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Development of an Auxiliary Indicator for Improving the Rationality and Reliability of the National-Level Carbon Productivity Indicator

Jong Hyo Lee ¹, Hong Yoon Kang ^{1,*} and Yong Woo Hwang ²

¹ Program in Circular Economy Environmental System, Inha University, 100, Inha-ro, Michuhol-gu, Incheon 22212, Republic of Korea; leejonghyo@inha.edu

² Department of Environmental Engineering, Inha University, 100, Inha-ro, Michuhol-gu, Incheon 22212, Republic of Korea; hwangyw@inha.ac.kr

* Correspondence: kanghy@inha.ac.kr

Abstract: Global attention to climate change has surged since the advent of the Paris Agreement, intensifying the importance of measuring and managing carbon productivity indicators on a national level. Nevertheless, concerns persist regarding the reliability of such measurements because of inherent discrepancies in implementing and operating national-level carbon productivity indicators, coupled with their inherent uncertainty. This study proposes a multiple regression model to address these issues aimed at refining national-level carbon productivity indicator metrics, accounting for factors such as the gross domestic product and total greenhouse gas emissions by sectors. The objective was to offer insights into enhancing and effectively utilizing current indicators, enabling a more nuanced interpretation of the variation in the carbon productivity indicators across diverse industrial landscapes. This study showed that adjustments of the carbon productivity metrics reflect disparities in emissions across industrial structures, with countries characterized by high emissions from non-service industries showing improving trends. In addition, this paper proposes an auxiliary indicator estimating method for carbon productivity that, when utilized with current methodologies, is more usable to interpret productivity indicators within the context of varying industrial compositions across OECD countries. Moreover, by elucidating the nuances of industrial structures, this study advocates for more sophisticated approaches to interpreting and managing the productivity indicators tailored to the unique economic landscape of each country. Nevertheless, the limitations stemming from data availability underscore the need for further research, particularly in refining the national-level carbon resource productivity indicators analyses and exploring the thematic productivity variations in greater depth. By addressing these gaps, future studies will contribute to a more comprehensive understanding of national-level carbon resource productivity indicators dynamics and reveal targeted strategies for sustainable development.

Keywords: carbon productivity; gross domestic product (GDP); total greenhouse gas emission (TGE); the auxiliary indicator; environmental statistics research; multiple regression analysis



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1. Introduction

Human civilization has developed at the expense of the global environment, leading to widespread destruction and negative impacts. Governments and international organizations are exploring various strategies for sustainable development in response to rapid population growth and increasing issues of environmental pollution and resource depletion. Two prominent international strategies are the transitions to a circular economy and a green economy [1,2]. These strategies are focused on how the changes in global environmental management and economic strategies affect regional economies and, ultimately, the achievement of sustainable development goals. This topic is a crucial agenda for policymakers worldwide [3,4].

In particular, global interest in climate change has surged since the signing of the Paris Agreement in 2015, emphasizing the importance of calculating and managing carbon productivity indicators at the national level. Monitoring and evaluating the value-added generated relative to the greenhouse gas emissions of a country provides crucial insights for policymakers, aiding in setting the priorities from macroeconomic and microeconomic perspectives [5–7].

The Republic of Korea also strives to enhance the usability of carbon productivity indicators in line with global trends. Significant capital is being invested in R&D for technology and process innovations at the business level, in facility construction to increase the value-added relative to greenhouse gas emissions, and in businesses within the circular economy or those promoting carbon neutrality, such as remanufacturing [8]. Efforts are being made to calculate carbon productivity indicators more precisely at the national and regional levels, facilitating more rational comparisons and analyses between countries.

Generally, the national-level carbon productivity is calculated as the gross domestic product (GDP) divided by the total greenhouse gas emissions (TGEs). The result expresses the value-added generated per ton of CO₂-equivalent greenhouse gas emissions, measured in USD/ton CO₂-eq. On the other hand, this method cannot account for the characteristics of the industries that comprise the economy of a country in detail, potentially distorting the interpretation of the carbon productivity indicator of that country. For example, although the TGEs vary according to the primary, secondary, and tertiary industries, GDP measures the final products and the total value-added of services. Thus, the carbon productivity indicator can be structurally biased, either advantageous or disadvantageous, depending on the industrial structure of each country.

Given the broad nature of the GDP and TGEs indicators, the current carbon productivity indicator cannot consider the detailed properties of greenhouse gas emission sources according to industry. For example, the concrete industry in Canada [9], the metal industry in China [10], and the industrial growth trends in Pakistan [11] cannot be efficient in terms of carbon productivity compared to other industries. The impact of specific industries on carbon productivity varies significantly according to country or region, with high greenhouse gas-emitting industries lowering carbon productivity at the national or regional levels [12].

In light of these issues, this study designed an auxiliary indicator to complement the current national carbon productivity indicator by considering industry-specific greenhouse gas emissions. This will provide a more reasonable interpretation of carbon productivity, reflecting the differences in the industrial structure of each country. This paper proposes ways to improve and utilize the current national carbon productivity indicator and suggests using auxiliary indicators that consider the industrial structure of each country to enhance the interpretation and management of carbon productivity indicators.

2. Research Background

Previous studies reported that national-level productivity indicators related to the environment, such as GDP and the domestic material consumption (DMC), can lead to incorrect interpretations because of the failure to account for the industrial structure of each country and the role of energy and resource use in greenhouse gas emissions. The current indicator, calculated by simply dividing the GDP by total greenhouse gas emissions, has limitations in reflecting the productivity of a country in environmental terms [13–16]. Furthermore, although TGEs statistics are useful for understanding economic drivers and predicting future trends, they cannot adequately explain the value-added generated within the external economy because of the TGEs in a specific country [13,17–21].

Furthermore, the national-level carbon productivity results using these statistics can be distorted if greenhouse gas emissions are outside the calculation scope. For example, when a developed country relocates a greenhouse-gas-intensive industry to a developing country, the TGEs of the developed country decrease, which should be reflected in the

carbon productivity calculation of the developed country through a separate adjustment process [22].

3. Disparity between the National-Level Carbon Productivity Indicators and Per Capita Greenhouse Gas Emissions

According to OECD Data Explorer (<https://data-explorer.oecd.org/>, accessed on 31 July 2024) on GDP and TGEs [23], Korea's average per capita greenhouse gas emissions in 2019 was 13.5 tons CO₂-eq., the sixth highest among 38 OECD countries and over 40% higher than the OECD average of 9.5 tons CO₂-eq. Australia had the highest per capita emissions at 21.9 tons CO₂-eq., approximately 1.6 times more than Korea. The United States and Canada followed, with 20.0 and 19.2 tons CO₂-eq. per capita emissions, respectively. In contrast, Japan, with a high manufacturing sector similar to Korea, had per capita emissions of 9.6 tons, ranking 14th among OECD countries and approximately 70% of Korea's emissions. Costa Rica had the lowest per capita emissions at 1.6 tons CO₂-eq., followed by Colombia with 3.6 tons CO₂-eq. and Sweden with 4.9 tons CO₂-eq.

By contrast, the carbon productivity indicator (GDP/TGEs) showed different results from per capita emissions. In 2019, Korea generated an average value-added of 2355.1 USD/ton CO₂-eq., approximately half of the OECD average of 4490.0 USD/ton CO₂-eq., ranking 32nd out of 38 OECD countries. Switzerland had the highest carbon productivity, producing 15,524.2 USD/ton CO₂-eq., approximately 6.6 times higher than Korea. Sweden and Norway followed, with 10,549.5 and 8021.1 USD/ton CO₂-eq., respectively. Japan ranked 19th with 4234.3 USD/ton CO₂-eq., approximately 1.8 times higher than Korea. Turkey had the lowest carbon productivity at 1493.8 USD/ton CO₂-eq., approximately one-tenth of Switzerland, followed by Poland with 1542.6 USD/ton CO₂-eq. and Mexico with 1722.7 USD/ton CO₂-eq.

These disparities highlight the need to improve the rationality and validity of the current carbon productivity indicator through additional formula design or to use auxiliary indicators for relative comparison. The GDP/TGEs indicator tends to overestimate or underestimate certain countries by not considering their industrial and geographical characteristics. For example, Luxembourg's average per capita greenhouse gas emissions were 17.3 tons CO₂-eq., approximately three times higher than Turkey's. On the other hand, Luxembourg's value-added creation per unit of greenhouse gas emissions was 6501.5 USD/ton CO₂-eq., approximately 4.4 times higher than Turkey's. Despite the higher per capita emissions, Luxembourg, with a service industry focus and relatively high indirect greenhouse gas emissions, generates significantly more value-added than greenhouse gas emissions (Table 1).

Table 1. Greenhouse gas emission per capita and carbon productivity ranking of OECD countries (as of 2019).

Countries	Greenhouse Gas Emission (per Capita, ton CO ₂ -eq.)	Ranking	Countries	Carbon Productivity (USD/ton CO ₂ -eq.)	Ranking
Australia	21.9	1	Switzerland	15,524.2	1
United States	20.0	2	Sweden	10,549.5	2
Canada	19.2	3	Norway	8021.1	3
Luxembourg	17.3	4	Costa Rica	7901.3	4
New Zealand	16.0	5	Denmark	7381.5	5
Korea	13.5	6	Ireland	6545.6	6
Iceland	13.1	7	Luxembourg	6501.5	7
Ireland	12.4	8	United Kingdom	6303.7	8
Czech Republic	11.6	9	France	6235.3	9

Table 1. Cont.

Countries	Greenhouse Gas Emission (per Capita, ton CO ₂ -eq.)	Ranking	Countries	Carbon Productivity (USD/ton CO ₂ -eq.)	Ranking
Estonia	11.0	10	Austria	5558.2	10
Netherlands	10.4	11	Iceland	5221.0	11
Belgium	10.1	12	Finland	5092.6	12
Poland	10.1	13	Israel	5083.5	13
Japan	9.6	14	Netherlands	5030.5	14
Germany	9.6	15	Germany	4893.1	15
Finland	9.5	16	Italy	4763.0	16
Norway	9.5	17	Belgium	4601.1	17
Austria	9.0	18	Spain	4500.5	18
Israel	8.7	19	Japan	4234.3	19
Slovenia	8.2	20	Portugal	3743.0	20
Denmark	8.1	21	United States	3230.8	21
Greece	8.0	22	Slovenia	3157.9	22
Slovak Republic	7.3	23	Latvia	3085.2	23
Lithuania	7.2	24	Lithuania	2704.9	24
Italy	7.1	25	New Zealand	2664.0	25
United Kingdom	6.8	26	Slovak Republic	2645.7	26
Hungary	6.6	27	Hungary	2532.3	27
Spain	6.6	28	Chile	2508.3	28
France	6.5	29	Australia	2478.3	29
Portugal	6.2	30	Canada	2409.5	30
Turkiye	6.2	31	Greece	2382.5	31
Mexico	5.9	32	Korea	2355.1	32
Latvia	5.8	33	Estonia	2138.0	33
Chile	5.8	34	Czech Republic	2045.7	34
Switzerland	5.4	35	Colombia	1836.6	35
Sweden	4.9	36	Mexico	1722.7	36
Colombia	3.6	37	Poland	1542.6	37
Costa Rica	1.6	38	Turkiye	1493.8	38

Note. Bolded and backgrounded countries have clear disparities between greenhouse gas emissions and carbon productivity. Details are described in the manuscript.

These trends and limitations indicate that it is necessary to improve the current indicator to ensure its rationality and validity through additional formula design or using auxiliary indicators for relative comparison. This study suggests developing auxiliary indicators that consider the industrial structure and resource value differences of each country by closely analyzing the trends and relationships between the value-added generated and the sources of value-added creation or the factors accompanying it.

4. Research Methods

The existing national carbon productivity indicator is calculated by dividing the GDP by total greenhouse gas emissions (GDP/TGEs), indicating the economic value-added generated per ton of greenhouse gas emitted. This study examined the extent of the advantages or disadvantages of this calculation due to differences in industrial and economic structures and other factors among countries.

This study conducted multiple regression analyses to identify these disparities, considering the value-added generated from greenhouse gas emissions by the service and non-service sectors. The OECD countries' GDP and TGEs statistics from 2017 to 2019 were used as the data sources.

The scope of research ensures data integrity and an appropriate sample size. Although the GDP data are available for all timeseries data until 2022, the TGEs data lack completeness beyond 2019. Therefore, the most recent complete data set available from

2019, along with the data from 2017 and 2018, provided 114 samples for analysis, meeting the requirements for multiple regression analysis.

Previous studies and the data presented in this research show that the value-added compared to greenhouse gas emissions is lower in non-service industries than in service industries.

Cross-analysis between GDP and TGEs statistics according to the industries revealed Spearman correlation coefficients of 0.444 for the non-service industry and 0.714 for the service industry, respectively. Hence, a moderate positive correlation exists between GDP and TGEs for the non-service industry and a very strong positive correlation exists for the service industry. The significance probabilities were all $p < 0.001$, indicating a clear statistical basis for the interaction between the variables (Table 2).

Table 2. Results of correlation analysis between GDP and TGEs and the service and non-service industrial sectors.

			Value	Asymptotic Standards Error ^a	Approximate T ^b	Approximate Significance
Spearman correlation	Ordinal by ordinal	Non-service industry (GDP × TGEs)	0.444	0.067	3.690	<0.001 ^c
		Service industry (GDP × TGEs)	0.714	0.054	10.784	<0.001 ^c

^a Not assuming the null hypothesis. ^b Using the asymptotic standard error assuming the null hypothesis. ^c Based on normal approximation. (Note. GDP: Gross Domestic Product, TGEs: Total Greenhouse gas Emissions).

Therefore, this study used the OECD real GDP (base year 2015) and TGEs statistics (excluding LULUCF) by country and industry to design a regression model. This model derives the adjusted carbon productivity (*adjCP*) as a dependent variable and uses the value-added created by industry—where $GDP_{1st+2nd}$ represents the non-service industry GDP and GDP_{3rd} represents the service industry GDP—versus greenhouse gas emissions by industry—where $GHGs_{1st+2nd}$ represents the non-service industry greenhouse gas emissions and $GHGs_{3rd}$ represents the service industry greenhouse gas emissions—as independent variables ($\frac{GDP_{1st+2nd}}{GHGs_{1st+2nd}}$ and $\frac{GDP_{3rd}}{GHGs_{3rd}}$, respectively). Multiple regression analysis was then performed based on this model.

The carbon productivity is the value-added created per 1 kg CO₂-eq. of greenhouse gas emissions. The mathematical structure of the regression model is expressed as Equation (1).

$$adjCP = \beta_{nsevGHGs} \frac{GDP_{1st+2nd}}{GHGs_{1st+2nd}} + \beta_{sevGHGs} \frac{GDP_{3rd}}{GHGs_{3rd}} + c_{GHGs} \quad (1)$$

$GDP_{1st+2nd}$	the sum of the GDP from the primary and secondary industries	GDP_{3rd}	the GDP of the tertiary industry
$GHGs_{1st+2nd}$	the sum of total greenhouse gas emissions from the primary and secondary industries	$GHGs_{3rd}$	the total greenhouse gas emissions from the tertiary industry
$\beta_{nsevGHGs}$	the carbon productivity determination coefficient of the non-service industry	$\beta_{sevGHGs}$	the carbon productivity determination coefficient of the service industry
$adjCP$	adjusted carbon productivity	c_{GHGs}	the carbon productivity constant

5. Results

This study performed multiple regression analyses with GDP and TGEs statistics from OECD data [23] to adjust the carbon productivity of 38 OECD countries, using carbon productivity by industry as the independent variable. The explanatory power of the model

was very high, with $R^2 = 0.909$ and adjusted $R^2 = 0.907$. In addition, the difference between R^2 and adjusted R^2 was less than 0.1%, indicating sufficient validity (Table 3).

Table 3. Summary of a multiple regression model for adjusting the GDP using carbon productivity by the service and non-service sectors.

	<i>R</i>	R^2	Adjusted R^2	Std. Error of the Estimate	R^2 Change
<i>adjCP</i> ^b	0.953 ^a	0.909	0.907	0.834697376	0.909
Change Statistics					
	F Change	df1	df2	Sig.f Change	
	552.682	2	111	0	

^a Predictors: (Constant), carbon productivity of non-service industry (primary industry + secondary industry), carbon productivity of service industry (tertiary industry). ^b Dependent Variable: *adjCP*.

The regression equation derived based on the explanatory power of the model was $adjCP = 0.732 \cdot \frac{GDP_{1st+2nd}}{GHGS_{1st+2nd}} + 0.367 \cdot \frac{GDP_{3rd}}{GHGS_{3rd}} - 0.368$, and the variance inflation factor (VIF) was 1.362, indicating no multicollinearity issues among the variables (Table 4).

Table 4. Result of a multiple regression model for adjusting GDP using carbon productivity by the service and non-service sectors.

		Unstandardized Coefficients		Standardized Coefficients Beta	<i>t</i>	Sig.	Collinearity Statistics	
		B	Std. Error				Tolerance	VIF
<i>adjCP</i> ^a	(Constant)	−0.368	0.18		−2.04	0.044		
	$\frac{GDP_{1st+2nd}}{GHGS_{1st+2nd}}$	0.732	0.047	0.518	15.482	0	0.734	1.362
	$\frac{GDP_{3rd}}{GHGS_{3rd}}$	0.367	0.021	0.576	17.224	0		

^a Dependent Variable: *adjCP*.

The sample distribution was normal (Figure 1). The normal P–P plot of the regression standardized residuals also showed significant convergence to the regression line (Figure 2). Similarly, the partial regression plots for the variables $\frac{GDP_{1st+2nd}}{GHGS_{1st+2nd}}$ and $\frac{GDP_{3rd}}{GHGS_{3rd}}$ indicated that the samples of the variables that make up the regression equation were linear at a significant level (Figures 3 and 4).

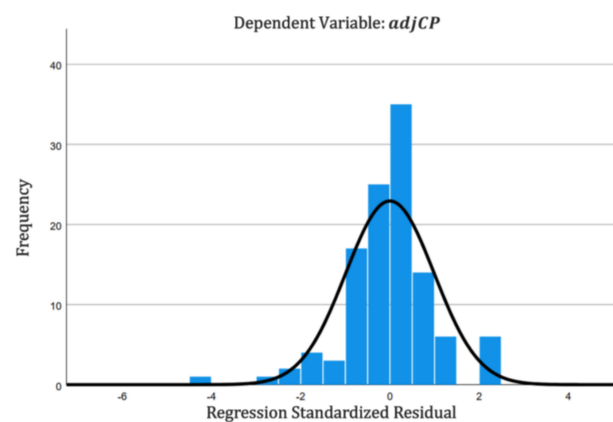


Figure 1. Normal distribution histogram of a multiple regression model for adjusting the GDP using carbon productivity by service and non-service sectors. (Note. *adjCP*: adjusted carbon productivity).

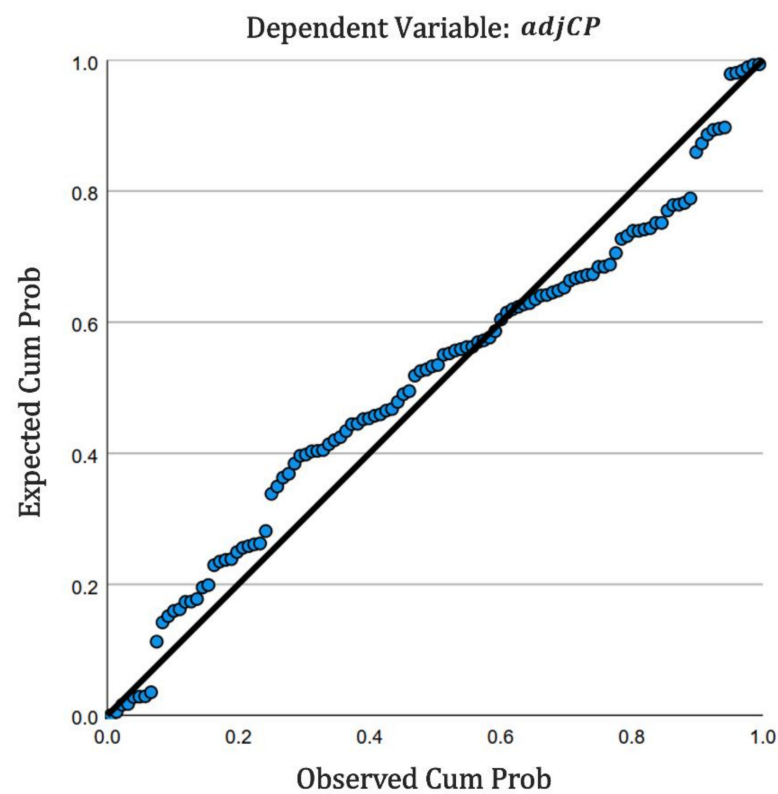


Figure 2. Normal P–P plots of the regression standardized residual of a multiple regression model for adjusting the GDP using carbon productivity by the service and non-service sectors. (Note. *adjCP*: adjusted carbon productivity).

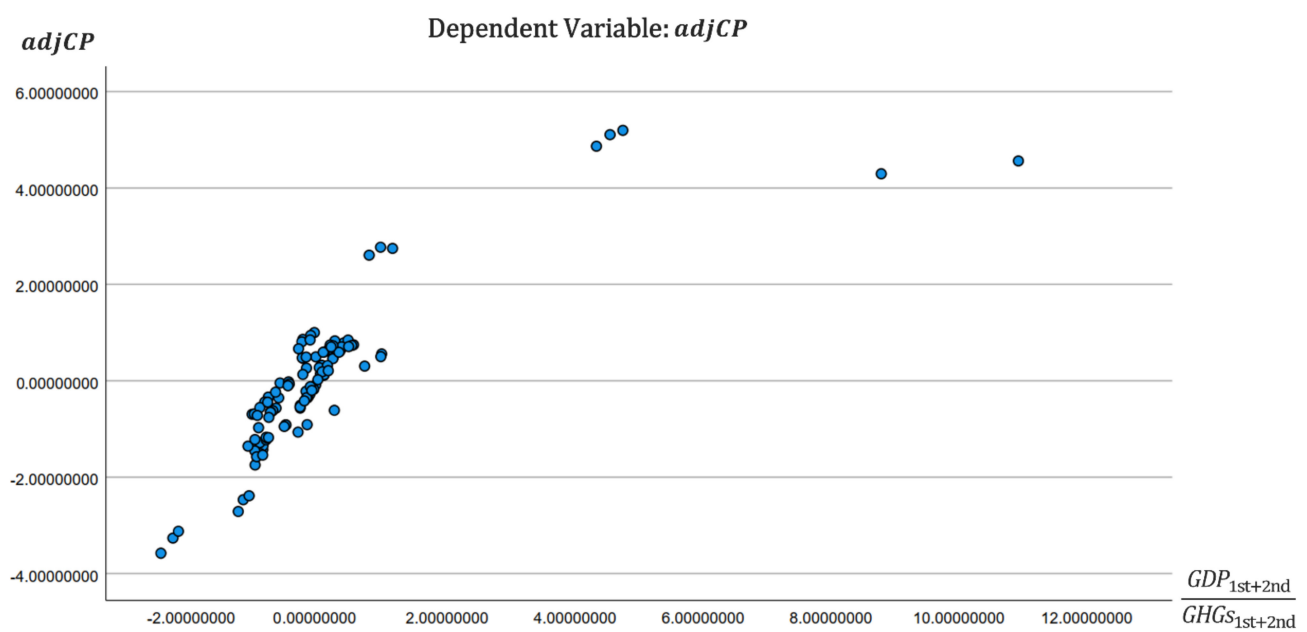


Figure 3. Partial regression plots of a multiple regression model for adjusting the GDP using carbon productivity of the non-service sector. (Note. *adjCP*: adjusted carbon productivity).

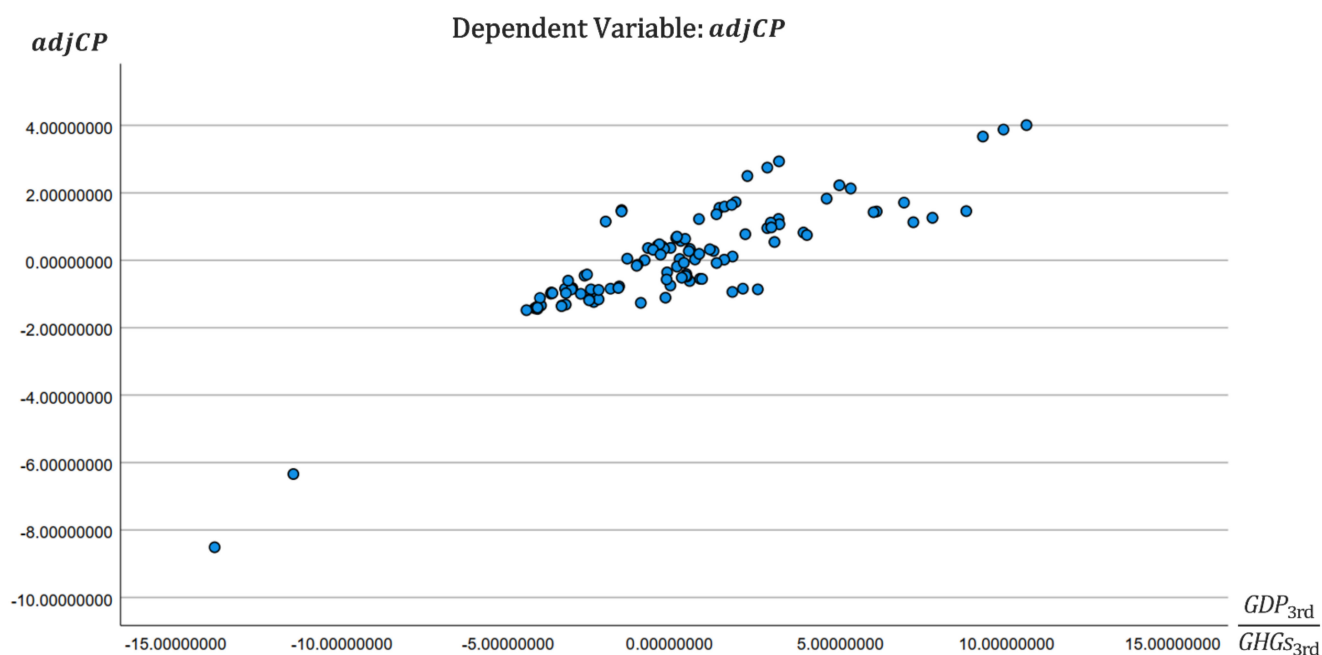


Figure 4. Partial regression plots of a multiple regression model for adjusting the GDP using carbon productivity of the service sector. (Note. *adjCP*: adjusted carbon productivity).

As a result of re-estimating carbon productivity using the coefficients derived from regression analysis, the countries with the greatest improvement in carbon productivity were Korea, Estonia, Israel, and Australia. Korea's carbon productivity increased from 2337.5 USD/ton CO₂-eq., ranking 31 out of 38 OECD countries, to 3996.0 USD/ton CO₂-eq., approximately a 71.0% improvement, moving up 13 places to 18th. Similarly, Estonia's carbon productivity increased from 1651.8 USD/ton CO₂-eq., ranking 35, to 2525.3 USD/ton CO₂-eq., approximately a 52.9% improvement, moving up seven places to 28th. Israel's carbon productivity increased from 4832.7 USD/ton CO₂-eq., ranking 13, to 6460.1 USD/ton CO₂-eq., approximately a 33.7% improvement, moving up to sixth. Australia's carbon productivity increased from 2531.8 USD/ton CO₂-eq., ranking 27, to 3360.7 USD/ton CO₂-eq., approximately a 32.7% improvement, moving up five places to 22nd.

On the other hand, the countries with the greatest decline in carbon productivity were Luxembourg, Latvia, France, and the United Kingdom. Luxembourg's carbon productivity decreased from 6542.6 USD/ton CO₂-eq., ranking 6, to 4543.5 USD/ton CO₂-eq., approximately a 30.6% decrease, falling 10 places to 16th. Latvia's carbon productivity decreased from 2989.4 USD/ton CO₂-eq., ranking 22, to 2443.9 USD/ton CO₂-eq., a decrease of approximately 18.2%, falling eight places. France's carbon productivity decreased from 6018.6 USD/ton CO₂-eq., ranking eight, to 5006.6 USD/ton CO₂-eq., approximately a 16.8% decrease, falling three places. The carbon productivity of the UK decreased from 6027.7 USD/ton CO₂-eq. to 5047.0 USD/ton CO₂-eq., approximately a 16.3% decrease, also falling three places (Table 5).

Regarding a carbon productivity correction, an improvement or decline in carbon productivity reflects the adjustments in the current estimation method. The adjusted carbon productivity in this study does not mean the actual carbon productivity but rather the current carbon productivity indicator. The adjusted carbon productivity indicator designed in this study highlights the discrepancies and adjusts for factors that might underestimate the carbon productivity of a country.

Table 5. Summary of the multiple regression results for adjusting national-level carbon productivity considering greenhouse gas emissions by the service and non-service sectors.

Countries	The Current Carbon Productivity		The Adjusted Carbon Productivity		Difference	Relative Change		Non-Service-Based Industry's Carbon Productivity (Exponentiated)		Service Based Industry's Carbon Productivity (Exponentiated)		Service Based Industry Share	
	USD/tCO ₂ -eq.	Rank	USD/tCO ₂ -eq.	Rank		%	Rank	Value	Rank	Value	Rank	%	Rank
Korea	2337.5	31	3996.0	18 (△ 13)	1658.5	71.0	1	−0.3775	17	0.6285	1	64.4	37
Estonia	1651.8	35	2525.3	28 (△ 7)	873.5	52.9	2	−0.4994	33	0.6171	2	74.1	18
Israel	4832.7	13	6460.1	6 (△ 7)	1627.4	33.7	3	−0.5808	37	0.5220	3	80.1	8
Australia	2531.8	27	3360.7	22 (△ 5)	828.9	32.7	4	−0.4586	29	0.5210	4	72.8	23
Costa Rica	6551.4	5	8224.7	4 (△ 1)	1673.2	25.5	5	0.0953	1	0.0373	38	76.2	16
New Zealand	2661.6	24	3267.9	23 (△ 1)	606.3	22.8	6	−0.4615	31	0.4819	6	73.9	20
Greece	2248.5	32	2686.0	26 (△ 6)	437.6	19.5	7	−0.6326	38	0.5100	5	82.7	2
Colombia	1836.4	34	2126.0	32 (△ 2)	289.5	15.8	8	−0.3656	15	0.4535	7	67.1	33
Japan	4041.0	19	4582.9	14 (△ 5)	541.8	13.4	9	−0.3811	18	0.3995	11	70.0	27
Finland	4888.7	12	5521.7	8 (△ 4)	633.1	12.9	10	−0.4293	25	0.4049	10	73.6	21
Mexico	1616.7	36	1807.5	36 (—)	190.8	11.8	11	−0.3459	12	0.4420	8	65.7	35
Norway	7997.4	3	8797.7	3 (—)	800.3	10.0	12	−0.3230	7	0.3374	20	67.2	32
Czech Republic	1880.9	33	2061.7	34 (▼ 1)	180.8	9.6	13	−0.3432	11	0.4174	9	66.0	34
Chile	2588.5	25	2762.0	25 (—)	173.5	6.7	14	−0.3563	14	0.3832	13	68.5	31
Ireland	5960.8	9	6158.0	7 (△ 2)	197.2	3.3	15	−0.2531	3	0.2717	27	63.0	38
Iceland	5255.0	11	5346.3	9 (△ 2)	91.3	1.7	16	−0.4462	26	0.3520	16	76.4	15
Portugal	3473.0	20	3528.4	21 (▼ 1)	55.4	1.6	17	−0.5036	34	0.3859	12	78.8	9
Germany	4592.2	16	4571.9	15 (△ 1)	−20.3	−0.4	18	−0.3673	16	0.3170	21	72.0	24
Slovak Republic	2470.4	28	2455.6	29 (▼ 1)	−14.8	−0.6	19	−0.3427	10	0.3441	18	68.8	29

Table 5. Cont.

Countries	The Current Carbon Productivity		The Adjusted Carbon Productivity		Difference	Relative Change		Non-Service-Based Industry's Carbon Productivity (Exponentiated)		Service Based Industry's Carbon Productivity (Exponentiated)		Service Based Industry Share	
	USD/tCO ₂ -eq.	Rank	USD/tCO ₂ -eq.	Rank		%	Rank	Value	Rank	Value	Rank	%	Rank
Netherlands	4756.0	14	4721.5	13 (△ 1)	−34.5	−0.7	20	−0.5272	36	0.3661	14	80.6	6
Sweden	10,522.9	2	10,320.6	2 (—)	−202.3	−1.9	21	−0.4226	23	0.3040	23	76.6	14
Denmark	6985.8	4	6748.0	5 (▼ 1)	−237.8	−3.4	22	−0.4529	28	0.3165	22	78.0	10
Turkiye	1535.7	37	1439.6	37 (—)	−96.1	−6.3	23	−0.3091	5	0.3479	17	65.3	36
Austria	5469.5	10	4983.1	12 (▼ 2)	−486.4	−8.9	24	−0.3424	9	0.2453	31	73.5	22
United States	3079.6	21	2796.4	24 (▼ 3)	−283.2	−9.2	25	−0.5138	35	0.3402	19	80.7	5
Poland	1421.6	38	1285.2	38 (—)	−136.4	−9.6	26	−0.3480	13	0.3567	15	68.6	30
Spain	4248.9	18	3831.3	20 (▼ 2)	−417.5	−9.8	27	−0.4236	24	0.2880	25	77.3	12
Lithuania	2579.4	26	2303.2	31 (▼ 5)	−276.2	−10.7	28	−0.3381	8	0.2801	26	71.2	26
Switzerland	15,152.3	1	13,430	1 (—)	−1722.4	−11.4	29	−0.2275	2	0.1139	36	74.9	17
Canada	2368.7	30	2083.9	33 (▼ 3)	−284.9	−12.0	30	−0.3838	20	0.3002	24	74.0	19
Slovenia	2979.9	23	2620.4	27 (▼ 4)	−359.4	−12.1	31	−0.2874	4	0.2314	35	69.5	28
Italy	4691.0	15	4089.6	17 (▼ 2)	−601.4	−12.8	32	−0.3838	19	0.2467	30	76.6	13
Belgium	4507.4	17	3859.4	19 (▼ 2)	−648.0	−14.4	33	−0.4590	30	0.2700	28	80.2	7
Hungary	2400.2	29	2021.6	35 (▼ 6)	−378.5	−15.8	34	−0.3176	6	0.2438	33	71.5	25
United Kingdom	6027.7	7	5047.0	10 (▼ 3)	−980.7	−16.3	35	−0.4684	32	0.2479	29	81.7	3
France	6018.6	8	5007.3	11 (▼ 3)	−1011.3	−16.8	36	−0.4478	27	0.2361	34	81.1	4
Latvia	2989.4	22	2443.9	30 (▼ 8)	−545.5	−18.2	37	−0.3929	22	0.2445	32	77.4	11
Luxembourg	6542.6	6	4543.5	16 (▼10)	−1999.1	−30.6	38	−0.3870	21	0.0890	37	88.6	1

Note. △: Increase in rank, ▼: decrease in rank.

The carbon productivity adjustment results can be summarized as follows.

Korea, Estonia, Israel, and Australia, where the carbon productivity improved the most, were three representative countries where the carbon productivity in non-service industries significantly reduced the overall carbon productivity of the country. The change could be identified more clearly when the existing carbon productivity was exponentiated.

In this study, when industrial productivity is exponentiated based on country-level carbon productivity, a positive number can be interpreted as an industry group that increases the carbon productivity of a country, a negative number can be interpreted as an industry group that decreases carbon productivity, and the size of the absolute value represents the degree of impact on the carbon productivity of the entire country.

Comparative analysis was conducted on exponentiating the carbon productivity of the service and non-service industries in 38 OECD countries (2017 to 2019). The country group with the lowest non-service industry carbon productivity and the highest service industry carbon productivity was the country group with the largest change rate in the adjusted carbon productivity estimation results. The carbon productivity of non-service industries in Korea, Estonia, Israel, and Australia was only 50.9% (Korea), 27.2% (Estonia), 65.9% (Israel), and 45.7% (Australia) of the OECD average non-service industry carbon productivity of 1925.3 USD/ton CO₂-eq. In the case of Korea, the carbon productivity in the service industry was 9936.1 USD/ton CO₂-eq. (13th), which was approximately 12% higher than the OECD average service industry carbon productivity of 8909.1 USD/ton CO₂-eq. The carbon productivity auxiliary indicator designed in this study can be appropriately utilized to adjust the size of the corresponding deviation because the carbon productivity in the non-service industry was very low.

Korea is a representative manufacturing-centered country, but it relies on overseas imports for most of its resources, such as oil, bituminous coal, and gas, because it lacks natural resources. Nevertheless, Korea is one of the most energy-consuming countries, accounting for approximately 2% of global energy consumption. In particular, the proportion of energy consumption in the industrial sector is relatively high. The reason for the high proportion of greenhouse gas emissions in the industrial sector is due to the characteristics of the domestic industrial structure centered on energy-intensive manufacturing. The greenhouse gas emissions from manufacturing are approximately 150 million tons CO₂-eq. from the steel industry, approximately 40 million tons CO₂-eq. from petrochemicals, approximately 35 million tons CO₂-eq. from cement, and approximately 15 million tons CO₂-eq. from oil refining. These four industries account for approximately 75% of the greenhouse gas emissions of the entire industrial sector. Looking at the proportion of each industry within the OECD industrial sector, Korea has the highest proportion of manufacturing among the 38 OECD countries, and the proportion of the steel and metal industry, which is the industry that emits the most greenhouse gas, is much higher than that of major countries [24].

Estonia has significant greenhouse gas emissions. The average annual greenhouse gas emissions per capita in the European Union from 2005 to 2019 was 8.4 tons CO₂-eq. In 2005, however, Estonia's average annual greenhouse gas emissions per capita reached 14.1 tons CO₂-eq. Afterward, it showed a steadily decreasing trend. In 2019, it emitted 11.5 tons CO₂-eq. of greenhouse gas. Even based on the average annual greenhouse gas emissions per person in 2019, this was approximately 37% higher than the 15-year average for the European Union. Estonia's greenhouse gas is emitted mainly from the energy industry, which comes from shale oil processing, which is abundant in Estonia. Shale oil, which is used as a raw material for power generation and diesel production, emits significant amounts of greenhouse gas during extraction and processing. Estonia aims to phase out shale oil power production by 2035 and shale oil use in the entire energy sector by 2040. Nevertheless, shale oil remains a major source of power that Estonia relies on locally [25].

Australia is a global exporter of fossil fuels and a representative country of energy demands from fossil fuels. According to Australia's 2019 Greenhouse Gas National Inventory Report, the TGEs from Australia was 530 million tons CO₂-eq., with per capita emissions at

21 tons CO₂-eq., approximately three times the world average, and emissions from coal accounted for approximately 30% of the TGEs [26]. As of 2020, 66% and 7.5% of Australia's total energy production came from coal and natural gas, respectively [27]. In addition to these resource characteristics, Australia's TGEs is influenced by its geographical and economic landscape. The agricultural and livestock sectors, which utilize the country's vast territory, produce significant amounts of methane. In addition, a relatively large number of people use cars and airplanes for intercity travel [28].

Israel is a service-industry-centered country, with the service sector accounting for more than 80% of the national economy. Although most industries are not major greenhouse gas emitters, high greenhouse gas emissions sectors, such as paper, petrochemicals, and cement, contribute 28% of the total industrial economy, leading to relatively more greenhouse gas emissions from the manufacturing field than other OECD countries [29].

These industrial and geographical factors, such as the industrial structure and resource types, can adversely affect carbon productivity calculations. The carbon productivity auxiliary indicator proposed in this study is adjusted by the service and non-service industrial character to calibrate discrepancies. By classifying carbon productivity by industries and applying specific coefficients, the study provides an upward adjustment for countries that inherently emit significant greenhouse gases because of their industrial and geographical characteristics.

Among the countries where the carbon productivity decreased the most, Luxembourg, France, and the United Kingdom had the highest average tertiary industry GDP share over the three years (2017 to 2019) among 38 OECD countries. Hence, the current carbon productivity estimation method, which can estimate high carbon productivity from value-added creation in service industries, tends to skew the national carbon productivity of service-industry-based countries favorably. Therefore, countries with a high proportion of the service industry in their economy are calculated relatively favorably when assessing carbon productivity.

Figure 5 presents a graph comparing current carbon productivity with adjusted carbon productivity. The adjusted carbon productivity bulges outward, centered around the current carbon productivity, represented by the blue line. Upward bulges indicate countries whose carbon productivity has been adjusted upward. These countries exhibit high greenhouse gas emissions relative to created value-added in their non-service industries and have a relatively low proportion of the service industry in their overall economy. Conversely, downward bulges signify countries with a downward adjustment in carbon productivity. These countries typically have a very high proportion of the service industry in their overall economy or very low direct greenhouse gas emissions from their non-service industries.

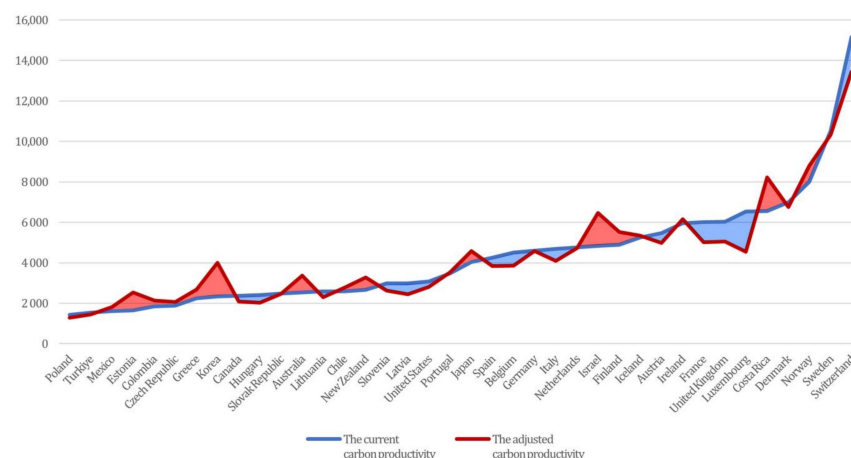


Figure 5. Comparison graph between the current carbon productivity and the adjusted carbon productivity.

6. Proposal and Utilization

The national-level carbon productivity auxiliary indicator designed in this study identifies countries that require additional interpretation of productivity indicators because of their industrial and geographical characteristics. In addition, it adjusts the national-level carbon productivity to an appropriate level, making it a useful auxiliary tool in utilizing the current national carbon productivity indicator.

The carbon productivity auxiliary indicator is based on the adjusted carbon productivity results of OECD countries, derived from multiple regression analysis. This indicator considers the tendency of countries to show large deviations from the current carbon productivity results and the productivity distribution by the service and non-service industries. The indicator uses a non-service industry carbon productivity coefficient of 0.732, a service industry carbon productivity coefficient of 0.367, and a carbon productivity constant of -0.368 , rounding to the second decimal place for ease of application.

Figure 6 presents the formula for the carbon productivity auxiliary indicator. This indicator appropriately compensates for the blind spots not addressed by the current carbon productivity measure because it considers the explanatory power ($R^2 = 0.909$, $adjR^2 = 0.907$) of the multiple regression model and the country-specific classifications based on the industrial structure characteristics and carbon productivity by the service and non-service classification. The indicator considers the greenhouse gas emissions according to the industries of OECD member countries and reflects the added value created according to the level of emissions in the service and non-service industries of each country.

Estimating formula of national-level carbon productivity auxiliary indicator	$= \left(0.7 \times \frac{\text{Total value-added from primary and secondary industry}}{\text{Total greenhouse gas emissions from primary and secondary industry}} \right) + \left(0.4 \times \frac{\text{Total value-added from tertiary industry}}{\text{Total greenhouse gas emission from tertiary industry}} \right) - 0.4$
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Figure 6. Auxiliary indicator estimating formula of national-level carbon productivity.

On the other hand, while the industrial structure characteristics by country can be categorized, the detailed industrial and geographical characteristics, as well as the social and cultural factors, differ even within the same category. Thus, using the multiple regression model correction value directly based on simple statistics may seem unreasonable. Therefore, this study proposes the following. First, the carbon productivity was compared by dividing the countries into service and non-service industry categories based on the proportion of the tertiary industry. The share of the tertiary industry was a major factor in determining the direction of productivity adjustment. Thus, the share of the tertiary industry can serve as a reference point for distinguishing countries where a simple comparison of carbon productivity is possible.

Significant variations among countries were evident when estimating the carbon productivity of OECD member countries based on the current carbon productivity calculation system. For example, Switzerland's carbon productivity in 2019 was 15,143.7 USD/ton CO₂-eq., approximately 3.5 times the OECD average of 4290.9 USD/ton CO₂-eq. In contrast, Poland's carbon productivity was 1419.4 USD/ton CO₂-eq., approximately one-third of the OECD average. This statistical deviation can be stabilized by clustering countries with similar industrial characteristics (Table 6 and Figure 7).

This study set the tertiary industry share of 74% as the criterion for distinguishing service and non-service industry countries. Countries where the tertiary industry accounts for more than 74% of the total economy are classified as service-centered, whereas those below 74% are classified as non-service-centered. This threshold approximates the median tertiary industry share of the 38 OECD countries chosen for the convenience of application. In addition, the carbon productivity auxiliary indicator calculated in this study will be used alongside the current carbon productivity indicator to show the relative gap.

Table 6. The current national-level carbon productivity ranking of OECD countries (average of 2017 to 2019).

Countries	Gross Domestic Product (Million USD)	Total Greenhouse Gas Emission (ton CO ₂ -eq.)	Carbon Productivity (GDP/TGEs, USD/ton CO ₂ -eq.)	Ranking	Deviation from the Mean	Comparing to Average
Switzerland	714,060.0	47,152.3	15,143.7	1	10,852.8	352.93%
Sweden	543,451.2	51,651.4	10,521.5	2	6230.6	245.21%
Norway	416,758.9	52,113.3	7997.2	3	3706.3	186.37%
Denmark	345,153.7	49,480.5	6975.5	4	2684.6	162.57%
Luxembourg	68,846.0	10,521.0	6543.7	5	2252.8	152.50%
Costa Rica	62,451.3	10,291.0	6068.6	6	1777.6	141.43%
United Kingdom	2,806,296.1	465,992.6	6022.2	7	1731.3	140.35%
France	2,704,992.9	449,992.9	6011.2	8	1720.3	140.09%
Ireland	373,757.0	62,774.6	5954.0	9	1663.1	138.76%
Austria	438,957.7	80,327.0	5464.6	10	1173.7	127.35%
Iceland	25,217.6	4798.0	5255.9	11	965.0	122.49%
Finland	266,623.6	54,568.9	4886.0	12	595.1	113.87%
Israel	379,135.8	78,429.5	4834.1	13	543.2	112.66%
Netherlands	886,035.6	186,562.6	4749.3	14	458.4	110.68%
Italy	2,021,676.4	431,082.7	4689.8	15	398.9	109.30%
Germany	3,851,172.0	840,795.9	4580.4	16	289.5	106.75%
Belgium	527,309.7	116,986.0	4507.5	17	216.6	105.05%
Spain	1,376,422.4	324,474.3	4242.0	18	−48.9	98.86%
Japan	5,028,745.1	1,245,731.5	4036.8	19	−254.1	94.08%
Portugal	234,552.6	67,761.5	3461.4	20	−829.5	80.67%
United States	20,463,790.0	6,644,857.7	3079.6	21	−1211.3	71.77%
Latvia	33,085.6	11,060.1	2991.4	22	−1299.5	69.72%
Slovenia	52,366.2	17,588.1	2977.4	23	−1313.5	69.39%
New Zealand	210,512.6	79,092.5	2661.6	24	−1629.3	62.03%
Chile	283,420.3	109,504.0	2588.2	25	−1702.7	60.32%
Lithuania	52,090.2	20,201.0	2578.6	26	−1712.3	60.09%
Australia	1,414,240.6	558,551.2	2532.0	27	−1758.9	59.01%
Slovak Republic	102,499.3	41,550.5	2466.9	28	−1824.0	57.49%
Hungary	155,899.4	64,959.4	2400.0	29	−1891.0	55.93%
Canada	1,706,096.8	720,176.3	2369.0	30	−1921.9	55.21%
Korea	1,666,623.5	712,945.6	2337.7	31	−1953.2	54.48%
Greece	205,716.9	91,706.9	2243.2	32	−2047.7	52.28%
Czech Republic	240,059.2	127,861.1	1877.5	33	−2413.4	43.76%
Colombia	323,032.3	175,881.4	1836.6	34	−2454.3	42.80%
Mexico	1,216,775.7	753,112.2	1615.7	35	−2675.2	37.65%
Estonia	29,543.7	18,488.0	1598.0	36	−2692.9	37.24%
Türkiye	799,133.4	520,133.3	1536.4	37	−2754.5	35.81%
Poland	569,826.5	401,464.5	1419.4	38	−2871.5	33.08%
Average			4290.9			

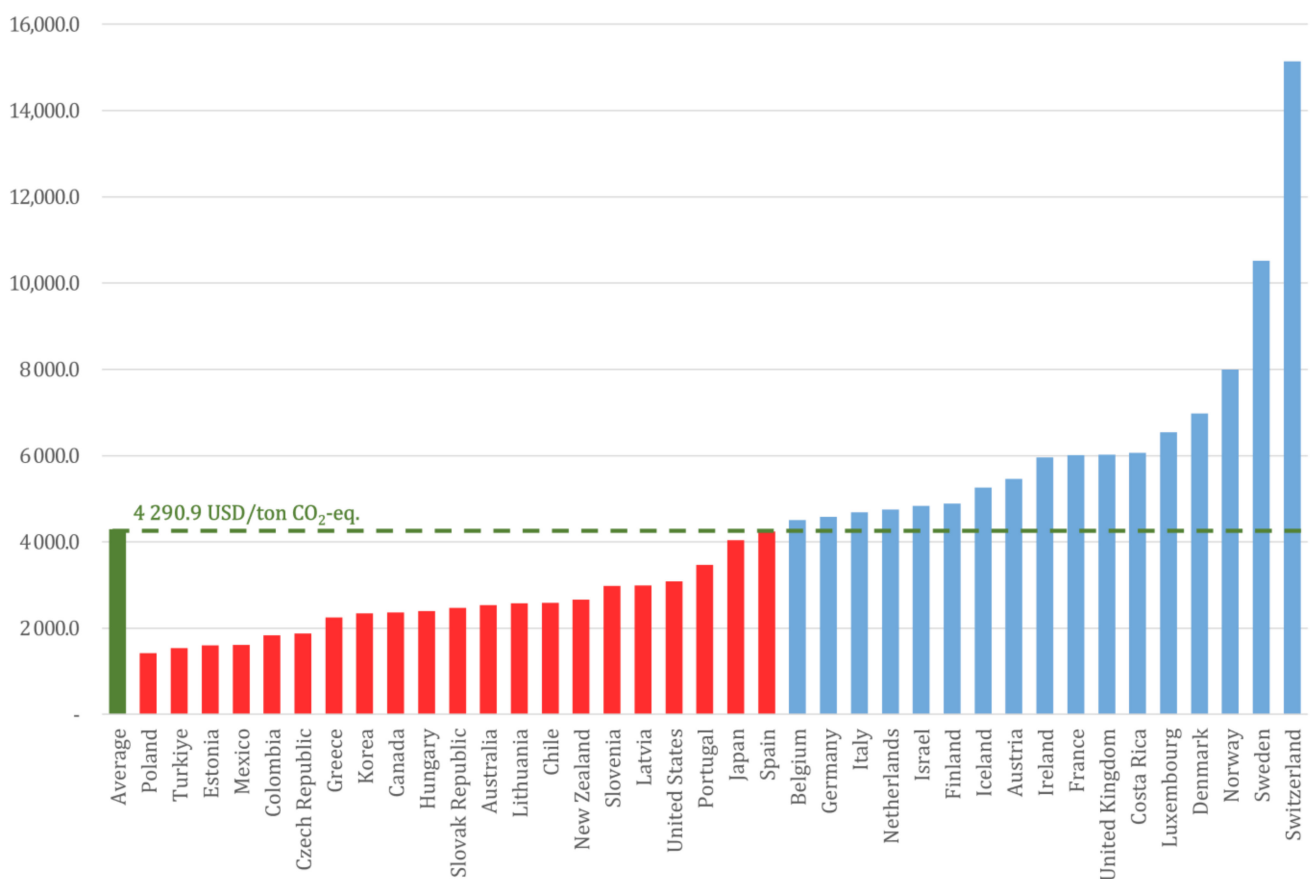


Figure 7. The current national-level carbon productivity ranking graph of OECD countries (average of 2017 to 2019). (Note. The red color is below the average and the blue color is above the average).

The carbon productivity auxiliary indicator calculated in this study will be used alongside the current carbon productivity indicator to show the relative gap. The comparison and analysis confirmed that the auxiliary indicator reduced the deviation for service-industry-centered countries and increased the deviation for non-service-industry-centered countries.

For example, Switzerland recorded the highest carbon productivity among service-industry-centered countries at 13,760.8 USD/ton CO₂-eq., approximately 2.5 times the average of 5371.5 USD/ton CO₂-eq. among 16 OECD service-industry-centered countries. In contrast, Canada, which had the lowest ranking among service-industry-centered countries, had a carbon productivity of 2176.6 USD/ton CO₂-eq., which was less than half the OECD average for service-industry-centered countries. This reduction in deviation can be interpreted as homogeneity in carbon productivity, driven largely by the tertiary industry.

In contrast, the gap in carbon productivity actually increased for non-service-industry-centered countries. Norway recorded the highest carbon productivity among non-service-industry-centered countries at 9218.0 USD/ton CO₂-eq., approximately 2.5 times the average of 3651.2 USD/ton CO₂-eq. among 19 non-service-industry-centered countries. Poland, with the lowest ranking among non-service-industry-centered countries, had a carbon productivity of 1339.5 USD/ton CO₂-eq., approximately one-third of the OECD average. This increased gap was attributed to the varying forms and structures of primary and secondary industries and their economic dependence.

For example, Korea and Australia, which showed the greatest improvement, have a high dependence on greenhouse-gas-emitting industries, resulting in significant adjustments to their carbon productivity. In contrast, Hungary and Slovenia, which showed the largest decrease, have relatively high shares of the secondary industry, but a significant

proportion of their economy is in assembly industries [30], which import parts or intermediate goods and produce finished products [31,32]. This resulted in a decrease in carbon productivity (Tables 7 and 8, Figures 8 and 9).

Table 7. Current and adjusted carbon productivity rankings of service-sector-based countries in the OECD list (average of 2017 to 2019).

Countries	The Current Carbon Productivity (\$/tCO ₂ -eq.)		The Adjusted Carbon Productivity (\$/tCO ₂ -eq.)		Relative Change
	Value	Rank	Value	Rank	
Switzerland	15,143.7	1	13,760.8	1 (—)	9.1%
Sweden	10,521.5	2	10,860.7	2 (—)	3.2%
Costa Rica	6068.6	5	8167.2	3 (△2)	34.6%
Denmark	6975.5	3	7115	4 (▼1)	2.0%
Israel	4834.1	9	6917.9	5 (△4)	43.1%
Iceland	5255.9	8	5644.1	6 (△2)	7.4%
United Kingdom	6022.2	6	5301.4	7 (▼1)	−12.0%
France	6011.2	7	5248.7	8 (▼1)	−12.7%
Netherlands	4749.3	10	5009.0	9 (△1)	5.5%
Luxembourg	6543.7	4	4690.6	10 (▼6)	−28.3%
Italy	4689.8	11	4268.8	11 (—)	−9.0%
Belgium	4507.5	12	4054.2	12 (—)	−10.1%
Spain	4242.0	13	4020.2	13 (—)	−5.2%
Portugal	3461.4	14	3740.2	14 (—)	8.1%
United States	3079.6	15	2956.7	15 (—)	−4.0%
Greece	2243.2	18	2877.4	16 (△2)	28.3%
Estonia	1598.0	19	2702.3	17 (△2)	69.1%
Latvia	2991.4	16	2546.4	18 (▼2)	−14.9%
Canada	2369.0	17	2176.6	19 (▼2)	−8.1%
Average	5332.0		5371.5		

Note. △: Increase in rank, ▼: decrease in rank.

Table 8. Current and adjusted carbon productivity rankings of non-service-sector-based countries in the OECD list (average of 2017 to 2019).

Countries	The current Carbon Productivity (\$/tCO ₂ -eq.)		The adjusted Carbon Productivity (\$/tCO ₂ -eq.)		Relative Change
	Value	Rank	Value	Rank	
Norway	7997.2	1	9218.0	1 (—)	15.3%
Ireland	5954.0	2	6387.3	2 (—)	7.3%
Finland	4886.0	4	5841.4	3 (△1)	19.6%
Austria	5464.6	3	5189.1	4 (▼1)	−5.0%
Japan	4036.8	6	4831.7	5 (△1)	19.7%
Germany	4580.4	5	4791.2	6 (▼1)	4.6%
Korea	2337.7	14	4260.5	7 (△7)	82.3%
Australia	2532.0	11	3577.8	8 (△3)	41.3%
New Zealand	2661.6	8	3472.8	9 (▼1)	30.5%
Chile	2588.2	9	2899.9	10 (▼1)	12.0%
Slovenia	2977.4	7	2706.8	11 (▼4)	−9.1%
Slovak Republic	2466.9	12	2567.7	12 (—)	4.1%
Lithuania	2578.6	10	2395.6	13 (▼3)	−7.1%
Colombia	1836.6	16	2240.8	14 (△2)	22.0%
Czech Republic	1877.5	15	2164.7	15 (—)	15.3%
Hungary	2400.0	13	2091.5	16 (▼3)	−12.9%
Mexico	1615.7	17	1899.8	17 (—)	17.6%

Table 8. Cont.

Countries	The current Carbon Productivity (\$/tCO ₂ -eq.)		The adjusted Carbon Productivity (\$/tCO ₂ -eq.)		Relative Change
	Value	Rank	Value	Rank	
Turkiye	1536.4	18	1496.4	18 (—)	−2.6%
Poland	1419.4	19	1339.5	19 (—)	−5.6%
Average	3249.8		3651.2		

Note. △: Increase in rank, ▼: decrease in rank. Bolded and backgrounded countries show clear difference between the current carbon productivity and the adjusted carbon productivity. Details are described in the manuscript.

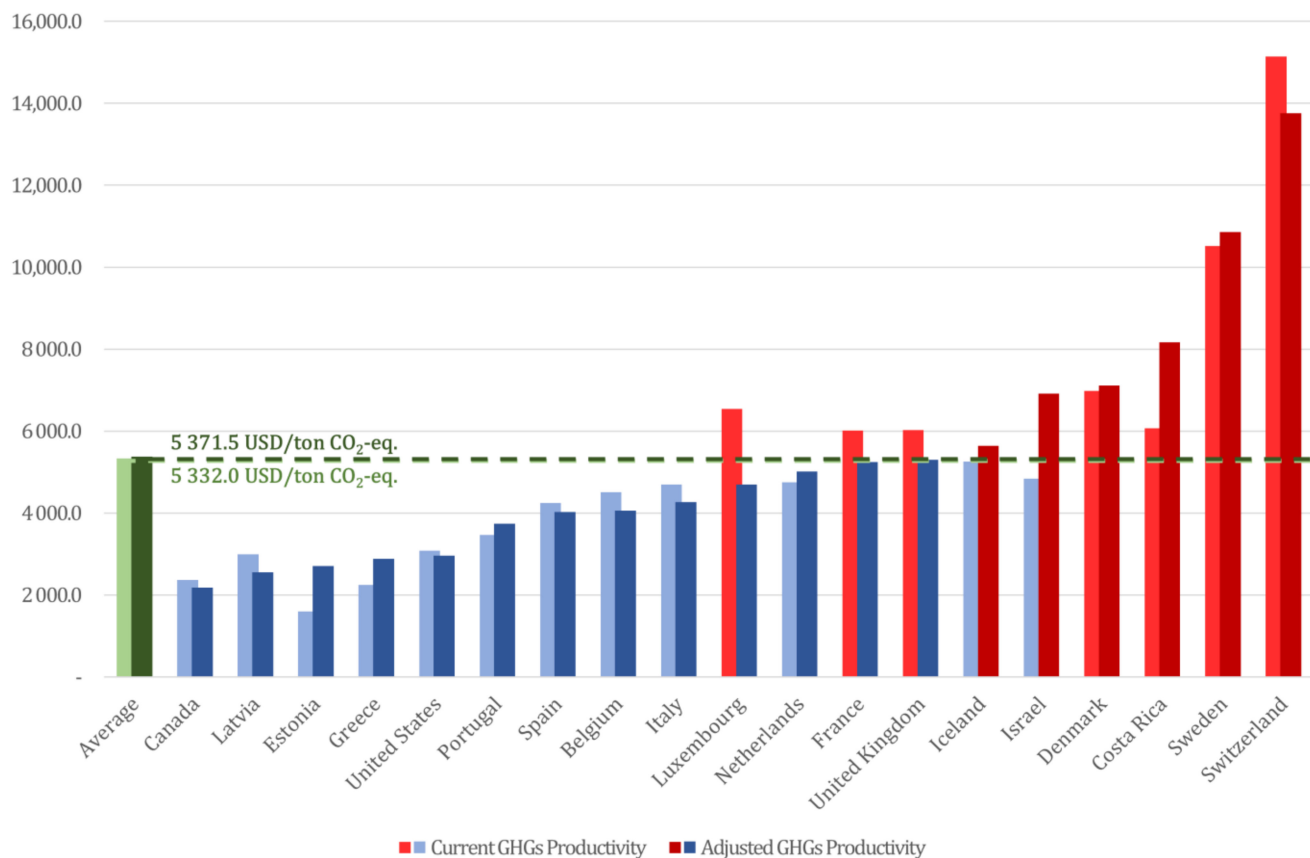


Figure 8. Current and adjusted carbon productivity rankings of service-sector-based countries in the OECD list (average of 2017 to 2019). (Note. The red color is below the average and the blue color is above the average).

Thus, the auxiliary indicator of this study for carbon productivity can be seen as compensating for the gaps not considered by the current carbon productivity measures, especially those related to industrial and geographical characteristics. This study sets the tertiary industry share of 74% as the criterion for distinguishing service and non-service industry countries. Countries where the tertiary industry accounts for more than 74% of the total economy are classified as service-centered, and those below 74% are classified as non-service-centered. This threshold approximates the median tertiary industry share of the 38 OECD countries chosen for the convenience of application. In addition, the carbon productivity auxiliary indicator calculated in this study will be used alongside the current carbon productivity indicator to show the relative gap.

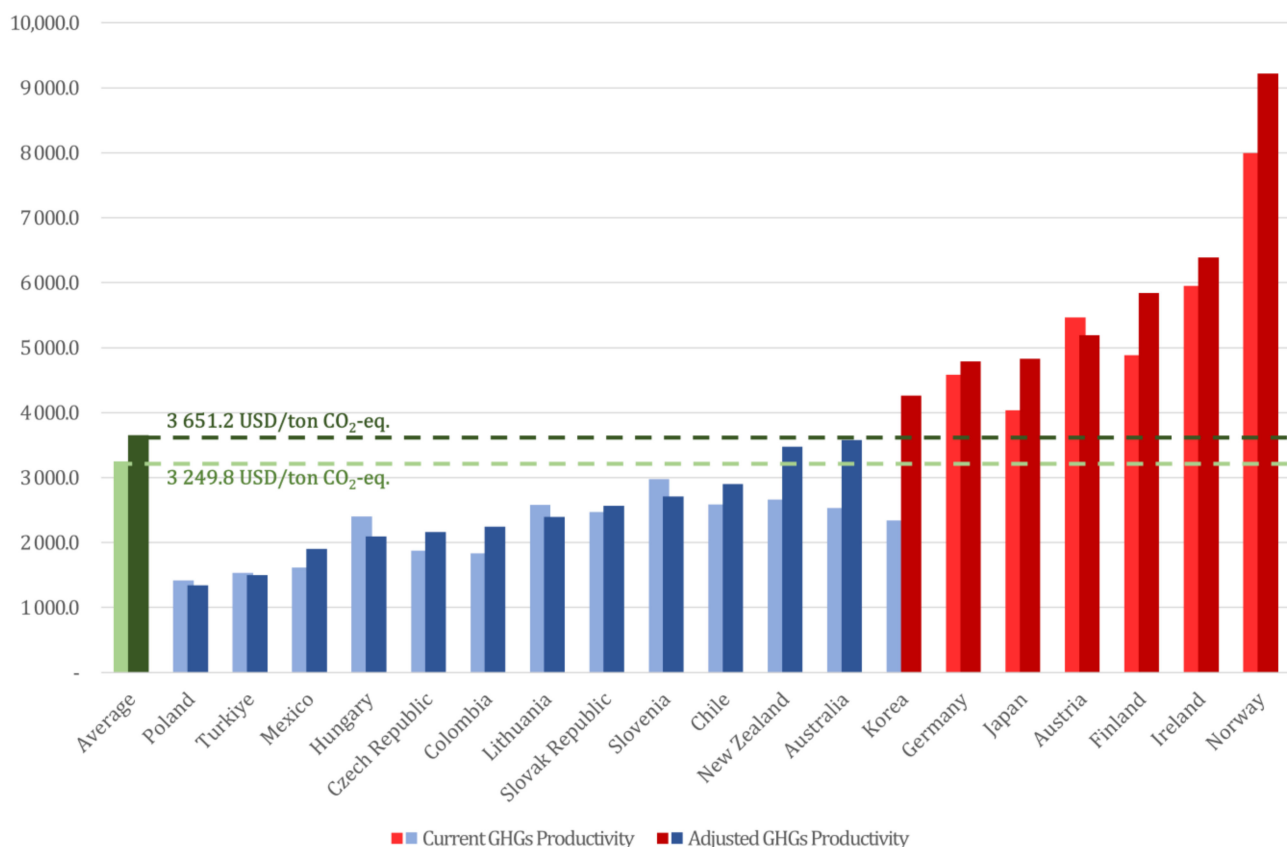


Figure 9. Current and adjusted carbon productivity rankings of non-service-sector-based countries in the OECD list (average of 2017 to 2019). (Note. The red color is below the average and the blue color is above the average).

7. Conclusions

This study designed a multiple regression model using GDP and industry-specific greenhouse gas emissions statistics and corrected the GDP/TGEs, the current national carbon productivity calculation method. In addition, the carbon productivity in the service and non-service industry sectors, which was the criterion for variable division in the regression model, was calculated separately, the carbon productivity and ranking fluctuation ranges were compared and analyzed, and auxiliary indicators and utilization methods that can be used with the current carbon productivity indicator were proposed.

The research results for each productivity indicator can be summarized as follows.

For carbon productivity, countries with high greenhouse gas emissions in non-service industries because of their industrial structures (e.g., Korea, Estonia, and Australia) were appropriately selected and corrected. On the other hand, some countries (e.g., Luxembourg and Costa Rica) with low carbon productivity in the service industry but evaluated as having high overall carbon productivity because of the small absolute amount of greenhouse gas emitted by the service industry were corrected downward. The carbon productivity auxiliary indicator was designed using a non-service industry carbon productivity coefficient of 0.732, a service industry carbon productivity coefficient of 0.367, and a carbon productivity constant of -0.368 , rounded to the second decimal place for convenience $((0.7 \times \text{non-service industry productivity}) + (0.3 \times \text{service industry productivity}) - 0.4)$. A comparative analysis was conducted using the current carbon productivity and the carbon productivity auxiliary indicators by dividing service and non-service industry countries based on the proportion of the service industry in the economy of that country.

The analysis showed that the carbon productivity auxiliary indicator designed in this study reduced the deviation for service-industry-centered countries compared to

the current carbon productivity indicator while increasing the deviation for non-service-industry-centered countries. For service-industry-centered countries, despite differences in the form and structure of primary and secondary industries, the tertiary industry essentially drives GDP, suggesting homogeneity in carbon productivity. For non-service-industry-centered countries, the main differences in the form and structure of the primary and secondary industries, as well as the large difference in economic dependence by each industrial group, mean that the auxiliary indicator can appropriately quantify the gaps difficult to consider using the current carbon productivity indicator.

For example, Korea and Luxembourg, which have large upward and downward ranges of carbon productivity adjustments, can be compared through their carbon-intensive steel industries. According to the ESG report of company P, the largest steel company in Korea, the greenhouse gas emitted per ton of steel products is approximately 2 tons CO₂-eq. [33]. Similarly, company A, a leading steel company in Luxembourg, reports very similar emissions per ton of steel products (2 tons CO₂-eq.) [34]. This means that greenhouse gas emissions per unit weight are similar regardless of the country, with absolute emissions increasing with production volume. Luxembourg has a high proportion of the service industry in its national economy. Therefore, it is likely to be calculated favorably under the current method, whereas Korea, with a high proportion of manufacturing, is likely to be calculated unfavorably.

The carbon productivity auxiliary indicator designed in this study provides insight into which areas may be advantageous or disadvantageous in terms of the carbon productivity because of the industrial structure of each country and the extent of these advantages and disadvantages.

In summary, the carbon productivity adjustment multiple regression model designed in this study, the comparative analysis of carbon productivity by the service and non-service industries, and the results of applying the carbon productivity auxiliary indicator highlight the limitations of the current national carbon productivity indicator. This paper also provided insights into improving the productivity indicators by considering each country's industrial structure. The proposed carbon productivity auxiliary indicator is expected to enhance the rationality of the current indicator by being used alongside the existing national carbon productivity calculation.

For example, the proposed auxiliary indicator can be useful for comparing and analyzing carbon productivity between service- and non-service-industry-centered countries or among countries with similar export structures by sector. The auxiliary indicator directly reflects the value-added created from greenhouse gas emissions. Therefore, it is a valuable supplement to the existing GDP/TGEs indicator, which overlooks the industrial structure characteristics. Nevertheless, implications are derived at the level of descriptive statistics analysis regarding the differences in rankings by category (service and non-service) and the results of the carbon productivity changes by adjustments. These results suggest conducting a more sophisticated and detailed national-level carbon productivity analysis.

Author Contributions: J.H.L. devised the research, the main conceptual ideas, and the proof outline. In addition, he worked out almost all of the technical details and conducted the current and adjusted national-level carbon productivity estimation by multiple regression analysis. H.Y.K. and Y.W.H. supervised and reviewed the research. All authors discussed the results and commented on the manuscript. All authors have read and agreed to the published version of the manuscript.

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