particularly pronounced in high-income countries, while its effect was approximately half as strong in middle-income countries. According to the results of model (D) in **Table 2**, a 1% increase in the export share of services (%) was associated with an annual reduction in per capita CO_2 emissions of up to 0.15% in high-income countries. In contrast, the same structural shift corresponded to a reduction of only about 0.07% in middle-income countries (see **Figure 8**).

These findings imply that most high-income countries—having already entered the decoupling phase—are now experiencing absolute decoupling, whereby per capita CO_2 emissions decline year-over-year. This trend appears to be driven by the continued transformation of their industrial structure toward globally competitive, service-oriented sectors. By contrast, middle-income countries, which have yet to reach the income turning point, appear to remain in the stage of weak decoupling, in which emissions continue to rise but at a slower pace, partially due to the gradual expansion of the service sector.

[Figure 8] Estimated effects of structural change on CO_2 emissions, by income group



Note: 1) For the middle- and high-income groups, the estimators of $\ln ser_{c,t-1}$ from model (D) in **Table 2**. For the full sample (59 countries), the result is drawn from model (D) in **Table 1**.
Source: Author's own estimations

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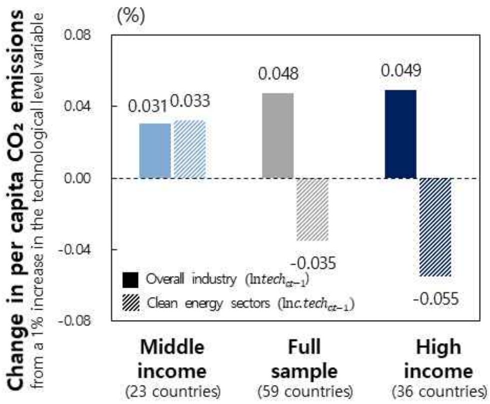
20) During the 20-year period from 2000 to 2019, per capita CO_2 emissions and the export share of services ($\ln ser_{c,t-1}$) declined at average annual rates of 0.29% and 1.02%, respectively, across the full sample of 59 countries. This concurrent decline may imply a correlation between the shift toward service-oriented economies and reductions in per capita CO_2 emissions.

3.3 Effects of Technological Advancements

As shown in **Table 1**, the regression coefficient of $\ln tech_{c,t-1}$ was positive across all model specifications. Specifically, a 1% increase in the number of patent applications per billion USD of GDP was associated with a 0.05–0.07% increase in per capita CO_2 emissions. This suggests that technological advancements, rather than facilitating emission reductions and promoting decoupling, may have reinforced carbon-intensive economic expansion through a scale effect.[21] In addition, the results presented in **Table 2** indicate that this emission-increasing effect of technological progress was observed in both high- and middle-income countries. These results suggest that, to date, innovation efforts in general have not been effectively directed toward achieving decarbonization objectives.[22]

Model (C) in **Table 2** estimates the impact of advancements in low-carbon technologies, proxied by the number of international clean energy patent applications per billion USD of GDP ($\ln c.tech_{c,t-1}$). The results indicate that the effect of innovation in clean energy technologies on per capita CO_2 emissions differs by income group. In high-income countries, a 1% increase in clean energy technology intensity was associated with a 0.06% reduction in per capita CO_2 emissions. This suggests that these countries are not only developing clean energy technologies but also deploying them effectively to mitigate CO_2 emissions (see **Figure 9**).

[Figure 9] Estimated effects of technological advancements on CO_2 emissions, by income group



Note: 1) For the middle- and high-income groups, the estimators of $\ln tech$ and $\ln c.tech$ from models (D) and (C) in **Table 2**. For the full sample (59 countries), the result is drawn from models (D) and (C) in **Table 1**.

Source: Author's own estimations

On the other hand, in middle-income countries, advancements in clean energy technologies were associated with an increase in per capita CO_2 emissions (see **Figure 9**). This result, which runs contrary

21) This result can be interpreted in light of the explanation provided by Stern (2004): although cleaner and more efficient technologies reduce CO_2 emissions per unit of output, total emissions may still rise if such technologies significantly boost overall output by accelerating economic growth.

22) In models (B) and (D) of **Table 2**, the regression coefficient tended to be higher for high-income countries (0.05) than for middle-income countries (0.03), suggesting that technological advancements may have contributed more to the increase in CO_2 emissions in high-income economies.

to theoretical expectations, may reflect a misalignment between the economic structure and low-carbon transition stage of middle-income countries and the pace of clean energy technology development. It may also stem from institutional and infrastructural barriers that hinder the effective adoption and deployment of new clean and low-carbon technologies, thereby sustaining a high reliance on carbon-intensive activities and driving continued growth in CO_2 emissions.

3.4 Effects of Financial Development

As shown in **Tables 1 and 2**, the effect of financial development on decoupling differed by income group and was statistically significant only when the analysis was conducted separately for each group. In high-income countries, a 1% increase in the Financial Markets Development (FMD) index was associated with a 0.05% reduction in per capita CO_2 emissions, suggesting that the expansion of financial markets has effectively contributed to decoupling in the real economy. This likely reflects the fact that most high-income countries, having surpassed the income turning point, have long pursued structural shifts toward cleaner and more efficient industries, underpinned by the overall maturity of their economic and institutional systems.

In contrast, in middle-income countries, a 1% increase in the FMD index was associated with a 0.03% increase in per capita CO_2 emissions. As highlighted in previous studies (e.g., Svirydzenka, 2016), financial development at early stages of economic growth tends to promote quantitative expansion rather than structural transformation. In many middle-income countries that are still in the scale effect phase—where growth is primarily driven by industrialization—financial market development can lead to increased capital flows into carbon-intensive sectors. This, in turn, may accelerate economic growth in tandem with an increase in CO_2 emissions, thereby delaying the onset of decoupling pattern.

These findings suggest that financial development, on its own, does not directly contribute to reducing CO_2 emissions. Its impact on decoupling is highly dependent on the structural features of the real economy—such as industrial composition, energy efficiency, and the level of technological advancement. Therefore, in countries that have not yet reached the stage of absolute decoupling, expanding financial markets must be accompanied by targeted policy efforts to align capital allocation with climate goals—for example, through the promotion of green finance (Javid & Sharif, 2016).

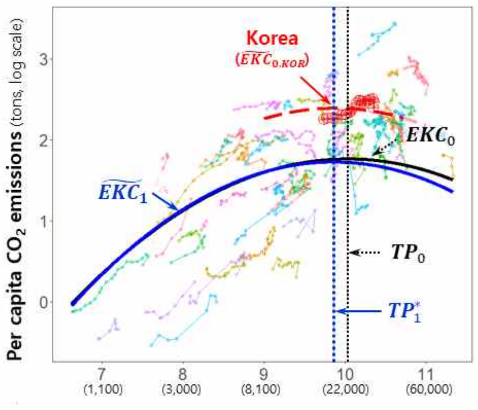
In this study, to specifically evaluate the effect of green finance, a separate model —model (E) in **Table 2**—was estimated, replacing the FMD index with a green finance variable, defined as green bond issuance relative to GDP ($\ln g.bond_{c,t-1}$). The findings suggest that in high-income countries, the expansion of the green finance market is associated with a modest yet statistically significant reduction in CO_2 emissions. In contrast, no statistically significant relationship was found between green bond issuance and CO_2 emission reductions in middle-income countries.[23]

3.5 Robustness Tests

Table 3 presents the estimation results from the direct effect model—equation (4)—which incorporates the influence of key explanatory variables on both the curvature of the EKC and the income turning point. First, the linear and quadratic income terms remain statistically significant across all model specifications, reaffirming the robustness of the EKC pattern. Structural change ($\ln ser_{c,t-1}$), clean technology ($\ln c.tech_{c,t-1}$), and green finance ($\ln g.bond_{c,t-1}$) also exhibit consistent and statistically significant effects, reinforcing the findings from the baseline model.

Under model (D) in **Table 3**, the estimated income turning point is USD 19,000—lower than the USD 23,000 turning point derived in **Table 1**, where key variables were specified as indirect drivers of decoupling. This suggests that structural changes, technological advances,[24] and financial development may help lower the turning point at which decoupling begins ($TP_0 \rightarrow TP_1^*$), while accelerating the pace of decoupling beyond that threshold ($EKC_0 \rightarrow \widetilde{EKC}_1$) (see **Figure 10**).

[Figure 10] Robustness of the EKC pattern: Comparison between baseline and direct effect models



Notes: 1) The solid black curve and the dotted black line represent the estimated EKC and the income turning point from the baseline model (as shown in **Figure 7**).
2) The solid blue curve and the dotted blue line illustrate the EKC and the turning point under model (D) in **Table 3**, using only statistically significant variables.
3) The dotted red curve represents the EKC for Korea, using the estimates of model (D) in **Table 3**.

Source: Author's own estimations

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23) This result may be attributable to the relatively low level of green bond issuance activity in middle-income countries. The unbalanced panel data, in particular, used to estimate model (E) for this group contains significantly more missing time-series observations compared to the high-income country sample. The limited data availability may have hindered the detection of a statistically significant green finance effect, as implied by the large χ^2 statistic.

24) However, the estimation results from models (B) to (E) in **Table 3** show that the effect of technological advancements varies in sign and lacks statistical significance in several specifications. Unlike the clear emission-increasing effect found in **Table 1**, these results suggest no direct or consistent impact on the EKC's shape or turning point.

[Table 3] Robustness check: Panel regression results using the direct effect model (equation (4)) on the EKC and turning point dynamics (Full sample)[1)2)]

	Dependent variable: $\ln CO2pc_{c,t}$				
Explanatory variable	(A)	(B)	(C)	(D)	(E)
Income level:					
$\ln GDPpc_{c,t}$	3.655***	3.346***	3.102***	3.353***	3.953***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
$(\ln GDPpc_{c,t})^2$	-0.186***	-0.166***	-0.151***	-0.167***	-0.179***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Changes in economic structure:					
$\ln mnf_{c,t-1} \times (\ln GDPpc_{c,t})^2$ [3)]	0.000523***				
	(0.000)				
$\ln ser_{c,t-1} \times (\ln GDPpc_{c,t})^2$		-0.000991***	-0.00243***	-0.00100***	-0.000581*
		(0.000)	(0.000)	(0.000)	(0.077)
Technological advancements:					
$\ln tech_{c,t-1} \times (\ln GDPpc_{c,t})^2$		-0.0000837**		-0.0000649	0.000969***
		(0.027)		(0.122)	(0.000)
$\ln c.tech_{c,t-1} \times (\ln GDPpc_{c,t})^2$			-0.000337***		
			(0.000)		
Financial development:					
$\ln fmd_{c,t-1} \times (\ln GDPpc_{c,t})^2$				0.000132	
				(0.244)	
$\ln g.bond_{c,t-1} \times (\ln GDPpc_{c,t})^2$					-0.0000476**
					(0.000)
Constant: β_0	-15.74***	-14.39***	-13.60***	-14.38***	-17.26***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Income turning point (TP*)[4)] (per capita GDP, USD)	19,920	19,740	18,648	19,106	61,052
△	(-6,051)	(-2,940)	(-9,247)	(-3,721)	(+34,320)
Fixed effects	Country	Country	Country	Country	Country
Number of observations	736	687	457	687	97
Number of countries	60	59	31	59	28
Chi-squared	99,535	101,425	59,073	102,732	794,821

Notes: 1) Results are based on the estimation of equation (4). *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively.
2) Values in parentheses indicate p-values.
3) This variable (log-transformed GDP share of manufacturing %) is included to cross-validate the effect and direction of structural changes, based on the hypothesis that a higher manufacturing share is associated with greater CO_2 emissions.
4) Turning points are calculated by applying the estimated coefficients (β_1, β_2, and γ_{2j}) and the average values of each variable ($\ln \bar{x}_j$) to **equation (5).**
5) Difference between the two income turning points calculated using **equation (5)** and **equation (2),** respectively, based on the same set of variables (i.e., TP* in **Table 3** minus TP in **Table 1**). A negative value indicates that the inclusion of an additional variable lowers the income turning point.
Source: Author's own estimations

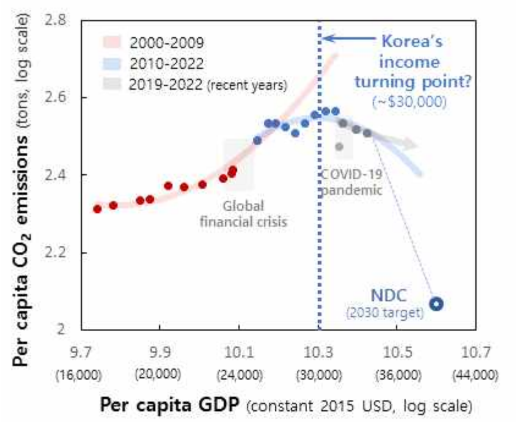
Ⅲ. Decoupling Conditions in Korea: Challenges and Strategic Responses

This section examines Korea’s progress in decoupling, drawing on the empirical findings from the regression analysis presented in the previous chapter. It reviews the current enabling conditions and limitations for achieving decoupling, with a focus on key contributing factors —structural change, technological advancement, and financial development. The section concludes with a discussion of policy implications for designing a decoupling strategy tailored to Korea.

1. Korea's Stage of Decoupling

Prior to the global financial crisis, Korea had an economic structure in which per capita CO_2 emissions increased in a linear or accelerative fashion in tandem with income growth. However, since the crisis, a new pattern has been observed in which per capita CO_2 emissions increase at a slower pace than per capita GDP.[25] Korea's per capita CO_2 emissions, which peaked in 2018 and plateaued since then, recently began a slight downward trend. When a quadratic trend line is fitted to the relationship between Korea's per capita GDP and per capita CO_2 emissions since 2010, the income turning point is estimated at around USD 30,000 (dotted blue line, **Figure 11**).[26] Given that its per capita GDP reached approximately USD 34,000 in 2023,[27] Korea now appears to be at the threshold of transitioning from relative to absolute decoupling.

[Figure 11] Relationship between per capita GDP and per capita CO_2 emissions in Korea



Notes: 1) The red line represents the quadratic trend line estimated for the pre-global financial crisis period (2000–2009).
2) The blue inverted U-shaped curve corresponds to the post-crisis period (2010–2020), with the vertical dotted line indicating the estimated income turning point. The solid gray line represents the trend for the most recent three years (2019–2022), excluding temporary shocks such as the COVID-19 pandemic.

Sources: World Bank; author's own estimations

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25) Threshold regression analysis (2000–2018) identified the global financial crisis (2008–2009) as a structural break, after which the growth rate of CO_2 emissions slowed notably. Based on this, the sample period was divided into pre- and post-crisis phases (2000–2009 and 2010–2022, respectively) for analysis (**Figure 11**).

26) The trend line is defined by the function: $y = -2.193x^2 + 45.165x - 235.03$. The income turning point was calculated using equation (2): TP = exp (-45.165/ (-2.193 x 2)) ≃ exp (10.298) ≃ 29.673.

27) World Bank statistics, based on constant 2015 prices.

However, it remains uncertain whether the recent decline in CO_2 emissions will evolve into a stable and sustained trend. Without fundamental shifts in the economy, Korea's progress in reducing per capita CO_2 emissions is likely to remain limited. Key structural changes—such as expanding the share of high value-added services, transitioning to a cleaner energy mix with greater reliance on renewables, scaling up the deployment of clean and low-carbon technologies, and broadening the uptake of green finance—are essential. In the absence of such transformations, future per capita CO_2 emissions may follow a flatter trajectory than the estimated EKC pattern (i.e., solid gray line, **Figure 11**),[28] stagnate near the income turning point for an extended period.

2. Changes in Economic Structure

As shown in the previous section, in many other countries, the decoupling trend has tended to strengthen with the expansion of globally competitive service industries. In contrast, in Korea, the growth of the service sector does not yet appear to have made a significant contribution to decoupling.

While Korea's economy and industrial structure have generally followed a similar trajectory to those of other countries over the past two decades—with increasing employment and value-added shares in the service sector (**Figure 12**)—the positive impact of this shift on reducing per capita CO_2 emissions[29] has been less pronounced in Korea than in other high-income countries. In 2021, per capita CO_2 emissions from the service sector in Korea reached 1.87 tons, largely due to indirect emissions.[30][31] This marks a 27% increase from 2000 (1.47 tons). By contrast, in the United States, CO_2 emissions from the service sector fell by

28) This curve is based on post-2019 data (excluding 2020, the peak of the pandemic), and exhibits a flatter slope compared to the EKC observed since 2010 (blue curve, **Figure 11**).

29) The IEA publishes CO_2 emission statistics based on total emissions from final energy consumption, calculated by applying emission factors to each energy source. To facilitate sectoral comparisons—across manufacturing, services, transport, and buildings—the IEA also provides various carbon intensity indicators, such as emissions per capita, per employee, per unit of floor area, and per unit of value-added. In this study, per capita CO_2 emissions are used as the population-based intensity metric to ensure consistency with the analysis.

30) In **Table 4**, CO_2 emissions from the services sector include both direct emissions—from the use of coal, oil, natural gas, biofuels, and other fuels—and indirect emissions resulting from the consumption of purchased electricity and heat.

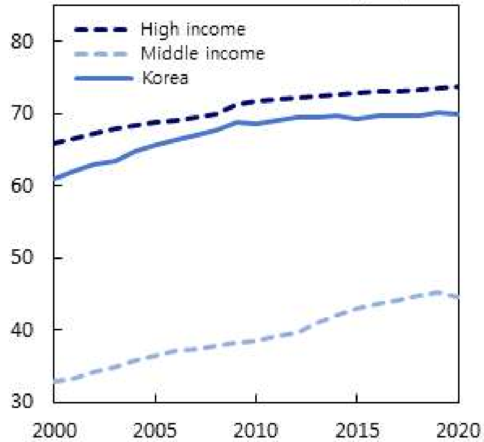
31) Between 2009 and 2019, electricity consumption by the service and other sectors increased by 22.4%, from 121 TWh to 148 TWh (Korea Electric Power Statistics, 2023). In this context, Roberts et al. (2021) questioned the common perception of the service sector as "emission-light," arguing that its total emissions would more than double if indirect emissions associated with labor and energy use were fully accounted for.

30% (from 3.69 to 2.29 tons), despite continued growth in its GDP share over the same period[32] (see **Table 4**).

[Figure 12] Trends in employment, value-added, and export shares of services

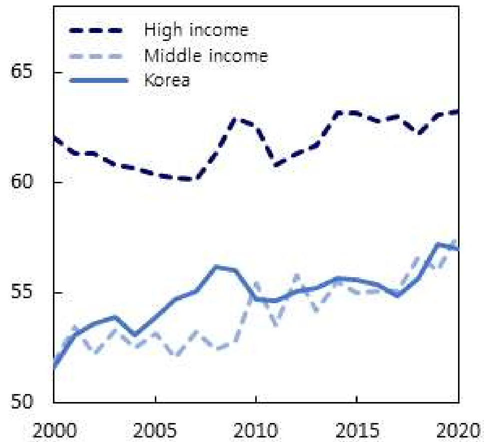
Employment share of services

(%, relative to the total number of employed persons)



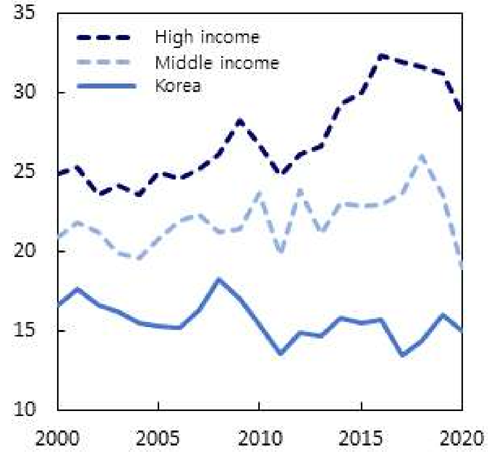
Value-added share of services

(%, relative to GDP)



Export share of services

(%, relative to total exports)



Sources: KOSIS; World Bank

[Table 4] Per capita CO_2 emissions from service sector in Korea and major advanced economies

	Total emissions by year[1] (tons, per capita)			Change[2] (2000–2021)		
	2000	2010	2021	Total (①+②)	① Direction emissions	② Indirect emissions
▪ Korea	**1.47**	**2.15**	**1.87**	**0.40**	**-0.41**	**0.81**
▪ G7	**1.65**	**1.52**	**1.14**	**-0.52**	**-0.13**	**-0.39**
Canada	2.06	1.66	1.44	-0.62	-0.15	-0.48
France	0.67	0.70	0.47	-0.20	-0.14	-0.07
Germany	1.61	1.55	1.00	-0.61	-0.15	-0.47
Italy	0.77	0.95	0.69	-0.09	0.02	-0.10
Japan	1.39	1.42	1.43	0.04	-0.22	0.26
UK	1.36	1.12	0.64	-0.73	-0.10	-0.63
U.S.	3.69	3.22	2.29	-1.40	-0.17	-1.23

Notes: 1) Total CO_2 emissions divided by the number of inhabitants.
2) Includes both direct emissions from the use of coal, oil, natural gas, biofuels, and other fuels, and indirect emissions from the consumption of purchased electricity and heat.

Source: IEA

32) Based on World Bank data, the value-added share of the U.S. service sector rose from 72.8% in 2000 to 76.4% in 2021, marking a 3.6%p increase.

Unlike in other advanced economies, Korea exhibits a coupling between the expansion of the service sector and rising CO_2 emissions. This appears to be largely attributable to the nature of Korea's service sector growth, which has been led by labor-intensive, low value-added services rather than high value-added, low-carbon services. While the service sector's employment share in Korea (70% in 2020) is comparable to the high-income country's average (73.7%), its value-added share (57.0%) aligns more closely with the average for middle-income countries (57.8%). Furthermore, in terms of export share, Korea's service sector (15.0%) lags even behind the middle-income country average (19.0%) (see **Figure 12**).

To ensure that the expansion of Korea's service sector contributes positively to decoupling, targeted policy efforts are needed to shift resources toward low-carbon, high value-added service industries—such as ICT-based carbon emissions monitoring, and low-carbon green transportation—while curbing the excessive growth of labor-intensive service segments.[33] In Korea, the recently launched "Green Digital Ecosystem" initiative[34] is a notable example of service-led structural transformation for decoupling. The project aims to develop carbon data services, including carbon accounting for the manufacturing sector, as well as AI-based systems for managing the supply and demand of renewable energy. In addition, to foster green transportation and strengthen port logistics competitiveness, the government is encouraging private investment in eco-friendly shipbuilding and establishing green fuel supply hubs across the country.[35]

33) The Financial Services Commission (FSC) attributes the weakness of Korea's service sector primarily to the high proportion of small, self-employed businesses concentrated in unskilled, labor-intensive, and low value-added trades such as wholesale and retail, food service, and hospitality. To enhance the sector's competitiveness, the government plans to implement measures that (1) support marginal small businesses in exit planning and career transitions, and (2) assist promising firms in expanding their services into global markets and online platforms (Government of Korea, Comprehensive Measures for Small Businesses and the Self-Employed: Fresh Start–Hope Project, interagency press release, July 3, 2024).

34) For further details, see "Achieving Carbon Neutrality through Digital Transformation: DX/GX (Digital Transformation/Green Transformation)-based Carbon Neutrality Strategy" (interagency press release, November 23, 2023). To enhance its impact, the project could be complemented by a financing program that supports the growth of high-productivity service industries through technology-based financial support.

35) For further information, see the press release titled "Expanding Economic Territory through Leadership in Global Aviation, Maritime Transportation, and Logistics" (Ministry of Land, Infrastructure and Transport; Ministry of Oceans and Fisheries, March 7, 2024).

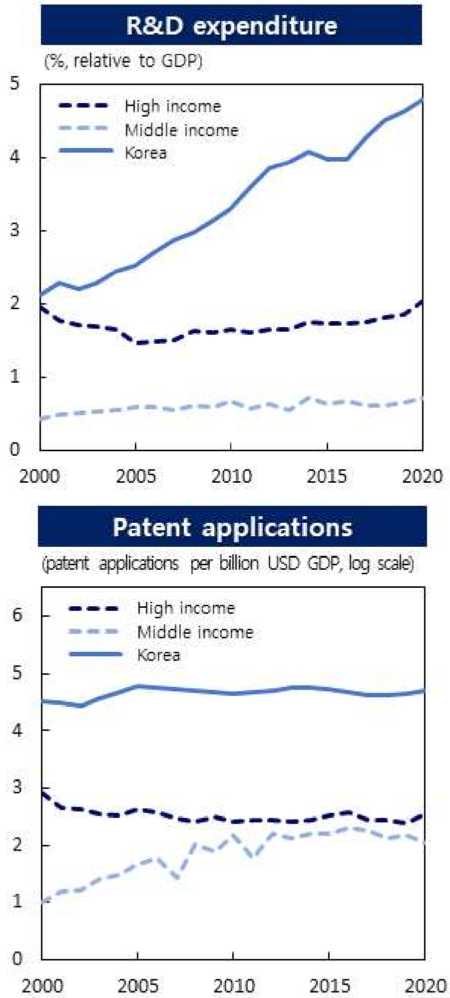
3. Technological Advancements

As demonstrated in the regression analysis, clean energy innovation does contribute to decoupling; however, broader technological progress across industries can intensify the scale effect, ultimately offsetting these gains and increasing CO_2 emissions by all. In Korea, technological advancements may appear to have contributed to slowing the pace of emissions growth by improving productivity and energy efficiency. Nevertheless, due to Korea's heavy reliance on manufacturing and a fossil fuel-intensive energy mix, the scale effect of technological progress still seems to outweigh its decoupling impact.

Korea is widely recognized for having achieved sustained economic growth through technological innovation, primarily driven by its manufacturing sector. In 2020, R&D expenditure accounted for 4.8% of GDP—more than twice the average for high-income countries (2.0%)—and the number of industrial patent applications ranked among the highest globally (**Figure 13**). Such targeted investment in technological innovation has strengthened Korea's manufacturing competitiveness and brought production energy efficiency in line with global best practices.[36)]

Nonetheless, Korea's long-standing manufacturing-driven growth strategy—marked by a persistent reliance on high-emission industries such as steel, petrochemicals, cement, and nonmetallic minerals—has been accompanied by a steady increase in economy-wide CO_2 emissions.[37)]

[Figure 13] Trends in R&D expenditure and patent application



Source: World Bank

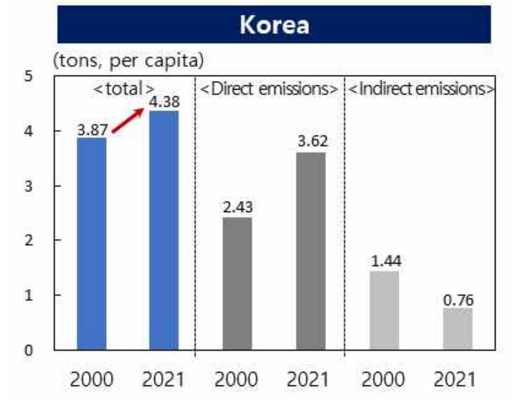
36) According to the IEA's Energy End-uses and Efficiency Indicators database, the energy intensity of Korean manufacturing (MJ/USD, PPP 2015) declined to 52.4 in 2021 (2000 = 100), a faster drop than in G7 countries (to 78.0) and IEA members overall (to 58.2).

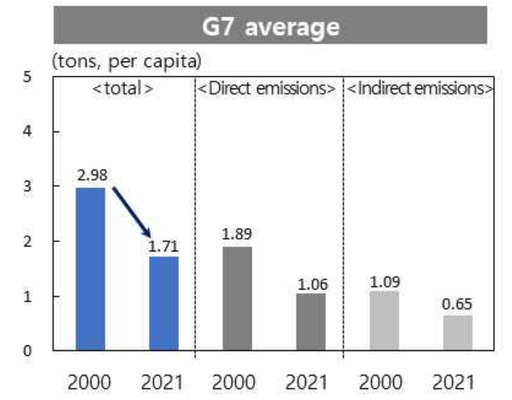
37) As of 2019, the value-added shares of manufacturing and carbon-intensive industries (steel, chemicals, oil refining, cement, etc.) in Korea were 28.4% and 8.4%, nearly twice the G5 averages (14.4% and 4.2%, respectively) (Federation of Korean Industries, 2021).

Between 2000 and 2021, Korea's per capita indirect CO_2 emissions from manufacturing fell significantly—from 1.44 to 0.76 tons—due to improved energy efficiency (see **Figure 14**). However, the sector's total emissions increased from 3.87 to 4.38 tons per capita over the same period. In contrast, total manufacturing emissions in G7 countries declined from 2.98 to 1.71 tons, driven by reductions in both direct and indirect emissions.

Korea records a high number of international patent applications in clean and renewable energy technology,[38] but these advances have yet to lead to meaningful decoupling, as dependence on fossil fuels remains high. As of 2022, renewables accounted for just 7.4% of Korea's electricity generation—well below the G7 average of 36.8%—while fossil fuels made up 62.9%, in sharp contrast to the G7 average of 44.7%. Furthermore, between 2010 and 2022, Korea's reduction in the fossil fuel share (△4.2%p) was less than half the G7 average (△9.0%p), indicating that Korea's energy transition remains markedly slower than in other advanced economies (**Table 5**).

[Figure 14] Changes in per capita CO_2 emissions[1)2)] from manufacturing in Korea and G7 countries[3)]





Notes: 1) Total CO_2 emissions from manufacturing divided by population.
2) Includes both direct emissions from production activities (e.g., combustion of coal, natural gas, and biofuels) and indirect emissions from the consumption of purchased electricity and heat.
3) United States, United Kingdom, Japan, Canada, France, Germany, and Italy.

Source: IEA

38) The number of international patent family (IPF) applications in clean energy technology filed by Korean residents reached 2.14 per billion USD of GDP in 2020—over four times the average for high-income countries (0.49). This indicator (*c.tech*) is used as an explanatory variable in this study.

[Table 5] Electricity generation by source[1] in Korea, G7, and World

	Renewable sources (%)[2]			Fossil fuels (%)[3]		
	2000	2010	2021	2000	2010	2021
▪ G7	**16.9**	**20.5**	**36.8**	**55.0**	**53.7**	**44.7**
Canada	60.6	61.3	69.0	27.3	23.2	17.5
France	12.7	13.6	24.2	9.3	9.9	12.4
Germany	6.2	16.8	43.7	63.2	59.4	48.9
Italy	18.8	25.8	35.6	80.7	73.3	63.3
Japan	9.2	9.1	21.7	58.4	63.6	69.0
UK	2.7	6.9	42.0	74.5	76.3	41.6
U.S.	8.2	10.1	21.4	71.6	70.3	60.3
▪ World	**18.4**	**19.6**	**29.4**	**64.5**	**67.2**	**61.0**
▪ Korea	**1.4**	**1.3**	**7.4**	**60.7**	**67.1**	**62.9**

Notes: 1) Includes renewables, fossil fuels, and nuclear power.
2) Share of solar, wind, tidal, hydro, and biomass energy in total electricity (GWh).
3) Share of coal, oil, natural gas, shale oil, and peat in total electricity (GWh).
Source: IEA

This implies that, for Korea to achieve decoupling, its technological innovation policy must broaden its focus beyond productivity gains and improvements in energy and resource efficiency, toward the large-scale deployment of clean and low-carbon technologies across the manufacturing sector.[39] To this end, the government should identify and eliminate regulatory barriers to the adoption of clean energy technologies and infrastructure,[40] strengthen incentives for firms to adopt best available technologies (BAT),[41] and facilitate financing for related investment projects.[42]

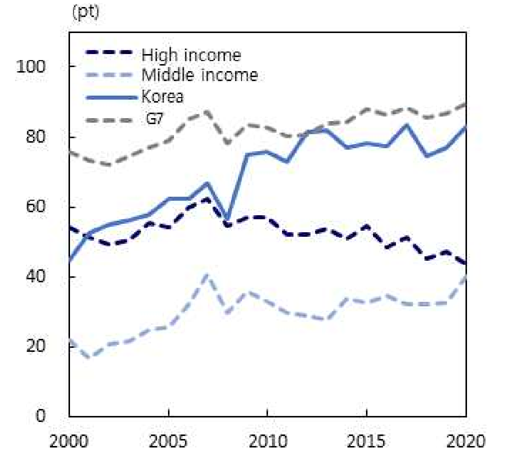
4. Financial Development

The analysis in the previous section shows that while financial development promotes decoupling in high-income countries, it tends to increase CO_2 emissions in middle-income countries by amplifying the scale effect. In Korea's case, although the level of financial development is comparable to that of advanced economies, it remains unclear whether the financial system has effectively supported decoupling. This is due to the manufacturing-heavy industrial structure and limited financial support for investments needed in the low-carbon transition.[43]

39) To accelerate the low-carbon transition of Korea's industry and energy sectors and foster new growth engines, the government has increased support for low-carbon technologies—such as hydrogen-based steelmaking and eco-friendly alternative materials—and promoted the deployment of CCUS, clean hydrogen, and renewable energy systems ("Vision and Strategy for Carbon Neutrality Transition of Industry and Energy," interagency press release, December 10, 2021).
40) This could include measures such as expanding tax incentives and subsidies for alternative energy sources that reduce fossil fuel demand, easing restrictions on production facilities and sites that hinder the adoption of renewable technologies, and establishing standards and certification procedures for environmentally friendly new technologies.
41) Efforts in this direction could include improving the emissions trading system and rationalizing carbon pricing to encourage wider adoption of BAT among carbon credit–eligible firms, as well as providing tax breaks or grants to support economically viable investment in new technology development.
42) A good example of this effort is the "Future Environmental Industry Investment Project" (Ministry of Environment, March 2024).
43) Since around 2020, domestic banks (including financial holding companies) have declared carbon neutrality targets and begun efforts to reduce their financed emissions. However, these

Amid the rapid economic growth, Korea's financial system has also reached a level where its credit capacity is comparable to that of advanced economies. The financial market depth score rose from 45 in 2000 to 83 in 2020, narrowing the gap with the G7 average of 90 (see **Figure 15**). However, given Korea's industrial structure—heavily concentrated in carbon-intensive manufacturing—and the corresponding concentration of credit in these sectors,[44] financial development over the past decades may have contributed more to increasing CO_2 emissions than reducing them.

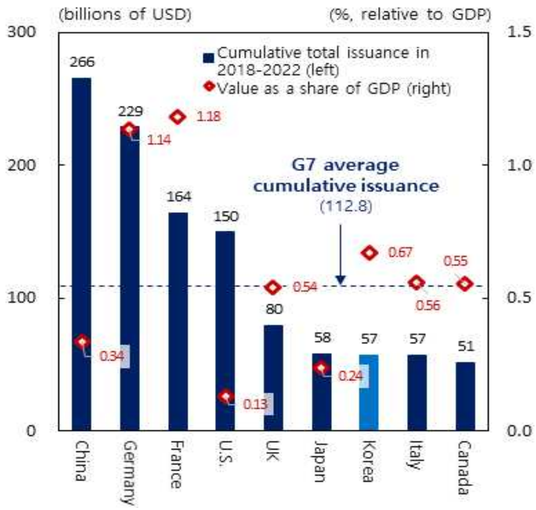
[Figure 15] Financial market depth index[1)]



Note: 1) Raw data used for the variable $\ln fmd_{c,t}$ in the regression analysis. The G7 figure represents the average across the United States, United Kingdom, Japan, Canada, France, Germany, and Italy.
Source: IMF

Meanwhile, green bond issuance for decarbonization and sustainability projects has increased in recent years, but it remains far below the level needed to support Korea's transition to carbon neutrality.[45] Between 2018 and 2022, Korea's cumulative green bond issuance totaled USD 57.4 billion—just half the G7 average of USD 112.8 billion during the same period (see **Figure 16**).

[Figure 16] Cumulative green bond issuance by county



Note: 1) Bars represent the cumulative issuance of green bonds by governments, corporations, and financial institutions during the period 2018–2022; dots indicate the issuance as a percentage of GDP.
Source: IMF

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efforts have yet to gain full traction, due to structural limitations such as high exposure to the manufacturing sector and the lack of green finance infrastructure (Park et al., 2024).

44) As of 2023, the manufacturing sector accounted for 38.0% of domestic banks' business credit exposure, significantly exceeding its share of value-added in the economy (25.6% as of 2022) (Park et al., 2024).

45) According to Song (2023), achieving carbon neutrality by 2050 will require cumulative investment of up to KRW 2,097 trillion. Meanwhile, Boston Consulting Group (BCG) estimates that decarbonizing Korea's high-emission industries will require nearly KRW 1,000 trillion (USD 770 billion) by 2030, and an additional KRW 2,600–3,900 trillion (USD 2–3 trillion) between 2030 and 2050 (Choi, 2023).

To support decoupling, the domestic financial sector must be equipped to meet investment needs not only for the growth of green industries but also for the decarbonization of traditional manufacturing sectors. This first requires the timely creation of enabling conditions to ensure an adequate supply of green finance. In Korea, having already laid the groundwork for green finance through initial institutional arrangements, the government and supervisory authorities must now move swiftly to implement concrete measures—such as revising regulations, enhancing incentive schemes, and upgrading supporting infrastructure—to scale up market-based green capital flows. In parallel, financial institutions should develop and implement clear strategies to reduce their financed emissions and align their portfolios with the low-carbon transition.

Moreover, a transition finance framework tailored to Korea's industrial structure must be established to complement existing green finance initiatives. Transition finance[46) is intended to support the phased decarbonization of hard-to-abate sectors—those that are technically or economically challenging to decarbonize in the short term. Its focus lies on activities that fall outside the scope of current green taxonomies but can significantly contribute to reducing the emissions intensity of the overall economy. In Korea, such hard-to-abate sectors remain central to the industrial base, yet financing for their restructuring and for long-term investment in low-carbon transition technologies is not sufficiently supported under the current green finance framework. This underscores the urgency of building a credible transition finance system that aligns with Korea's economic structure and supports a more inclusive pathway toward net-zero.

In Japan and China, authorities are taking concrete steps to operationalize transition finance. Other jurisdictions, including Singapore[47) and the EU,[48) are also working to develop frameworks that

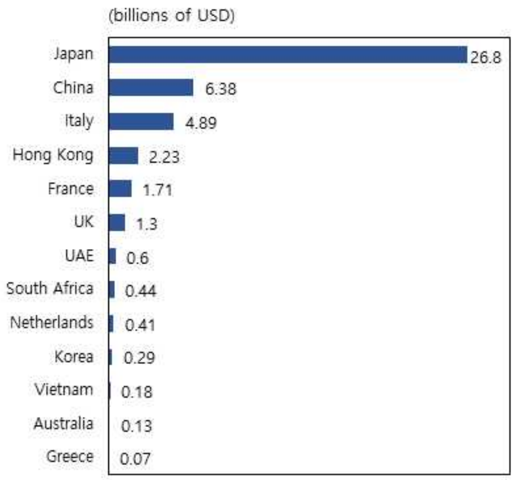
46) The OECD (2022) defines transition finance as financing that supports the "process of becoming sustainable" of carbon-intensive industries, including industries where it is difficult to reduce emissions, and the electricity generation sector, rather than supporting activities that are already sustainable (consistent with the taxonomy).

47) In the 2023 edition of the "Singapore-Asia Taxonomy for Sustainable Finance," the Monetary Authority of Singapore (MAS) introduced a "traffic light" classification system for economic activities—green, amber, and red. Under this system, transition financing is made available to amber activities, defined as those not yet aligned with the 1.5°C pathway but on a credible path toward decarbonization or facilitating emissions reductions.

48) In 2023, the European Commission (EC) identified four categories of investment that support the transition to net zero while avoiding carbon lock-in: ① investments in portfolios tracking EU Climate Transition or Paris-Aligned Benchmarks, which require an annual GHG emissions reduction of at least 7%; ② investments in Taxonomy-aligned activities, including those that are Taxonomy-eligible and expected to become aligned within five years; ③ investments in companies or activities with a credible transition plan; and ④ investments in companies or activities with credible science-based targets.

complement their existing green finance systems. Japan, home to the world's largest transition finance market, has mobilized substantial funding for transition activities aligned with industry-specific decarbonization roadmaps. In China,[49] under its national strategy to peak emissions by 2030, the government is actively deploying transition finance instruments to support the progressive reduction of emissions in carbon-intensive sectors such as steel and coal-fired power generation—alongside large-scale green finance deployment (see **Figure 17**).

[Figure 17] Transition finance[1] by country

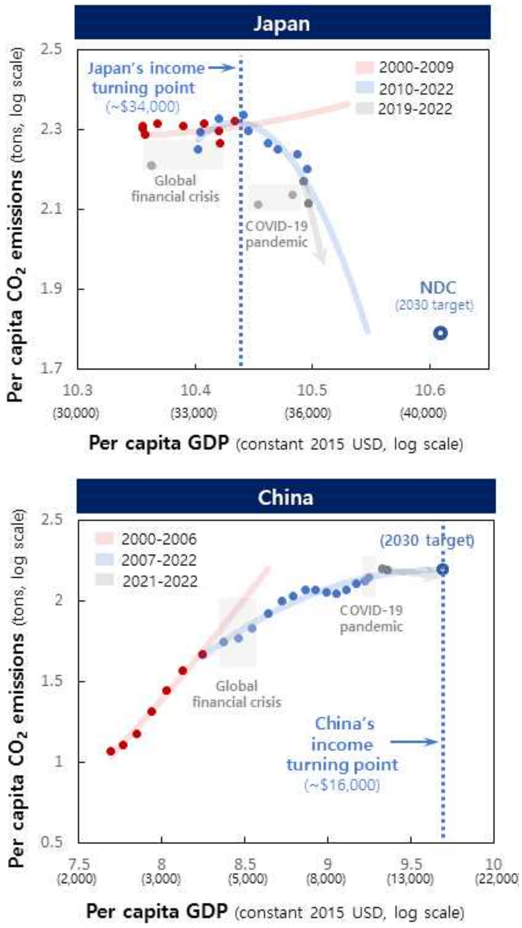


Note: 1) Cumulative volume as of Q3 2024, including transition bonds and certain transition loans internally labelled by BloombergNEF.
Source: BloombergNEF

Accordingly, transition finance is likely contributing to Japan and China's decoupling efforts, either by accelerating the trend or helping to sustain it. In Japan, recent data on income and CO_2 emissions indicate that the decoupling trend has gained momentum since the end of the COVID-19 pandemic, relative to the pre-pandemic EKC trajectory. This suggests that Japan may achieve its NDC target earlier than projected (see **Figure 18**). In China, the EKC pattern that emerged following the global financial crisis has exhibited only minor fluctuations in recent years. However, given the government's ongoing decarbonization efforts—including the expansion of transition finance instruments—there is a possibility that China's emissions will peak before 2030, ahead of its official target (see **Figure 18**).

49) Following President Xi Jinping's 2020 pledge that China would peak carbon emissions before 2030 and achieve carbon neutrality by 2060, the Chinese government has introduced a range of net-zero policies under its "1+N" framework. As part of this strategy, in November 2021 the People's Bank of China (PBOC) launched a loan facility to support low-carbon transition projects, including the development of carbon-reducing technologies and improvements in energy efficiency and coal use.

[Figure 18] Relationship between per capita GDP and CO_2 emissions in Japan[1)] and China[2)]



Note: 1) For Japan, a quadratic trend line is applied separately for 2000–2009 (solid red) and 2010–2022 (solid blue), excluding the pandemic. The dotted blue line shows the income turning point, and the gray line reflects recent trends (2019–2022) when transition finance expanded. Per capita CO_2 emissions are based on data from the Greenhouse Gas Inventory Office (GIO).

2) For China, the trend line is also divided into two phases based on a threshold regression: 2000–2006 (solid red line) and 2007–2022 (solid blue line). The dotted blue line shows the income turning point, and the solid gray line represents the recent trend (2021–2022).

Sources: World Bank; author's own estimations.

Transition finance developments in Japan and China provide valuable insights for Korea's decarbonization strategy, particularly given the structural similarities across the three countries' industrial systems. A well-designed framework that reflects the structural characteristics of Korea's economy could not only help close financing gaps in the low-carbon transition, but also play a critical role in mitigating transition risks—such as real-sector disruptions resulting from more stringent emissions regulation—and in maintaining the global competitiveness of carbon-intensive industries during the shift to a net-zero economy.[50)]

50) The FSC announced plans to explore a transition finance framework to support carbon-intensive industries, based on discussions at the December 2024 Climate Finance Task Force meeting ("6th Climate Finance TF and Climate Finance Activities in 2024," FSC press release, December 2024).

IV. Summary of Findings and Policy Implications

This study investigates the phenomenon of decoupling between economic growth and CO_2 emissions by estimating the income turning point at which decoupling begins and identifying the key factors that influence its trajectory. Based on panel regression analysis using data from 59 countries, the income turning point was found to be approximately USD 23,000 in per capita GDP. Most high-income countries have already surpassed this level and appear to be in a stable phase of decoupling, while many middle-income countries remain below it.

The analysis highlights three major drivers of decoupling: structural change, technological advancement, and financial development. A shift toward globally competitive service industries generally facilitates decoupling. In contrast, the impacts of technological and financial development are more complex—initially reinforcing emissions through scale effects, but eventually supporting decoupling in advanced economies with more mature green technologies and financing systems.

For Korea, the turning point was estimated at around USD 30,000, which is higher than the cross-country average. This suggests a relatively delayed onset of decoupling, attributable to Korea's carbon-intensive industrial structure, fossil fuel-based energy mix, and limited decarbonization effects from low-productivity service sector growth. Korea's green finance market, still in an early stage of development, may also have been insufficient to support a faster low-carbon transition.

To sustain and strengthen Korea's decoupling trajectory, a comprehensive policy response is required. First, industrial policy should promote globally competitive, low-carbon service sectors—such as green transport and AI services for energy and emissions management—rather than labor-intensive services. Second, regulatory barriers to green technology deployment must be removed, while incentives for firms to adopt Best Available Technologies (BAT) should be enhanced. Third, green and transition finance must be scaled up in a timely manner, with a framework aligned to Korea's industrial characteristics, to meet rising capital needs. Taken together, these measures are expected to reduce transition risks, support hard-to-abate sectors, and promote a more balanced and resilient path to net zero.

While this study offers empirical evidence on the drivers and thresholds of decoupling based on country-level data, it does not fully capture industry- or region-specific dynamics. Future research should incorporate sectoral and spatial heterogeneity to inform more targeted and effective policy strategies.

<BOX 1> Data and Descriptive Statistics

[Table A1] Raw data and descriptive statistics[1)]

\		Variable	Raw data	Source	Obs.	Mean	Std. Dev.
Dependent variable		$CO2pc$	Per capita CO2 emissions (t)	World Bank	740	6.865	7.146
Explanatory variables	Income level	$GDPpc$	Per capita GDP (real 2015 USD)	World Bank	740	22,443	17,420
	Changes in economic structure	mnf	Manufacturing value-added (% of GDP)	World Bank	722	15.312	5.657
		ser	Export share of services (% of total exports)	World Bank	740	25.552	15.683
	Technological advancements	$tech$	Number of patent applications (per billion USD GDP)	World Bank	695	11.115	22.726
		$c.tech$[2)]	Number of international clean energy patent applications (per billion USD GDP)	IEA	458	0.249	0.352
	Financial development	fmd[3)]	IMF financial market depth index (1-100)	IMF	740	45.601	27.898
		$g.bond$[4)]	Green bond issuance (% of GDP)	IMF	129	0.482	1.822

Notes: 1) The study covers the 21-year period from 2000 to 2020 and includes 59 middle- and high-income countries based on the World Bank classification.
2) Patent families are based on international applications filed in two or more countries, as categorized by technology area.
3) The IMF Financial Market Depth Index (1–100) is constructed using trading volume, stock market capitalization, and debt securities issuance as a percentage of GDP, and serves as a proxy for the financial sector's capacity to fund the real economy.
4) Total green bond issuance as a percentage of GDP, including issuances by governments, public institutions, and corporations, to support climate change mitigation and environmental sustainability.

[Table A2] Correlation matrix between explanatory variables

Variable	(1)	(2)	(3)	(4)	(5)	(6)
(1) $\ln GDPpc$	1.000					
(2) $\ln mnf$	-0.247	1.000				
(3) $\ln ser$	0.299	-0.295	1.000			
(4) $\ln tech$	0.016	0.435	0.000	1.000		
(5) $\ln fmd$	0.472	-0.260	0.304	0.158	1.000	
(6) $\ln c.tech$[1)]	0.512	0.253	0.294	0.657	0.400	1.000
$\ln g.bond$[2)]	0.069	-0.063	0.167	-0.305	-0.143	1.000

Notes: 1) Correlation between $\ln c.tech$ and other variables is based on 458 observations.
2) Correlation between $\ln g.bond$ and other variables is based on 129 observations.

[Table A3] Levin-Lin-Chu panel data unit root test results[1)2)]

Variable	t-statistic	p-value
$\ln CO2pc$	-2.627	0.004
$\ln GDPpc$	-4.882	0.000
$\ln mnf$	-1.075	0.141
$\ln ser$	-2.754	0.003
$\ln tech$	-3.026	0.001
$\ln fmd$	-3.436	0.000
$\ln c.tech$	-3.857	0.000

Notes: 1) Adjusted t-statistics are calculated using variables excluding the cross-sectional means.
2) Null hypothesis (H_0): The variable contains a unit root.

<BOX 2> Robustness check: Panel regression results using the direct effect model on the EKC and turning point dynamics (by income group)[1)2)]

Explanatory variable	Dependent variable:									
	(A)	(B)	(C)	(D)	(E)	(A)	(B)	(C)	(D)	(E)
	High-income group					Middle-income group				
Income group:										
$\ln GDPpc_{c,t}$	3.641***	2.451***	1.848***	2.378***	2.624	1.994***	2.155***	1.874***	2.253***	2.262**
	(0.000)	(0.000)	(0.000)	(0.000)	(0.256)	(0.000)	(0.000)	(0.000)	(0.000)	(0.016)
$(\ln GDPpc_{c,t})^2$	-0.193***	-0.125***	-0.0919***	-0.121***	-0.113	-0.0811***	-0.0903***	-0.0707***	-0.0988***	-0.0962*
	(0.000)	(0.000)	(0.000)	(0.000)	(0.310)	(0.000)	(0.000)	(0.000)	(0.000)	(0.073)
Changes in economic structure:[3)]										
$\ln mnf_{c,t-1} \times (\ln GDPpc_{c,t})^2$	0.00104***					-0.000173				
	(0.000)					(0.292)				
$\ln ser_{c,t-1} \times (\ln GDPpc_{c,t})^2$		-0.00124***	-0.00237***	-0.00122***	-0.000707		-0.000495	-0.000275	-0.000471	0.00110
		(0.000)	(0.000)	(0.000)	(0.157)		(0.100)	(0.541)	(0.113)	(0.104)
Technological advancements:										
$\ln tech_{c,t-1} \times (\ln GDPpc_{c,t})^2$		-0.000125**		-0.000161***	0.00122***		-0.0000443		0.0000181	0.000212
		(0.021)		(0.008)	(0.000)		(0.433)		(0.776)	(0.139)
$\ln c.tech_{c,t-1} \times (\ln GDPpc_{c,t})^2$			-0.000342***					0.0000708		
			(0.000)					(0.403)		
Financial development:										
$\ln fmd_{c,t-1} \times (\ln GDPpc_{c,t})^2$				-0.000194					0.000458**	
				(0.189)					(0.040)	
$\ln g.bond_{c,t-1} \times (\ln GDPpc_{c,t})^2$					-0.0000519*					-0.0000553
					(0.059)					(0.298)
Constant:	-14.17***	-8.759***	-6.339***	-8.451***	-9.516	-9.117***	-9.823***	-8.702***	-10.09***	-10.31***
	(0.000)	(0.000)	(0.001)	(0.000)	(0.428)	(0.000)	(0.000)	(0.000)	(0.000)	(0.010)
Fixed-effects	Country	Country	Country	Country	Country	Country	Country	Country	Country	Country
Number of observations	502	452	349	452	59	234	236	108	236	38
Number of countries	37	36	25	36	15	23	23	6	23	13
Chi-squared	15,307	12,956	11,464	13,199	13,847	48,032	43,331	20,981	46,071	119,181

Notes: 1) Results are based on the estimation of equation (4). *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively.
2) Values in parentheses indicate p-values.
3) This variable (log-transformed GDP share of manufacturing %) is included to cross-validate the effect and direction of structural changes, based on the hypothesis that a higher manufacturing share is associated with greater CO_2 emissions.

Source: Author's own estimations

<References>

<In Korean>

Choi, I. J. (2023). A strategy to promote green finance in Korea. 2050 Carbon Neutrality and Green Growth Committee-Bank of Korea Joint International Conference for Green Finance.

Federation of Korean Industries (2021). Conditions for the reduction of industrial carbon emissions in Korea based on international comparison. Global Insight, 68.

Lee, S. J. (2017). Trends in decoupling economic growth from GHG emissions in major countries and implications. KERI Insight, 17-6.

Lim, H. W. & Cho, H. H. (2019). Decoupling economic growth from carbon emissions: dynamic panel analysis of 63 countries (1980-2014). Environmental and Resource Economics Review, 28(4), 497-526.

Park, S. H., Kim, J. Y., & Ryu, K. B. (2024). Recent management of financial emissions by domestic banks and policy implications. BOK Issue Note, 2024-20.

Song, H. S. (2023). Tasks for the development of climate finance towards carbon neutrality. Korea Capital Market Institute Issue Report, 23-08.

<In English>

Acemoglu, D., Aghion, P., Bursztyn, L., & Hemous, D. (2012). The environment and directed technical change. American Economic Review, 102(1), 131-166.

Allard, A., Takman, J., Uddin, G. S., & Ahmed, A. (2018). The N-shaped environmental Kuznets curve: an empirical evaluation using a panel quantile regression approach. Environmental Science and Pollution Research, 25, 5848-5861.

Baum, C. F. (2001). Residual diagnostics for cross-section time series regression models. The Stata Journal, 1(1), 101-104.

Cole, M. A., Rayner, A. J., & Bates, J. M. (1997). The environmental Kuznets curve: an empirical analysis. Environment and development economics, 2(4), 401-416.

Dasgupta, S., Laplante, B., & Mamingi, N. (2001). Pollution and capital markets in developing countries. Journal of Environmental Economics and management, 42(3), 310-335.

De Haas, R., & Popov, A. A. (2019). Finance and carbon emissions (No. 2318). ECB Working Paper.

Dinda, S. (2004). Environmental Kuznets Curve Hypothesis: A Survey. Ecological Economics, 49(4), 431-455.

Grossman, G. M., & Krueger, A. B. (1991). Environmental Impacts of a North American Free Trade Agreement. NBER Working Paper, 3914.

Grossman, G. M., & Krueger, A. B. (1995). Economic Growth and the Environment. The Quarterly Journal of Economics, 110(2), 353-377.

IEA (2021). Net zero by 2050, IEA.

Javid, M., & Sharif, F. (2016). Environmental Kuznets curve and financial development in Pakistan. Renewable and Sustainable Energy Reviews, 54, 406-414.

Kaika, D., & Zervas, E. (2013). The Environmental Kuznets Curve (EKC) theory—Part A: Concept, causes and the CO2 emissions case. Energy policy, 62, 1392-1402.

Kaufmann, R. K., Davidsdottir, B., Garnham, S., & Pauly, P. (1998). The determinants of atmospheric SO2 concentrations: reconsidering the environmental Kuznets curve. Ecological economics, 25(2), 209-220.

Kuznets, S. (1955). Economic growth and income inequality. American Economic Review, 45(1), 1-28.

Levin, A., Lin, C. F., & Chu, C. S. J. (2002). Unit root tests in panel data: asymptotic and finite-sample properties. Journal of econometrics, 108(1), 1-24.

Nasreen, S., Anwar, S., & Ozturk, I. (2017). Financial stability, energy consumption and environmental quality: Evidence from South Asian economies. Renewable and sustainable energy reviews, 67, 1105-1122.

OECD (2022). OECD Guidance on Transition Finance: Ensuring Credibility of Corporate Climate Transition Plans. Green Finance and Investment, OECD Publishing.

Panayotou, T. (1993). Empirical tests and policy analysis of environmental degradation at different stages of economic development. Working Paper WP238, Technology and Employment Programme, International Labour Office (ILO), Geneva.

Panayotou, T. (2003). Economic growth and the environment. Economic survey of Europe, 45-72.

Porter, M. E., & Linde, C. V. D. (1995). Toward a new conception of the environment-competitiveness relationship. Journal of economic perspectives, 9(4), 97-118.

Roberts, S. H., Foran, B. D., Axon, C. J., & Stamp, A. V. (2021). Is the service industry really low-carbon? Energy, jobs and realistic country GHG emissions reductions. Applied Energy, 292, 116878.

Selden, T. M., & Song, D. (1994). Environmental quality and development: is there a Kuznets curve for air pollution emissions? Journal of Environmental Economics and management, 27(2), 147-162.

Shahbaz, M., & Sinha, A. (2019). Environmental Kuznets curve for CO2 emissions: a literature survey. Journal of Economic Studies, 46(1), 106-168.

Shafik, N. (1994). Economic development and environmental quality: An econometric analysis. Oxford Economic Papers, 46, 757-773.

Stern, D. I. (2004). The rise and fall of the environmental Kuznets curve. World Development, 32(8), 1419-1439.

Suri, V., & Chapman, D. (1998). Economic growth, trade and energy: implications for the environmental Kuznets curve. Ecological economics, 25(2), 195-208.

Svirydzenka, K. (2016). Introducing a New Broad-based Index of Financial Development. IMF Working Papers, 16(05), 1.

Torras, M., & Boyce, J. K. (1998). Income, inequality, and pollution: a reassessment of the environmental Kuznets curve. Ecological economics, 25(2), 147-160.

Wang, Q., Li, Y., & Li, R. (2024). Rethinking the environmental Kuznets curve hypothesis across 214 countries: the impacts of 12 economic, institutional, technological, resource, and social factors. Humanities and Social Sciences Communications, 11(1), 1-19.

Zhang, J., Lyu, Y., Li, Y., & Geng, Y. (2022). Digital economy: An innovation driving factor for low-carbon development. Environmental Impact Assessment Review, 96, 106821.