Article

Not peer-reviewed version

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

Jong-Hyo Lee , Hong-Yoon Kang * , Yong Woo Hwang

Posted Date: 15 July 2024

doi: 10.20944/preprints202407.1169.v1

Keywords: carbon productivity; Gross Domestic Product (GDP); Total Greenhouse gas Emission (TGE); the auxiliary indicator; environmental statistics research; multiple regression analysis

Article

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 (Lee, J. H.); kanghy@inha.ac.kr (Kang, H. Y.)
[2] Department of Environmental Engineering, Inha University, 100, Inha-ro, Michuhol-gu, Incheon 22212, Republic of Korea; hwangyw@inha.ac.kr (Hwang, Y. W.)
* 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 indicators 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, emphasizing its utility in interpreting productivity indicators within the context of varying industrial compositions across OECD countries. This study underscores the inadequacies of the current national productivity estimating method, pinpointing areas requiring refinement. Specifically, the method for estimating the auxiliary indicator for carbon productivity guarantees enhanced rationality when integrated with current methodologies. Moreover, by elucidating the nuances of industrial structures, this study advocates for more sophisticated approaches to interpreting and managing the productivity indicators tailored to each 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

---

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 transition 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

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 15 July 2024 doi:10.20944/preprints202407.1169.v1

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 (TGE). The result expresses the value-added generated per ton of CO_2-equivalent greenhouse gas emissions, measured in USD/ton CO_2-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 TGE 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 GDP and TGE 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 [13–15]. Furthermore, although TGE 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 TGE in a specific country [13,16–20].

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, TGE of the developed country decrease, which should be reflected in the carbon productivity calculation of the developed country through a separate adjustment process [21].

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 15 July 2024 doi:10.20944/preprints202407.1169.v1

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

According to OECD data (https://data.oecd.org/) on GDP [22] and TGE [23], Korea's average per capita greenhouse gas emissions in 2019 was 13.5 tons CO_2-eq., the 6th highest among 38 OECD countries and over 40% higher than the OECD average of 9.5 tons CO_2-eq. Australia had the highest per capita emissions at 21.9 tons CO_2-eq., approximately 1.6 times more than Korea. The United States and Canada followed, with 20.0 and 19.2 tons CO_2-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 CO_2-eq., followed by Colombia with 3.6 tons CO_2-eq. and Sweden with 4.9 tons CO_2-eq.

By contrast, the carbon productivity indicator (GDP/TGE) showed different results from per capita emissions. In 2019, Korea generated an average value-added of 2,355.1 USD/ton CO_2-eq., approximately half of the OECD average of 4,490.0 USD/ton CO_2-eq., ranking 32nd out of 38 OECD countries. Switzerland had the highest carbon productivity, producing 15,524.2 USD/ton CO_2-eq., approximately 6.6 times higher than Korea. Sweden and Norway followed, with 10,549.5 and 8,021.1 USD/ton CO_2-eq., respectively. Japan ranked 19th with 4,234.3 USD/ton CO_2-eq., approximately 1.8 times higher than Korea. Turkey had the lowest carbon productivity at 1,493.8 USD/ton CO_2-eq., approximately one-tenth of Switzerland, followed by Poland with 1,542.6 USD/ton CO_2-eq. and Mexico with 1,722.7 USD/ton CO_2-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/TGE indicator tends to overestimate or underestimate certain countries without considering their industrial and geographical characteristics. For example, Luxembourg's average per capita greenhouse gas emissions were 17.3 tons CO_2-eq., approximately three times higher than Turkey's. On the other hand, Luxembourg's value-added creation per unit of greenhouse gas emissions was 6,501.5 USD/ton CO_2-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	8,021.1	3
Luxembourg	**17.3**	**4**	Costa Rica	7,901.3	4
New Zealand	16.0	5	Denmark	7,381.5	5
Korea	**13.5**	**6**	Ireland	6,545.6	6
Iceland	13.1	7	**Luxembourg**	**6,501.5**	**7**
Ireland	12.4	8	United Kingdom	6,303.7	8
Czech Republic	11.6	9	France	6,235.3	9
Estonia	11.0	10	Austria	5,558.2	10
Netherlands	10.4	11	Iceland	5,221.0	11
Belgium	10.1	12	Finland	5,092.6	12
Poland	10.1	13	Israel	5,083.5	13
Japan	**9.6**	**14**	Netherlands	5,030.5	14
Germany	9.6	15	Germany	4,893.1	15
Finland	9.5	16	Italy	4,763.0	16

Countries	Greenhouse gas emission (per capita, ton CO_2-eq.)	Ranking	Countries	Carbon productivity (USD/ton CO_2-eq.)	Ranking
Norway	9.5	17	Belgium	4,601.1	17
Austria	9.0	18	Spain	4,500.5	18
Israel	8.7	19	**Japan**	**4,234.3**	**19**
Slovenia	8.2	20	Portugal	3,743.0	20
Denmark	8.1	21	United States	3,230.8	21
Greece	8.0	22	Slovenia	3,157.9	22
Slovak Republic	7.3	23	Latvia	3,085.2	23
Lithuania	7.2	24	Lithuania	2,704.9	24
Italy	7.1	25	New Zealand	2,664.0	25
United Kingdom	6.8	26	Slovak Republic	2,645.7	26
Hungary	6.6	27	Hungary	2,532.3	27
Spain	6.6	28	Chile	2,508.3	28
France	6.5	29	Australia	2,478.3	29
Portugal	6.2	30	Canada	2,409.5	30
Turkiye	**6.2**	**31**	Greece	2,382.5	31
Mexico	5.9	32	**Korea**	**2,355.1**	**32**
Latvia	5.8	33	Estonia	2,138.0	33
Chile	5.8	34	Czech Republic	2,045.7	34
Switzerland	5.4	35	Colombia	1,836.6	35
Sweden	4.9	36	Mexico	1,722.7	36
Colombia	3.6	37	Poland	1,542.6	37
Costa Rica	1.6	38	**Turkiye**	**1,493.8**	**38**

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/TGE), indicating the economic value-added generated per ton of greenhouse gas emitted. This study examined the extent of the advantages or disadvantages in 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 TGE 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 is available for all time series data, the TGE data lacks 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 TGE statistics according to the industries revealed Spearman correlation coefficients of .444 for the non-service industry and .714 for the service industry, respectively. Hence, a moderate positive correlation exists between GDP and TGE for the non-service industry, and a very strong positive correlation exists for the service industry. The significance probabilities were all $p < .001$, indicating a clear statistical basis for the interaction between the variables (Table 2).

Table 2. Results of correlation analysis between GDP and TGE by 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×TGE)	.444	.067	3.690	<.001[c]
		Service industry (GDP×TGE)	.714	.054	10.784	<.001[c]

[a] Not assuming the null hypothesis. [b] Using the asymptotic standard error assuming the null hypothesis. [c] Based on normal approximation. * GDP: Gross Domestic Product, TGE: Total Greenhouse gas Emission.

Therefore, this study used the OECD real GDP (base year 2015) and TGE 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 non-service industry greenhouse gas emissions, and $GHGs_{3rd}$ represents 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 CO_2-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 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 $R^2 = .909$ and adjusted $R^2 = .907$. In addition, the difference between R^2 and adjusted R^2 was less than 0.1%, indicating sufficient validity (Table 3).

 doi:10.20944/preprints202407.1169.v1

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

	R	R^2	Adjusted R^2	Std. Error of the Estimate	R^2 Change
adjCP[b]	.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 service and non-service sectors.

		Unstandardized Coefficients		Standardized Coefficients Beta	t	Sig.	Collinearity Statistics	
		B	Std. Error				Tolerance	VIF
adjCP	(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 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).

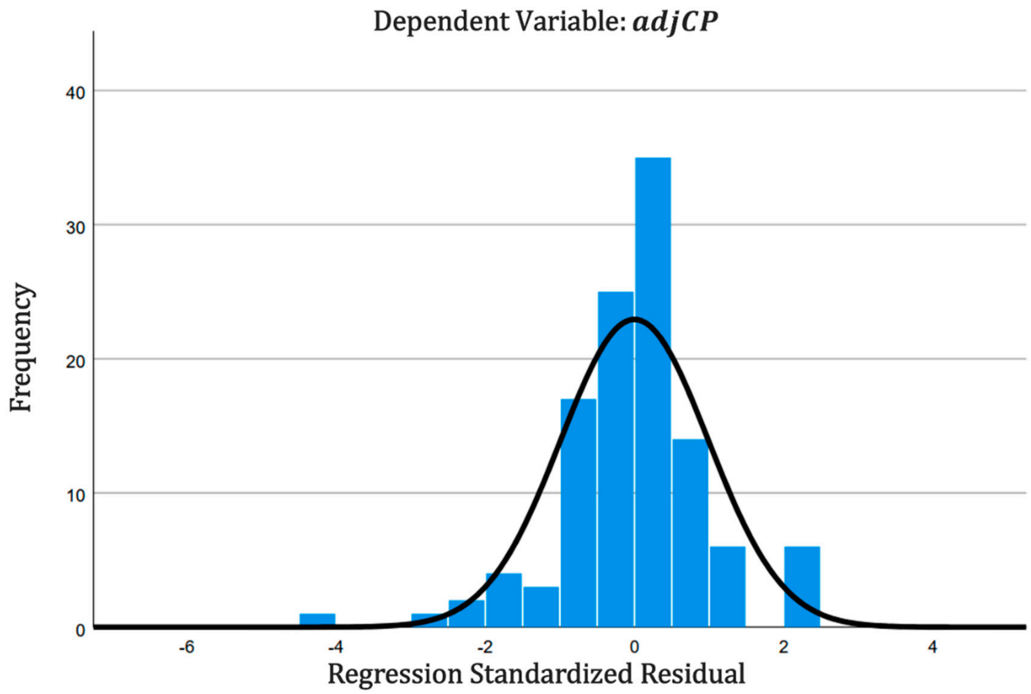

Figure 1. Normal distribution histogram of a multiple regression model for adjusting the GDP using carbon productivity by service and non-service sectors. (* *adjCP*: adjusted carbon productivity).

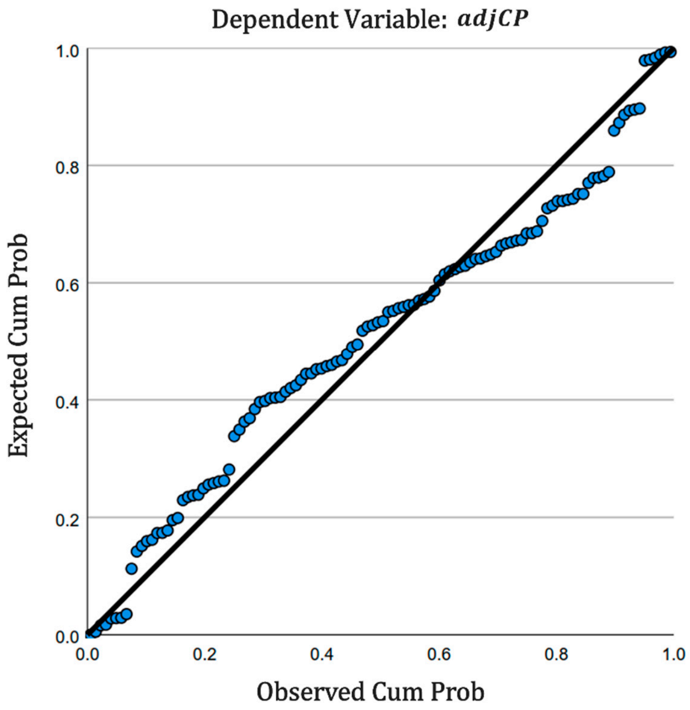

Figure 2. Normal P–P plots of the regression standardized residual of a multiple regression model for adjusting the GDP using carbon productivity by service and non-service sectors. (* *adjCP*: adjusted carbon productivity).

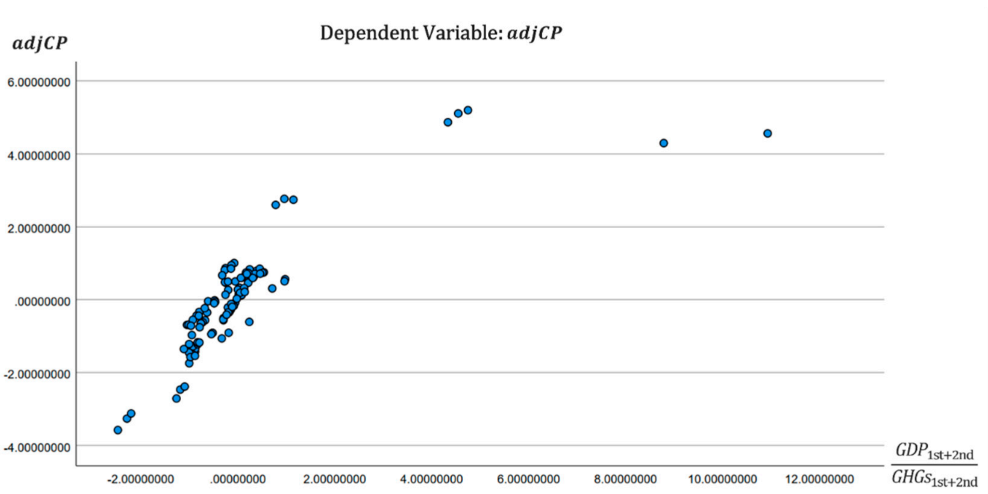

Figure 3. Partial regression plots of a multiple regression model for adjusting the GDP using carbon productivity of the non-service sector. (* *adjCP*: adjusted carbon productivity).

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 15 July 2024 doi:10.20944/preprints202407.1169.v1

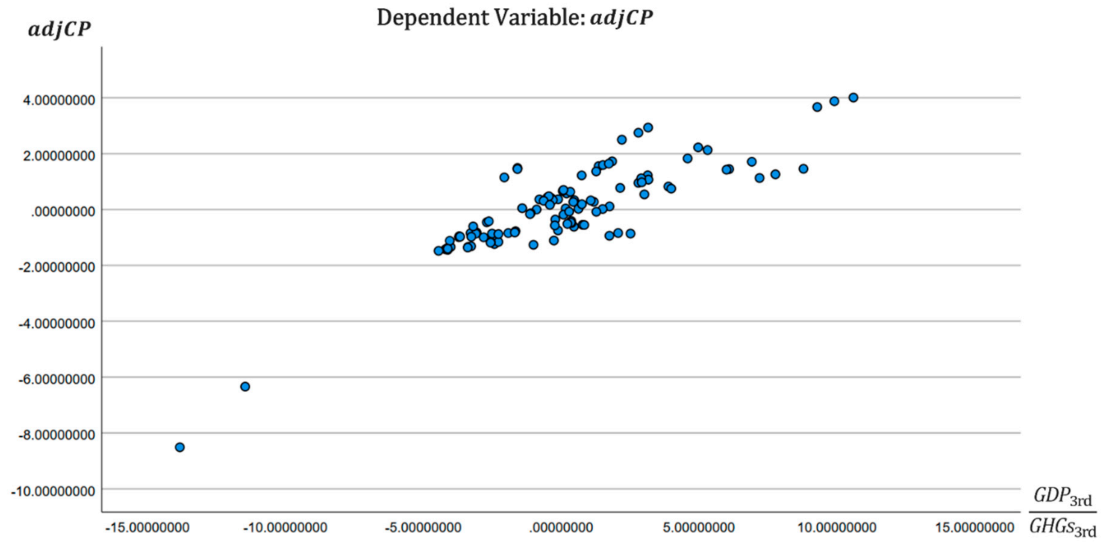

Figure 4. Partial regression plots of a multiple regression model for adjusting the GDP using carbon productivity of the service sector. (* adjCP: adjusted carbon productivity).

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 2,337.5 USD/ton CO_2-eq., ranking 31 out of 38 OECD countries, to 3,996.0 USD/ton CO_2-eq., approximately 71.0% improvement, moving up 13 places to 18th. Similarly, Estonia's carbon productivity increased from 1,651.8 USD/ton CO_2-eq., ranking 35, to 2,525.3 USD/ton CO_2-eq., approximately 52.9% improvement, moving up seven places to 28th. Israel's carbon productivity increased from 4,832.7 USD/ton CO_2-eq., ranking 13, to 6,460.1 USD/ton CO_2-eq., approximately 33.7% improvement, moving up to sixth. Australia's carbon productivity increased from 2,531.8 USD/ton CO_2-eq., ranking 27, to 3,360.7 USD/ton CO_2-eq., approximately 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 6,542.6 USD/ton CO_2-eq., ranking 6, to 4,543.5 USD/ton CO_2-eq., an approximately 30.6% decrease, falling 10 places to 16th. Latvia's carbon productivity decreased from 2,989.4 USD/ton CO_2-eq., ranking 22, to 2,443.9 USD/ton CO_2-eq., a decrease of approximately 18.2% decrease, falling eight places. France's carbon productivity decreased from 6,018.6 USD/ton CO_2-eq., ranking eight, to 5,006.6 USD/ton CO_2-eq., an approximately 16.8% decrease, falling three places. The carbon productivity of the UK decreased from 6,027.7 USD/ton CO_2-eq. to 5,047.0 USD/ton CO_2-eq., an approximately 16.3% decrease, also falling three places (Table 5).

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

Countries	Current GHG productivity		Adjusted GHGs productivity		Difference	Relative Change		Non-service-based industry's GHGs productivity (exponentiated)		Service based industry's GHGs productivity (exponentiated)		Service based industry share	
	USD/tCO_2-eq.	Rank	USD/tCO_2-eq.	Rank		%	Rank	Value	Rank	Value	Rank	%	Rank
Korea	2,337.5	31	3,996.0	18 (△ 13)	1,658.5	71.0	1	−0.3775	17	0.6285	1	64.4	37
Estonia	1,651.8	35	2,525.3	28 (△ 7)	873.5	52.9	2	−0.4994	33	0.6171	2	74.1	18
Israel	4,832.7	13	6,460.1	6 (△ 7)	1,627.4	33.7	3	−0.5808	37	0.5220	3	80.1	8
Australia	2,531.8	27	3,360.7	22 (△ 5)	828.9	32.7	4	−0.4586	29	0.5210	4	72.8	23
Costa Rica	6,551.4	5	8,224.7	4 (△ 1)	1,673.2	25.5	5	0.0953	1	0.0373	38	76.2	16
New Zealand	2,661.6	24	3,267.9	23 (△ 1)	606.3	22.8	6	−0.4615	31	0.4819	6	73.9	20
Greece	2,248.5	32	2,686.0	26 (△ 6)	437.6	19.5	7	−0.6326	38	0.5100	5	82.7	2
Colombia	1,836.4	34	2,126.0	32 (△ 2)	289.5	15.8	8	−0.3656	15	0.4535	7	67.1	33

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 15 July 2024 doi:10.20944/preprints202407.1169.v1

Japan	4,041.0	19	4,582.9	14 (△ 5)	541.8	13.4	9	−0.3811	18	0.3995	11	70.0	27
Finland	4,888.7	12	5,521.7	8 (△ 4)	633.1	12.9	10	−0.4293	25	0.4049	10	73.6	21
Mexico	1,616.7	36	1,807.5	36 -	190.8	11.8	11	−0.3459	12	0.4420	8	65.7	35
Norway	7,997.4	3	8,797.7	3 -	800.3	10.0	12	−0.3230	7	0.3374	20	67.2	32
Czech Republic	1,880.9	33	2,061.7	34 (▼ 1)	180.8	9.6	13	−0.3432	11	0.4174	9	66.0	34
Chile	2,588.5	25	2,762.0	25 -	173.5	6.7	14	−0.3563	14	0.3832	13	68.5	31
Ireland	5,960.8	9	6,158.0	7 (△ 2)	197.2	3.3	15	−0.2531	3	0.2717	27	63.0	38
Iceland	5,255.0	11	5,346.3	9 (△ 2)	91.3	1.7	16	−0.4462	26	0.3520	16	76.4	15
Portugal	3,473.0	20	3,528.4	21 (▼ 1)	55.4	1.6	17	−0.5036	34	0.3859	12	78.8	9
Germany	4,592.2	16	4,571.9	15 (△ 1)	−20.3	− 0.4	18	−0.3673	16	0.3170	21	72.0	24
Slovak Republic	2,470.4	28	2,455.6	29 (▼ 1)	−14.8	− 0.6	19	−0.3427	10	0.3441	18	68.8	29
Netherlands	4,756.0	14	4,721.5	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	6,985.8	4	6,748.0	5 (▼ 1)	−237.8	− 3.4	22	−0.4529	28	0.3165	22	78.0	10
Turkiye	1,535.7	37	1,439.6	37 -	−96.1	− 6.3	23	−0.3091	5	0.3479	17	65.3	36
Austria	5,469.5	10	4,983.1	12 (▼ 2)	−486.4	− 8.9	24	−0.3424	9	0.2453	31	73.5	22
United States	3,079.6	21	2,796.4	24 (▼ 3)	−283.2	− 9.2	25	−0.5138	35	0.3402	19	80.7	5
Poland	1,421.6	38	1,285.2	38 -	−136.4	− 9.6	26	−0.3480	13	0.3567	15	68.6	30
Spain	4,248.9	18	3,831.3	20 (▼ 2)	−417.5	− 9.8	27	−0.4236	24	0.2880	25	77.3	12
Lithuania	2,579.4	26	2,303.2	31 (▼ 5)	−276.2	−10.7	28	−0.3381	8	0.2801	26	71.2	26
Switzerland	15,152.3	1	1,343.0	1 -	−1,722.4	−11.4	29	−0.2275	2	0.1139	36	74.9	17
Canada	2,368.7	30	2,083.9	33 (▼ 3)	−284.9	−12.0	30	−0.3838	20	0.3002	24	74.0	19
Slovenia	2,979.9	23	2,620.4	27 (▼ 4)	−359.4	−12.1	31	−0.2874	4	0.2314	35	69.5	28
Italy	4,691.0	15	4,089.6	17 (▼ 2)	−601.4	−12.8	32	−0.3838	19	0.2467	30	76.6	13
Belgium	4,507.4	17	3,859.4	19 (▼ 2)	−64.8	−14.4	33	−0.4590	30	0.2700	28	80.2	7
Hungary	2,400.2	29	2,021.6	35 (▼ 6)	−378.5	−15.8	34	−0.3176	6	0.2438	33	71.5	25
United Kingdom	6,027.7	7	5,047.0	10 (▼ 3)	−980.7	−16.3	35	−0.4684	32	0.2479	29	81.7	3
France	6,018.6	8	5,007.3	11 (▼ 3)	−1,011.3	−16.8	36	−0.4478	27	0.2361	34	81.1	4
Latvia	2,989.4	22	2,443.9	30 (▼ 8)	−545.5	−18.2	37	−0.3929	22	0.2445	32	77.4	11
Luxembourg	6,542.6	6	4,543.5	16 (▼ 10)	−1,999.1	−30.6	38	−0.3870	21	0.0890	37	88.6	1

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.

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; the size of the absolute value means 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 industry 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 1,925.3 USD/ton CO_2-eq. In the case of Korea, the carbon productivity in the service industry was 9,936.1 USD/ton CO_2-eq. (13th), which was approximately 12% higher than the OECD average service industry carbon productivity of 8,909.1 USD/ton CO_2-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.

 doi:10.20944/preprints202407.1169.v1

Nevertheless, Korea is one of the 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. Greenhouse gas emissions from manufacturing are approximately 150 million tons CO_2-eq. from the steel industry, approximately 40 million tons CO_2-eq. from petrochemicals, approximately 35 million tons CO_2-eq. from cement, and approximately 15 million tons CO_2-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 CO_2-eq. In 2005, however, Estonia's average annual greenhouse gas emissions per capita reached 14.1 tons CO_2-eq. Afterward, it showed a steadily decreasing trend. In 2019, it emitted 11.5 tons CO_2-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, TGE of Australia was 530 million tons CO_2-eq., with per capita emissions at 21 tons CO_2-eq., approximately three times the world average, and emissions from coal accounted for approximately 30% of TGE [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 TGE 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. This carbon productivity auxiliary indicator proposed in this study is adjusted by the service and non-service industrial character calibrate discrepancies. 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.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 15 July 2024 doi:10.20944/preprints202407.1169.v1

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 service and non-service industry. 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 5 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=.909, $adjR^2$=.907) of the multiple regression model and the country-specific classifications based on industrial structure characteristics and carbon productivity by service and non-service classification. The indicator considers the greenhouse gas emissions according to the industry 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.

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

Figure 5. 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 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 CO_2-eq., approximately 3.5 times the OECD average of 4,290.9 USD/ton CO_2-eq. In contrast, Poland's carbon productivity was 1,419.4 USD/ton CO_2-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 6).

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.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 15 July 2024 doi:10.20944/preprints202407.1169.v1

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/TGE, \$/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	6,230.6	245.21%
Norway	416,758.9	52,113.3	7,997.2	3	3,706.3	186.37%
Denmark	345,153.7	49,480.5	6,975.5	4	2,684.6	162.57%
Luxembourg	68,846.0	10,521.0	6,543.7	5	2,252.8	152.50%
Costa Rica	62,451.3	10,291.0	6,068.6	6	1,777.6	141.43%
United Kingdom	2,806,296.1	465,992.6	6,022.2	7	1,731.3	140.35%
France	2,704,992.9	449,992.9	6,011.2	8	1,720.3	140.09%
Ireland	373,757.0	62,774.6	5,954.0	9	1,663.1	138.76%
Austria	438,957.7	80,327.0	5,464.6	10	1,173.7	127.35%
Iceland	25,217.6	4,798.0	5,255.9	11	965.0	122.49%
Finland	266,623.6	54,568.9	4,886.0	12	595.1	113.87%
Israel	379,135.8	78,429.5	4,834.1	13	543.2	112.66%
Netherlands	886,035.6	186,562.6	4,749.3	14	458.4	110.68%
Italy	2,021,676.4	431,082.7	4,689.8	15	398.9	109.30%
Germany	3,851,172.0	840,795.9	4,580.4	16	289.5	106.75%
Belgium	527,309.7	116,986.0	4,507.5	17	216.6	105.05%
Spain	1,376,422.4	324,474.3	4,242.0	18	−48.9	98.86%
Japan	5,028,745.1	1,245,731.5	4,036.8	19	−254.1	94.08%
Portugal	234,552.6	67,761.5	3,461.4	20	−829.5	80.67%
United States	20,463,790.0	6,644,857.7	3,079.6	21	−1,211.3	71.77%
Latvia	33,085.6	11,060.1	2,991.4	22	−1,299.5	69.72%
Slovenia	52,366.2	17,588.1	2,977.4	23	−1,313.5	69.39%
New Zealand	210,512.6	79,092.5	2,661.6	24	−1,629.3	62.03%
Chile	283,420.3	109,504.0	2,588.2	25	−1,702.7	60.32%
Lithuania	52,090.2	20,201.0	2,578.6	26	−1,712.3	60.09%
Australia	1,414,240.6	558,551.2	2,532.0	27	−1,758.9	59.01%
Slovak Republic	102,499.3	41,550.5	2,466.9	28	−1,824.0	57.49%
Hungary	155,899.4	64,959.4	2,400.0	29	−1,891.0	55.93%
Canada	1,706,096.8	720,176.3	2,369.0	30	−1,921.9	55.21%
Korea	1,666,623.5	712,945.6	2,337.7	31	−1,953.2	54.48%
Greece	205,716.9	91,706.9	2,243.2	32	−2,047.7	52.28%
Czech Republic	240,059.2	127,861.1	1,877.5	33	−2,413.4	43.76%
Colombia	323,032.3	175,881.4	1,836.6	34	−2,454.3	42.80%
Mexico	1,216,775.7	753,112.2	1,615.7	35	−2,675.2	37.65%
Estonia	29,543.7	18,488.0	1,598.0	36	−2,692.9	37.24%
Turkiye	799,133.4	520,133.3	1,536.4	37	−2,754.5	35.81%
Poland	569,826.5	401,464.5	1,419.4	38	−2,871.5	33.08%
Average			**4,290.9**			

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 15 July 2024 doi:10.20944/preprints202407.1169.v1

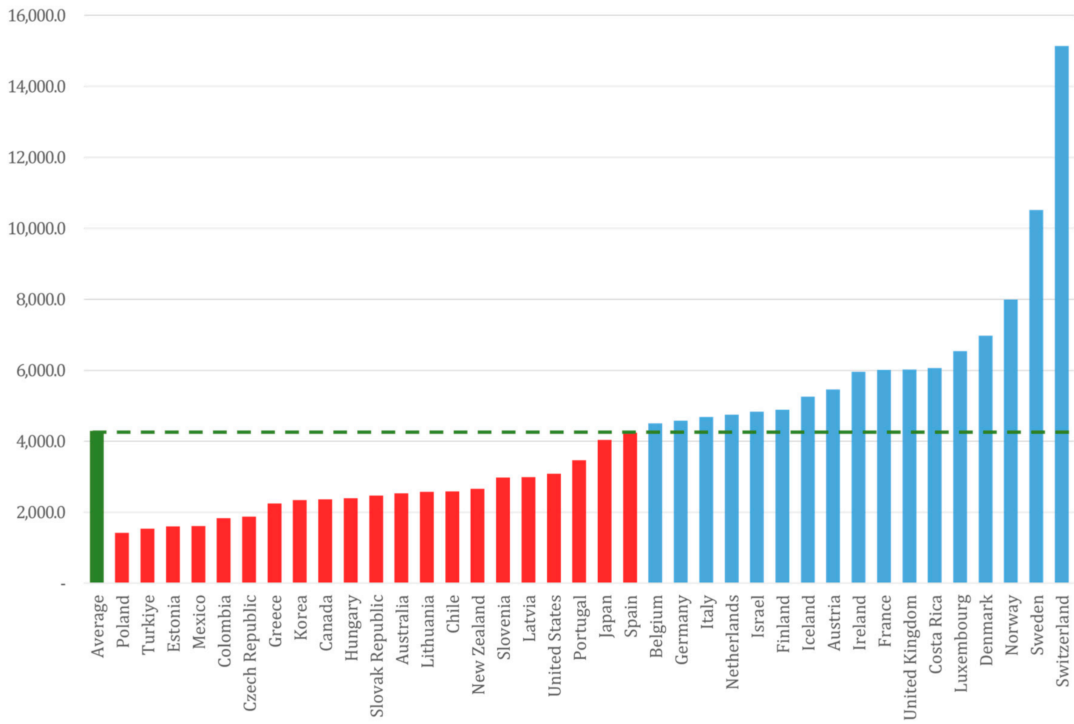

Figure 6. The current national-level carbon productivity ranking graph of OECD countries (average of 2017 to 2019).

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 CO_2-eq., approximately 2.5 times the average of 5,371.5 USD/ton CO_2-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 2,176.6 USD/ton CO_2-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 9,218.0 USD/ton CO_2-eq., approximately 2.5 times the average of 3,651.2 USD/ton CO_2-eq. among 19 non-service industry-centered countries. Poland, with the lowest ranking among non-service industry-centered countries, had a carbon productivity of 1,339.5 USD/ton CO_2-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.

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

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 15 July 2024 doi:10.20944/preprints202407.1169.v1

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.

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

Countries	Current carbon productivity ($/tCO2-eq.)		Adjusted carbon productivity ($/tCO2-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	6,068.6	5	8,167.2	3	(△2)	34.6%
Denmark	6,975.5	3	7,115	4	(▼1)	2.0%
Israel	4,834.1	9	6,917.9	5	(△4)	43.1%
Iceland	5,255.9	8	5,644.1	6	(△2)	7.4%
United Kingdom	6,022.2	6	5,301.4	7	(▼1)	−12.0%
France	6,011.2	7	5,248.7	8	(▼1)	−12.7%
Netherlands	4,749.3	10	5,009.0	9	(△1)	5.5%
Luxembourg	6,543.7	4	4,690.6	10	(▼6)	−28.3%
Italy	4,689.8	11	4,268.8	11	(-)	−9.0%
Belgium	4,507.5	12	4,054.2	12	(-)	−10.1%
Spain	4,242.0	13	4,020.2	13	(-)	−5.2%
Portugal	3,461.4	14	3,740.2	14	(-)	8.1%
United States	3,079.6	15	2,956.7	15	(-)	−4.0%
Greece	2,243.2	18	2,877.4	16	(△2)	28.3%
Estonia	1,598.0	19	2,702.3	17	(△2)	69.1%
Latvia	2,991.4	16	2,546.4	18	(▼2)	−14.9%
Canada	2,369.0	17	2,176.6	19	(▼2)	−8.1%
Average	**5,332.0**		**5,371.5**			

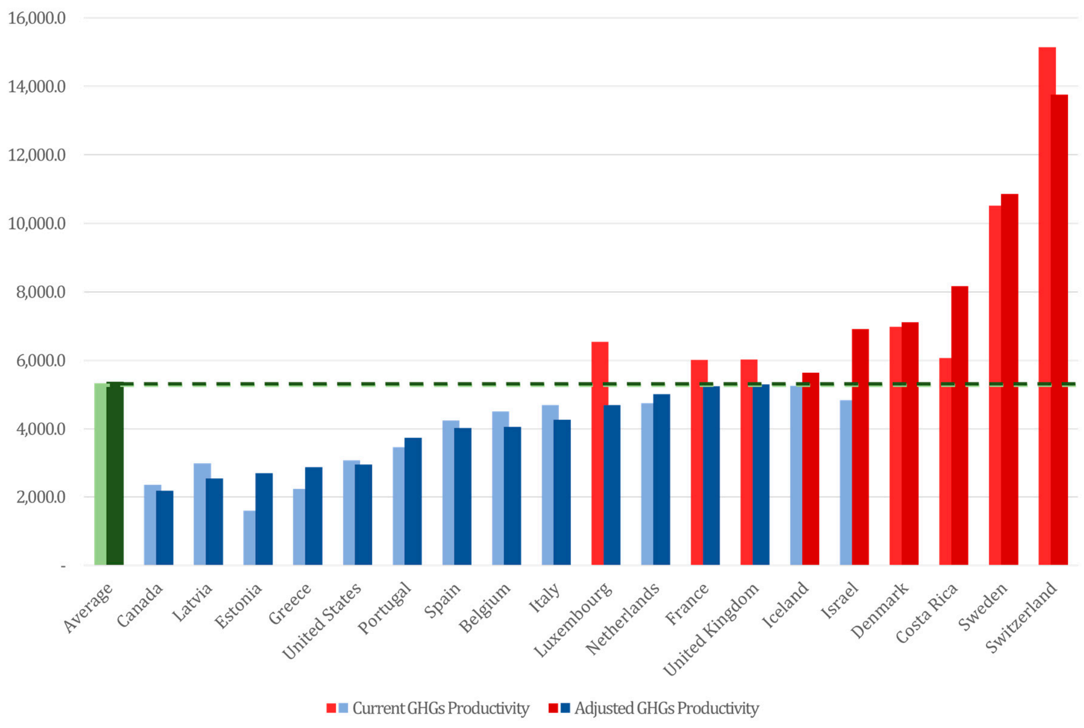

Figure 7. Current and adjusted carbon productivity rankings of service sector-based countries in the OECD list (average of 2017 to 2019).

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 15 July 2024 doi:10.20944/preprints202407.1169.v1

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

Countries	Current carbon productivity ($/tCO2-eq.)		Adjusted carbon productivity ($/tCO2-eq.)		Relative Change
	Value	Rank	Value	Rank	
Norway	7,997.2	1	9,218.0	1 (-)	15.3%
Ireland	5,954.0	2	6,387.3	2 (-)	7.3%
Finland	4,886.0	4	5,841.4	3 (△1)	19.6%
Austria	5,464.6	3	5,189.1	4 (▼1)	−5.0%
Japan	4,036.8	6	4,831.7	5 (△1)	19.7%
Germany	4,580.4	5	4,791.2	6 (▼1)	4.6%
Korea	2,337.7	14	4,260.5	7 (△7)	82.3%
Australia	2,532.0	11	3,577.8	8 (△3)	41.3%
New Zealand	2,661.6	8	3,472.8	9 (▼1)	30.5%
Chile	2,588.2	9	2,899.9	10 (▼1)	12.0%
Slovenia	2,977.4	7	2,706.8	11 (▼4)	−9.1%
Slovak Republic	2,466.9	12	2,567.7	12 (-)	4.1%
Lithuania	2,578.6	10	2,395.6	13 (▼3)	−7.1%
Colombia	1,836.6	16	2,240.8	14 (△2)	22.0%
Czech Republic	1,877.5	15	2,164.7	15 (-)	15.3%
Hungary	2,400.0	13	2,091.5	16 (▼3)	−12.9%
Mexico	1,615.7	17	1,899.8	17 (-)	17.6%
Turkiye	1,536.4	18	1,496.4	18 (-)	−2.6%
Poland	1,419.4	19	1,339.5	19 (-)	−5.6%
Average	**3,249.8**		**3,651.2**		

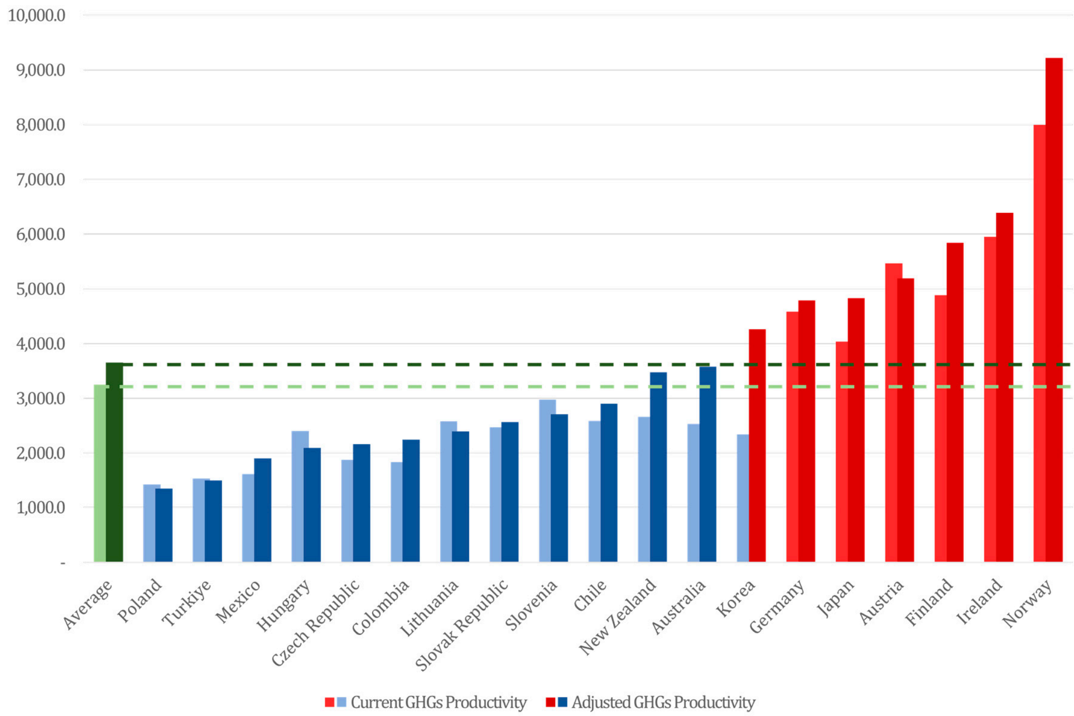

Figure 8. Current and adjusted carbon productivity rankings of non-service sector-based countries in the OECD list (average of 2017 to 2019).

7. Conclusion

This study designed a multiple regression model using GDP and industry-specific greenhouse gas emissions statistics and corrected the GDP/TGE, 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.

 doi:10.20944/preprints202407.1169.v1

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 are 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 × non-service industry productivity) + (0.3 × 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 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 in 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, greenhouse gas emitted per ton of steel products is approximately 2 tons CO_2-eq. [33]. Similarly, company A, a leading steel company in Luxembourg, reports very similar emissions per ton of steel products (2 tons CO_2-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 service and non-service industry, 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/TGE indicator, which overlooks 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: Jong-Hyo Lee devised the research, the main conceptual ideas, and the proof outline. In addition, he worked out almost all of the technical details and conducted current and adjusted national-level

carbon productivity estimation by multiple regression analysis. Hong-Yoon Kang and Yong Woo Hwang supervised and reviewed the research. All authors discussed the results and commented on the manuscript.

Funding: This work was supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korean government (Ministry of Trade, Industry and Energy) (No. 20214000000520, Human Resource Development Project in Circular Remanufacturing Industry and No. 2024000000420, Cultivating Global Human Resources in Circular Resources Field).

Data Availability Statement: The original contributions presented in the study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors have no conflicts of interest to declare that are relevant to the content of this study.

References

1. European Commission. An EU action plan for the circular economy. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Commitee and the Commitee of Regions. **2015**. Available online: https://eur-lex.europa.eu/resource.html?uri=cellar:8a8ef5e8-99a0-11e5-b3b7-01aa75ed71a1.0012.02/DOC_1&format=PDF (accessed on 17 June 2024).
2. United Nations Environment Programme. Towards a green economy: Pathways to sustainable development and poverty eradication: A synthesis for policy makers. **2011**. Available online: https://sustainabledevelopment.un.org/content/documents/126GER_synthesis_en.pdf (accessed on 17 June 2024).
3. Bachtler, J.; Martins, J. O.; Wostner, P.; Zuber, P. Towards Cohesion Policy 4.0: Structural transformation and inclusive growth. **2017**. Available online: https://3ftfah3bhjub3knerv1hneul-wpengine.netdna-ssl.com/wp-content/uploads/2018/08/RSA_Report_Web_22-6-17.pdf (accessed on 17 June 2024).
4. Fratini, C. F.; Georg, S.; Jørgensen, M. S. Exploring circular economy imaginaries in European cities: A research agenda for the governance of urbansustainability transitions. *J. Clean. Prod.* **2017**, 228, 974–989. https://doi.org/10.1016/j.jclepro.2019.04.193
5. Corvellec, H.; Campos, M. J. Z.; Zapata, P. Infrastructures, lock-in, and sustainable urban development: The case of waste incineration in the Göte-borg Metropolitan Area. *J. Clean. Prod.* **2013**, 50, 32–39. https://doi.org/10.1016/j.jclepro.2012.12.009
6. Mayer, A.; Haas, W.; Wiedenhofer, D.; Krausmann, F.; Nuss, P.; Blengini, G. A. Measuring progress towards a circular economy: A monitoring framework for economy-wide material loop closing in the EU28. *J. Ind. Ecol.* **2019**, 23(1), 62–76. https://doi.org/10.1111/jiec.12809
7. van Buren, N.; Demmers, M.; van der Heijden, R.; Witlox, F. Towards a circular economy: The role of Dutch logistics industries and governments. *Sustainability* **2016**, 8(7), 1–17. https://doi.org/10.3390/su8070647
8. Lee, J. H.; Kang, H. Y.; Kim, Y. W.; Hwang, Y. W.; Kwon, S. G.; Park, H. W.; Choi, J. W.; Choi, H. H. Analysis of the life cycle environmental impact reductions of remanufactured turbochargers. *J. Remanufacturing.* **2023**. 13, 187–206. https://doi.org/10.1007/s13243-023-00127-y
9. Adesina, A. (2020). Recent advances in the concrete industry to reduce its carbon dioxide emissions. *Environmental Challenges* **2020**. 1, 100004. https://doi.org/10.1016/j.envc.2020.100004
10. Benjamin, N. I.; Lin, B. Quantile analysis of carbon emissions in China metallurgy industry. *J. Clean. Prod.* **2020**, 243, 118534. https://doi.org/10.1016/j.jclepro.2019.118534
11. Ullah, S.; Ozturk, I.; Usman, A.; Majeed, M. T.; Akhtar, P. On the asymmetric effects of premature deindustrialization on CO2 emissions: Evidence from Pakistan. *Environ. Sci. Pollut. Res. Int.* **2020**, 27, 13692–13702. http://doi.org/10.1007/s11356-020-07931-0
12. Qi, W.; Song, C.; Sun, M.; Wang, L.; Han, Y. Sustainable Growth Drivers: Unveiling the Role Played by Carbon Productivity. *Int. J. Environ. Res. Public Health* **2020**, 19(3), 1374. https://doi.org/10.3390%2Fijerph19031374
13. Wiedmann, T. O.; Schandl, H.; Lenzen, M.; Moran, D.; Suh, S.; West, J.; Kanemoto, K. The material footprint of nations. Proceedings of the National Academy of Sciences of the United States of America 2015, 112(20), 6271–6276. https://doi.org/10.1073/pnas.1220362110
14. Mancini, L.; Benini, L.; Sala, S. Resource footprint of Europe: complementarity of material flow analysis and life cycle assessment for policy support. *Environ. Sci. Policy* **2015**, 54, 367–376. https://doi.org/10.1016/j.envsci.2015.07.025
15. Pothen, F.; Welsch, H. Economic development and material use. Evidence from international panel data. *World Dev.* **2019**, 115(C), 107–119. https://doi.org/10.1016/j.worlddev.2018.06.008
16. Baynes, T. M.; Musango, J. K. Estimating current and future global urban domestic material consumption. *Environ. Res. Lett.* **2018**, 13(6), 065012. https://doi.org/10.1088/1748-9326/aac391

17. Dong, L.; Dai, M.; Liang, H.; Zhang, N.; Mancheri, N.; Ren, J.; Dou, Y.; Hu, M. Material flows and resource productivity in China, South Korea and Japan from 1970 to 2008: A transitional perspective. *J. Clean. Prod.* **2017**, 141, 1164–1177. https://doi.org/10.1016/j.jclepro.2016.09.189
18. Krausmann, F.; Gingrich, S.; Eisenmenger, N.; Erb, K. H.; Haberl, H.; Fischer-Kowalski, M. Growth in global materials use, GDP and population during the 20th century. *Ecol. Econ.* **2009**, 68(10), 2696–2705. https://doi.org/10.1016/j.ecolecon.2009.05.007
19. Steinberger, J. K.; Krausmann, F.; Getzner, M.; Schandl, H.; West, J. Development and dematerialization: An international study. *PLoS ONE* **2013**, 8(10), e70385. https://doi.org/10.1371/journal.pone.0070385
20. Giljum, S.; Dittrich, M.; Lieber, M.; Lutter, S. Global patterns of material flows and their socio-economic and environmental implications: A MFA study on all countries worldwide from 1980 to 2009. *Resources* **2014**, 3(1), 319–339. https://doi.org/10.3390/resources3010319
21. Talmon-Gros, L. Material Productivity Measurement. Development Patterns of Material Productivity. **2014**, Springer, Cham, Switzerland. https://doi.org/10.1007/978-3-319-02538-4_5
22. OECD. Greenhouse gas emissions, OECD.Stat. Available online: https://stats.oecd.org/ (accessed on 17 June 2024).
23. OECD. Gross domestic product (GDP), National Accounts, OECD.Stat. Available online: https://stats.oecd.org/ (accessed on 17 June 2024).
24. Lee, S. W.; Lee, J. W. 2050 carbon neutrality and the way ahead for manufacturing. KIET Monthly Industrial Economic Review 2021, 275, 20-31. Available online: https://www.kdevelopedia.org/asset/99202109280168419/1632806649943.pdf (accessed on 17 June 2024).
25. European Parliament. Climate action in Estonia. **2021**. Available online: https://www.europarl.europa.eu/RegData/etudes/BRIE/2021/690684/EPRS_BRI(2021)690684_EN.pdf (accessed on 17 June 2024).
26. Australia Gorvernment. National Inventory Report 2017. **2019**. Available online: https://unfccc.int/sites/default/files/resource/aus-2019-nir-24May19.zip (accessed on 17 June 2024).
27. McConnell, D.; Holmes, S.; Tan, S.; Cubrilovic, N. An Open Platform for National Electricity Market Data. OpenNEM. Available online: https://opennem.org.au/energy/nem/?range=all&interval=1y&view=discrete-time (accessed on 17 June 2024).
28. Climate Council. Agriculture's contribution to Australia's greenhouse gas emissions. **2021**. Available online: https://web.archive.org/web/20210828170749/https://www.climatecouncil.org.au/resources/australia-agriculture-climate-change-emissions-methane/ (accessed on 17 June 2024).
29. The Israel Democracy Institute. Carbon Pricing in Israel. **2022**. Available online: https://en.idi.org.il/media/18866/carbon-pricing-in-israel-israel-2050-a-thriving-economy-in-a-sustainable-environment.pdf (accessed on 17 June 2024).
30. doopedia. Assembly Industry. Available online: https://terms.naver.com/entry.naver?docId=1141663&cid=40942&categoryId=31898 (accessed on 17 June 2024).
31. Boda, G. To what extent is Hungary a knowledge-based economy?. *Theory methodol. pract. - Rev. Bus. Manag.* **2017**, 13(1), 69-84. http://doi.org/10.18096/TMP.2017.01.06
32. Briški, M.,; Verbič, B. Remote Sessions of the National Assembly of the Republic of Slovenia and its Working Bodies. *Int. J. Parliam. Studs.* **2021**, 1(1), 199-206. https://doi.org/10.1163/26668912-bja10010
33. POSCO. ESG Factbook. **2022**. Available online: https://www.posco.co.kr/homepage/servlet/FileDown?file=/hfiles/enboard/6915f96b18aa6772235a61a30ebdc510.pdf&filename=POSCO%20ESG%20Factbook%202022.pdf (accessed on 17 June 2024).
34. ArcelorMittal. Annual Report 2021. **2022**. Available online: https://www.vernimmen.net/ftp/ArcelorMittal_2021.pdf (accessed on 17 June 2024).