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Lessons from the Pilot Project of Korean ETS on the Local Landscape of Economy

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Abstract: For a sustainable landscape of local economies, many researchers have emphasized the importance of field-oriented differentiation in government policies. In particular, the Paris Agreement, based on the bottom-up approach, aims to maximize the participation of all economic agents, in contrast to the top-down approach of the Tokyo Protocol. In response to these global paradigm shifts in the local landscape, local governments in Korea have made significant efforts to adapt to sustainable development during the pilot phase of emission trading scheme (ETS), during the period from 2015 to 2020. This study evaluates the performance of these local government policies in the transition to a carbon-zero economy. Using the general non-radial directional distance function (GNDDF), we found that Gyeongsang Province demonstrated enhanced environmental total factor productivity (TFP) during the pilot project, whereas the Seoul metropolitan area lagged behind due to a lack of governance. As the economic center of Korea, Seoul showed poor environmental performance because of the arbitrary elimination of green belt areas and unchecked land development, resulting in environmental degradation, a trend common in many developing countries facing climate adaptation challenges. To address these urbanization issues, this study concludes that a balanced approach combining stricter regulations with market-oriented promotional incentives is essential for optimizing the transition of local economies to a sustainable landscape.

Keywords: general non-radial directional distance function (GNDDF); environmental total factor productivity; technological efficiency; economic efficiency; emission trading scheme (ETS)

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1. Introduction

The World Meteorological Organization (WMO, 2023) declared 2023 as the "hottest year in history" with a 1.40 increase [1], a record that may get broken in the year 2024. Despite attempts by most governments to control them through policies, carbon emissions, unfortunately, seem to be increasing unabatedly, except in the COVID-19 era. Nonetheless, our question is not whether policies can control this ever-growing emission because emission reduction is not an optional but a necessary survival condition for humankind (Nie et al., 2021 [2]). To sustainably address carbon emission issues, most governments have focused on regulatory policies. According to Porter's hypothesis, stronger regulation results in better environmental performance of the economy. However (Tan et al., 2024 [3]) show that the decoupling of economic development and environmental protection is not always because of the lack of governance due to forceful regulation. Sometimes, weak regulation by the government may lag behind international competition. This is especially true for export-oriented developing countries, such as Korea.

The Korean government has promoted an export-oriented economy because of the lack of natural resources and relatively small local markets. Due to this political paradigm, the Korean government should emphasize the international competitiveness of production costs, and consider complaints from exporting industries regarding the extra burden of

the costs owing to the regulatory policies on emission reduction. Therefore, although the Korean government was the first country in the world to implement a emissions trading scheme (ETS), it learned from the EU ETS (Oesingmann, 2022 [4]; Verbruggen & Laes, 2021 [5]) that it has created a 'tiger's head and snake's tail' situation, meaning that the regulatory policy has not resulted in strong business participation. The Korean ETS is divided into three phases. The first phase is 2015–2017, which mainly focuses on allocating free allowances and accumulating experience to improve the market mechanism. The second phase is 2018–2020, or the maturity period, gradually reducing free allowances, increasing the proportion of compensated auctions, and introducing more sectors and emission entities. The third phase, on the other hand, is so far, reinforcing the emission reduction targets, further expanding the coverage and increasing the proportion of compensated auctions, as well as strengthening the supervision and management of the market. Since its introduction in 2015, Korea emission trading market has grown gradually, as shown in Figure 1. By 2020, the total trading volume had increased 16 times since 2015, and the price of the Korean allowance unit (KAU) had increased steadily until 2019. Trading volumes and prices fell in 2020 owing to the economic recession caused by the COVID-19 pandemic. As the system stabilized, transactions continued throughout the entire period. Nonetheless, even as the emission abatement volume increases, the nationwide emission has been increasing rapidly, except in the pandemic period, resulting in the failure for overall reduction in carbon emission. Figure 2 shows that as nationwide emissions increase, the distributed quota of emission abatement increases accordingly, but the realized emission reduction has been decreasing since 2017. Some large companies, such as Samsung, took the penalty, instead of making more efforts to reduce their carbon emissions. This is because the market price, KAU, and the penalty based on this lower market price, is more lucrative than bearing the extra burden of emission reduction. In particular, local governments did not want to lose opportunities due to the extra burden of carbon emissions abatement.

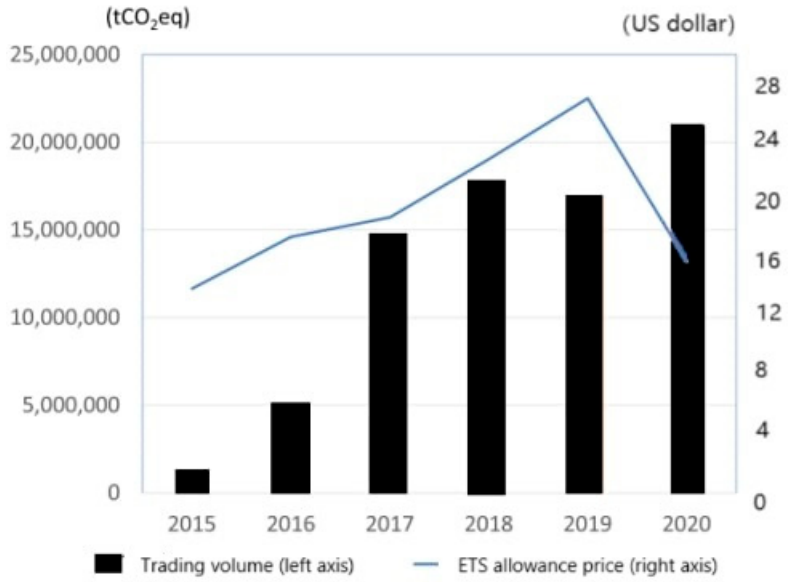


Figure 1. Emission trading volume and its market price. Source: Modified by the author from the Ministry of Environment Greenhouse Gas Statistics website (https://kosis.kr/statHtml/statHtml.do?orgId=106&tblId=DT_106N_99_2800021&vw_cd=MT_ZTITLE&list_id=&scrId=&seqNo=&lang_mode=ko&obj_var_id=&itm_id=&conn_path=E1&docId=0142328174&markType=S&itmNm=%EC%A0%84%EA%B5%AD.29.01.2024).

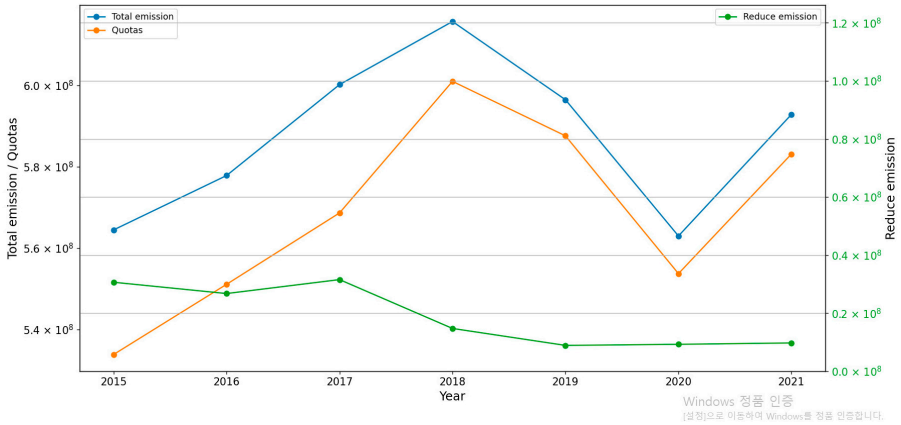


Figure 2. Trends in Total Emissions, Quotas, and Reduced Emissions in South Korea (2015–2021). Source: Modified by the author from the Greenhouse Gas Inventory & Research Center of Korea website (https://etrs.gir.go.kr/home/infoOpen/infoOpenList1.do).

Therefore, due to the invisible complaint from the manufacturing industries, the current government declared the new "carbon-zero roadmap 2050" (2050 Carbon Neutrality of the Republic of Korea, 2024 [6]) in 2023 at the end of pilot project of ETS, with more burden on the power generation industry than on the manufacturing sector, whose share reduced from 14.5% to 11.4% till 2030. The question is whether this is feasible. If the government gives the wrong signal to the participating companies not to make stricter efforts to reduce carbon emissions through this new roadmap, regulatory policies may not be effective for sustainable governance. There seems to be a conflict between economic development and environmental protection, particularly in the manufacturing sector. How can this conflict be resolved? Several local governments in Korea have been promoting differentiated, more geopolitical field-oriented policies to harmonize forceful regulations and market-friendly promotion policies, which may provide important implications and suggestions for the future challenges of Korea's carbon-zero economy. Therefore, the objective of this study was to identify governance mechanisms for the sustainable performance of environmentally friendly local development in Korea.

In the pilot phase of the Emissions Trading System (ETS) launched by the Korean government in 2015, the country adopted different strategies based on the economic structure and energy profile of each region. For example, Metro-Seoul focuses on strict environmental management, but faces challenges due to high urbanization and resource demands. Jeolla has emphasized renewable energy projects, especially solar and wind energy. Gyeongsang, driven by its heavy industrial base, favors nuclear energy to meet its energy needs. Each regional approach highlights Korea's diverse strategies for achieving carbon neutrality and provides a key basis for assessing environmental efficiency.

According to Figure 3, Korea is divided into several major regions that are distinct in terms of environmental efficiency and sustainable development. The Seoul metropolitan area (Metro-Seoul), which includes Seoul and its surrounding areas, is the political, economic, and cultural center of Korea. It is densely populated and faces enormous pressure on environmental management and resource use. Gangwon Province, located in northeastern Korea, is a tourist destination known for its clean and green mountainous terrain and natural beauty, with a focus on the sustainable use of natural resources and ecotourism. Chungcheong Province, located in the center of the country, focuses on agriculture and light industry and promotes environmental efficiency by promoting more effective management of traditional fossil fuel power generation facilities and the reduction of industrial pollution. Jeolla is located in southwest Korea and its main economic activities are agriculture and fisheries, with a focus on water quality management, agricultural waste treatment, and the sustainable use of fishery resources. Gyeongsang Province, located in southeastern Korea, is a major industrial base with a large number of manufacturing and heavy industrial

enterprises. It is also a major base of the nuclear power generation industry supporting these heavy industries. It is noteworthy that the five provinces of Korea possess unique positions in the pilot phase of the ETS. To determine their governance mechanism and geopolitical[1] performance, we use a gradient color to differentiate the average value of total factor productivity (TFP) changes in each region, with darker colors indicating more high values of TFP as explained later.

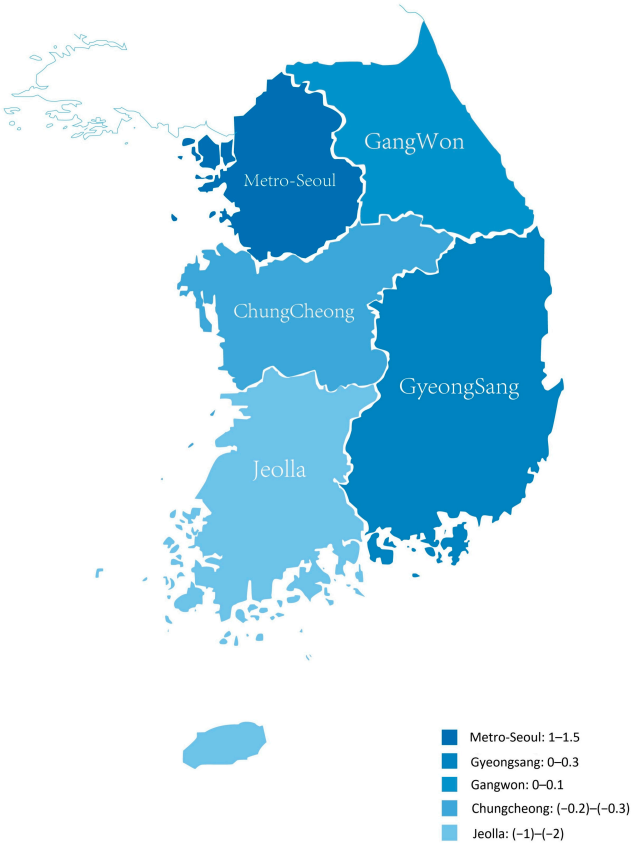


Figure 3. Distribution of 5 regions in Korea and mean value of TFP change.

As shown in the Table 1, the most important characteristic of these provinces is the management of their power-generation industries. Metro-Seoul area could not host many supporting electricity facilities in the densely urbanized area, thereby depending heavily on the traditional fossil fuel power industries in Chungcheong province. Owing to this strategic alliance, Chungcheong Province has suffered from environmental difficulties. Nonetheless, because the power facilities are important for economic activities, it should maintain its role as the supporting base of electricity power, emphasizing more on the better performance on the CO_2 emission. Gangwon Province is a mountainous area and does not have a large population or many industries. Thus, it is focused on innovative renewable energy sources such as solar and wind power. Contrary to this emphasis on renewable energy, Gyeongsang province must focus on the nuclear energy industry owing to its energy-intensive heavy chemical and car-manufacturing industries. Jeolla Province has maintained balanced policies between the traditional fossil fuel and renewable energy industries, but it did not emphasize any of these industries because of its focus on the agriculture and fishery industries. Therefore, all these provinces showed interesting contrasting approaches to electricity generation industries, which account for a major portion of carbon emission abatement in Korea. In particular, the current Korean government has emphasized more responsibility for the power generation industry toward a carbon-zero economy. Thus, a differentiated approach to the electricity generation industry of these five provinces will elucidate the optimal path toward a carbon-zero global economy. Therefore,

our study focuses on the environmental performance of Korean electric utilities in these five provinces to examine the landscape of the local economy.

Table 1. Overview of Regional Policies under the Korean Emissions Trading Scheme (K-ETS) Pilot Project.

Region	Policy Focus
Metro-Seoul	Energy Efficiency Improvement and Emissions Reduction
Jeolla	Renewable Energy Promotion
Chungcheong	Coal Phase-out and Renewable Energy Expansion
Gyeongsang	Nuclear Energy and Heavy Industry Efficiency
Gangwon	Clean Energy Development and Eco-tourism

2. Literature Review

Regarding the effects of the ETS, many studies have been conducted on the environmental efficiency of the transition toward sustainable development. (Xie et al., 2019 [7]) investigated the spatial and temporal differences in the total-factor green use efficiency (TGUEIL) of industrial land in China and its influencing factors. This study used industrial land, capital, energy, and labor as inputs; industrial GDP, CO_2 emissions, SO_2 emissions, and wastewater emissions as outputs; and the global non-radial directional distance function (GNDDF) model and the non-radial Malmquist index method for the dynamic evaluation of TGUEIL. TGUEIL showed a general upward trend between 2006 and 2015, being the highest in the eastern region; technological progress was the main driver of TGUEIL growth.

(Jing et al., 2024 [8]) investigated the impact of carbon emissions trading pilot policy (CETP) on green total factor productivity (GTFP) in Chinese provinces. The study used capital, labor, and energy as inputs and GDP and CO_2 emissions as outputs, and adopted the global nonradial directional distance function (GNDDF) model. They found that CETP policies significantly increased GTFP. (Ouyang et al., 2023 [9]) also investigated the impact of environmental regulation (ER) on green total factor productivity (GTFP) in Chinese industry. The study used capital, labor, and energy as inputs and industrial output value (IOV) and CO_2, industrial wastewater, and industrial solid waste emissions as outputs, analyzing them using the non-radial directional distance function (NDDF) based on slack variables and the global-Lünberg productivity index model. They emphasized that environmental regulation is significantly and positively associated with industrial green growth, with the GTFP increasing by 0.0683% on average for each standard deviation increase in environmental regulation intensity. Technological progress plays a more important role in driving industrial green growth than technological efficiency gains.

For the role of local government on the landscape development, (Feng Dong et al., 2022 [10]) investigated the impact of information infrastructure on the performance of greenhouse gas (GHG) emissions in Chinese cities. The study used capital stock, labor, and energy consumption as inputs, and GDP and GHG emissions (including CO_2, CH_4 and N_2O), as outputs, adopting a difference-in-differences (DID) model for analysis. They found that information infrastructure significantly improves a city's GHG emissions performance, playing a key role in technological innovation, industrial structure upgrading, factor allocation optimization, and tertiary industry aggregation [8]. (Shi et al., 2022 [11]) evaluated the impact of China's carbon-trading pilot policy on carbon emissions. The study used carbon quota, price, and trading volume as inputs and total regional carbon emissions and per capita carbon emissions as outputs and adopted the double difference-in-differences (DID) method for analysis. The results of this study show that the pilot carbon trading policy significantly reduced total regional and per capita carbon emissions, with long-term effects. Different carbon quota allocation methods led to different emission reduction effects, with

the historical method having the most significant effect. These two studies highlight the role of the local government in developing the landscape in terms of geopolitical policies.

Few studies have evaluated the Korean ETS. (Younghoon Kwak et al., 2019 [12]) studied the effectiveness of GHG emission reduction policies in office building design in South Korea. The study used the U-values of the building form, window system, and building envelope as design elements, and the cooling and heating loads of the building, as outputs. This study used a reference building model and an ideal load air system from the Energy Plus simulation tool to assess the impact of different combinations of design elements on energy consumption. The results of the study showed that the new building design slightly increased cooling loads, but significantly reduced heating loads, resulting in overall energy savings. Cases with new window systems and U-values achieved a 13.1% reduction in energy consumption compared with traditional building forms, exceeding the average GHG reduction rate of 12.8% under Business as Usual (BAU). These findings have important implications for enhancing GHG reduction goals. (Lee, S., Cho, Y., and Lee, S. K., 2017 [13]) investigated the effects of the GHG energy target management system (TMS) and the Korean emissions trading system (ETS) on CO_2 emission reduction. This study used the double difference (DID) method with carbon allowances, carbon prices, and carbon trading volumes as inputs and reduced CO_2 emissions, as outputs. The results of this study show that the GHG energy target management system and Korean ETS significantly reduced CO_2 emissions, demonstrating significant long-term effects. The effects of these policies are particularly significant in areas with high carbon intensity and strict environmental regulations. (Yu, Yoo, Kim, and Lee, 2017 [14]) examined the effectiveness of Korea's GHG emission reduction policies, especially the changes since the launch of the ETS. They used the double difference method (DID) with carbon quotas, carbon prices, and carbon trading volumes as inputs, and carbon emission reductions, as outputs. The results show that the implementation of the ETS has significantly reduced GHG emissions, and this effect is especially significant in industries with high carbon emission intensity. Further, the study indicates that policy plays a significant role in incentivizing enterprises, especially large-scale ones, to reduce emissions. These findings provide empirical evidence for further optimization of GHG emission reduction policies.

(Na Wang and Yongrok Choi, 2019 [15]) used the Global Non-Radial Directional Distance Function (GNDDF) model, taking industrial water, industrial labor, and industrial capital as inputs, and industrial GDP and major water pollutants (e.g., water waste and organic pollutants), as outputs, to assess the Green Industrial Water Use Efficiency (GUEIW) of Korean local governments, from 2006 to 2015. Their study concluded that the growth in GUEIW was driven mainly by economic efficiency (ECEIW).

(Tan et al., 2024 [3]) examined the complicated role of emission trading scheme (ETS) in Korean industries, with labor, capital, and energy consumption as inputs, and return on assets as outputs. Using the difference-in-difference (DID) model, they concluded that even if the effect appeared statistically insignificant in the analyses of the entire industry, it was possible to improve energy efficiency by 1.85%.

Therefore, there seem to be some conflicts in the main driver of land development between market power, represented by economic efficiency, and political support for technological innovation. Most of these studies support the Porter hypothesis that stronger regulatory policies result in more environment-friendly sustainable development in the local landscape [4–8,13]. However, some argue that indiscriminate regulatory policy is not the panacea to reduce carbon emissions, because it may result in some moral hazard type of selection, such as penalty, rather than carbon emission abatement. Using the bootstrap Data Envelopment Analysis (DEA) methodology, (Choi et al., 2024 [16]) evaluated the operational efficiency of 43 major airports in China from 2015 to 2022. It was found that airports in the eastern region performed the best, due to proactive market support, with rapidly increasing logistics demand, those in the west and northeast regions, supported by strong promotional policies, followed closely in terms of operational efficiency, while those in the central region lagged behind due to the lack of any government support or market demand. Is the

same phenomenon being observed in the Metro-Seoul area of Korea? If so, all developing countries should emphasize economic development directly because decoupling issues can be realized with economic development, like in the eastern Chinese provinces, such as Shanghai, as shown by the Kuznets curve. However, industrialization is not the only effective solution for improving environmental efficiency in developing countries. Our research examines environmental efficiency to determine the conflict between political support and geopolitical market conditions.

Many studies have emphasized field-oriented differentiation to enhance the sustainable efficiency of the local economy because a uniformly distributed emission quota is not appropriate for dealing with all geopolitical conditions of local landscape of the economy [10–12]. For example, Metro-Seoul may have the heaviest quota burden, resulting in much lower performance. On the contrary, Gyeongsang province is very special with the strategic importance of the nuclear power plant complex, while Chungcheong province may suffer severe disadvantages from concentrated fossil fuel power plants on which Metro-Seoul is heavily dependent. These contrasting provinces may provide insightful implications and strategic suggestions for sustainable local landscape development, owing to their differentiated geopolitical conditions in the pilot project of the Korean ETS.

Therefore, based on a comparative analysis of the literature, we utilize one of the most commonly used global nonradial directional distance functions (GNDDF) as our platform to evaluate the performance of five local governments regarding their role in ETS policies in the power generation industry. This study evaluates the total factor productivity and environmental efficiency changes in five regions in the Korean power sector through a non-radial directional distance function approach, using specific data and variables, and summarizes the performance of each region in the carbon-neutral transition, with corresponding policy recommendations.

3. Materials and Methodology

3.1. Data and Its Characteristics

Based on a review of the literature, we estimated total factor productivity, along with further factor decomposition and regional variance analysis, for Korean electric utilities from 2015 to 2021, using a full-domain or general non-radial directional distance function (GNDDF). Data samples were collected from the National Greenhouse Gas Management System (NGMS) and Data Analysis, Retrieval, and Transmission (DART) systems. Our sample comprised 37 representative electric utilities, covering 80% of the Korean market. The remaining 20% of regions were excluded because of the unavailability of key variables. The inputs used for the analysis included number of employees, capacity, and energy consumption. The outputs were categorized as desirable and undesirable: electricity generation (calculated by dividing the plant's electricity sales by the average electricity price) was the desirable output, and GHG emissions, the undesirable output. Tables 2 and 3 provide descriptive statistics for these variables nationwide and for each province, respectively.

Table 2. Descriptive statistics for total variables.

Variable	Symbol	Unit	Obs.	Mean	Stu. Dev.	Min	Max
Labor	L	Num.	259	1563.723	4106.77	8	23,551
Energy	E	10^3 TJ	259	85.43	157.62	0.137	670.23
Capital	K	10^{10} KRW	259	327	941	−6.56	5580
Power generation	Y	10^8 kWh	259	325	935	1.55	5540
CO_2 emissions	C	10^4 tons	259	663	1340	0.4506	5970

Table 3. Descriptive statistics for post-grouping variables.

Symbol	Unit	Obs.	Mean	Stu. Dev.	Min	Max
Group 1 Metro-Seoul (n = 19)						
L	Num.	133	2536.56	5466.77	15	23,551
E	10^3 TJ	133	81.64	154.58	0.137	670.23
K	10^{10} KRW	133	532	1260	−1.42	5580
Y	10^8 kWh	133	540	1250	2.52	5540
C	10^4 tons	133	631.32	1360	0.694	5970
Group 2 Jeolla (n = 7)						
L	Num.	49	154.19	151.89	8	496
E	10^3 TJ	49	21.63	24.46	0.436	57.79
K	10^{10} KRW	49	62.3	110	−6.56	519
Y	10^8 kWh	49	25.9	29.4	1.55	85.7
C	10^4 tons	49	138.45	167.13	0.4506	485.92
Group 3 Chungcheong (n = 4)						
L	Num.	28	696.61	1018.21	51	23,551
E	10^3 TJ	28	121.87	179.49	2.324	460.38
K	10^{10} KRW	28	125	153	8.36	3940
Y	10^8 kWh	28	133	159	5.51	4600
C	10^4 tons	28	947.69	1500	11.02	3800
Group 4 Gyeongsang (n = 5)						
L	Num.	35	71.29	72.03	10	216
E	10^3 TJ	35	9.23	6.53	1.085	20.08
K	10^{10} KRW	35	10.9	7.88	−0.659	29.9
Y	10^8 kWh	35	19.2	18.6	2.98	57.3
C	10^4 tons	35	62.51	42.25	5.49	124.92
Group 5 Gangwon (n = 2)						
L	Num.	14	2412.43	189.27	2065	2690
E	10^3 TJ	14	447.78	35.33	370.69	507.74
K	10^{10} KRW	14	436	30.2	369	4730
Y	10^8 kWh	14	423	52.8	363	5250
C	10^4 tons	14	3610	336	2900	4040

3.2. Methodology

3.2.1. Evaluation of CTFP

This study used the GNDDF method to evaluate the CTFP of the Korea Electric Power Enterprise Corporation (KEPEC) from 2015 to 2021. Assuming the presence of N power generation units as decision-making units (DMUs), each simultaneously produces a desirable output vector $Y \in R_+^m$ (the amount of carbon emissions), using an input vector $X \in R_+^n$ that includes labor (L), energy consumption (E), and capital stock (K). The baseline production technology (BPT) is defined as:

$$Q = \left\{ (L, E, K, Y, C) \in R_+^{n+m+j} \middle| L, E, K \; can \; produce (Y, C) \right\} \tag{1}$$

The Q group accepts traditional axioms of production theory (Fare et al., 1994 [17]), such as free disposability, and the two basic assumptions of Weak Disposabilit (if$(x, y, b) \in Q(x)$ and $0 \leq \theta \leq 1$, $(x, \theta_y, \theta_b) \in Q(x)$) of undesirable output and Null-jointness (if$(x, y, b) \in Q(x)$ and $b = 0, y = 0$) production (Chung et al., 1997 [18]).

Based on the above assumptions, we constructed the BPT, using nonparametric data envelopment analysis (DEA), based on constant return scales (CRS), as shown in the following equation:

$$\begin{aligned} Q(L, K, E) = \Big\{ & (L, K, E, Y, C) : \textstyle\sum_{n=1}^{N} \varphi_n L_n \leq L, \sum_{n=1}^{N} \varphi_n K_n \leq K, \\ & \textstyle\sum_{n=1}^{N} \varphi_n E_n \leq E, \sum_{n=1}^{N} \varphi_n Y_n \leq Y, \sum_{n=1}^{N} \varphi_n C_n \leq C, \varphi_n \geq 0, n = 1, \ldots, n \Big\} \end{aligned} \tag{2}$$

ϕ_n in the above equations are environmental variables for building ecological production technology by the convex combination method. By introducing $\sum_{n=1}^{N} \phi_n = 1$ as a constraint, the model shifts from assuming constant returns to scale (CRS) to variable returns to scale (VRS), thus reflecting the scale effects in the actual production process more flexibly. Further, VRS is now often widely used in environmental DEA methodologies (Pan, Zhang, Lee, & Lv, 2024 [19]).

3.2.2. Non-Radial Direction Distance Functions

The traditional directional distance function can combine multiple inputs and outputs to handle undesirable outputs. However, it cannot accurately handle slack bias[2]. However, the NDDF can solve the problem of slack variables, as defined in

$$\vec{D}(L, E, K, Y, C; g) = \sup\left\{\omega^{Q}\beta : ((L, K, E, Y, C) + g \cdot diag(\beta)) \in Q(L, E, K)\right\} \quad (3)$$

where ϖ denotes the vector of normalized weights associated with the inputs and outputs. According to (Zhou et al., 2012 [20]; Zhang and Choi, 2013 [21]; Zhao et al., 2023 [22]) we set the weights $(\varpi_L, \varpi_E, \varpi_K, \varpi_Y, \varpi_C)^{Q}$ to (1/9, 1/9, 1/9, 1/3, 1/3). The superscript "Q" is environmental production technology. $g = \left(-g_L, -g_E, -g_K, g_Y, -g_C\right)$ is the direction vector. $\beta = (\beta_L, \beta_K, \beta_E, \beta_Y, \beta_C)^{P} \geq 0$ denotes the set of factors that render each input or output inefficient. $diag(\cdot)$ is a diagonal matrix. Combining Equations (2) and (3), we derive the following DEA model to calculate the value of $\vec{D}(L, E, K, Y, C; g)$[3]:

$$\begin{aligned} \vec{D}(L, E, K, Y, C; g) = \quad & \max(\varpi_L\beta_L + \varpi_E\beta_E + \varpi_K\beta_K + \varpi_Y\beta_Y + \varpi_C\beta_C) \\ & s.t. \sum_{n=1}^{N} \lambda_n L_n \leq L_{n_1} - \beta_L g_L, \\ & \sum_{n=1}^{N} \lambda_n E_n \leq E_{n_1} - \beta_E g_E, \\ & \sum_{n=1}^{N} \lambda_n K_n \leq K_{n_1} - \beta_K g_K, \\ & \sum_{n=1}^{N} \lambda_n Y_n \geq Y_{n_1} - \beta_Y g_Y, \\ & \sum_{n=1}^{N} \lambda_n C_n = C_{n_1} - \beta_C g_C, \\ & \sum_{n=1}^{N} \lambda_n = 1, \lambda_n \geq 0, n = 1, \ldots, N, \\ & \beta_L\beta_E\beta_K\beta_Y\beta_C \geq 0. \end{aligned} \quad (4)$$

Figure 4 explains the principle of NDDF in detail:

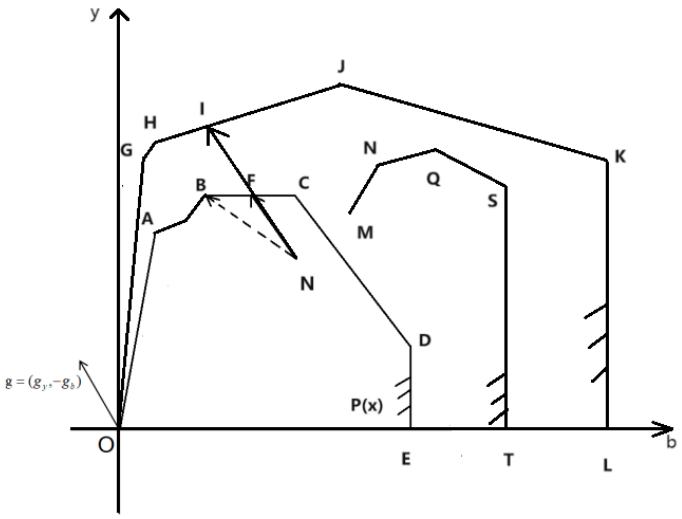


Figure 4. Non-radial direction distance function. Notes: The region formed by OABCDE is the BPT, as shown in Equation (3). When using a conventional radial DDF and direction vector g, the ideal

reference point for point N is on the left side of the boundary F. However, when using a nonradial DDF, the ideal reference point for point N is point B. Because point B has less unwanted power, but the same desired power as point F, the distance from BF is the relaxation value of the radially oriented DDF, and is called the relaxation bias. Based on non-radial technology, the relative efficiency of DMU *N* can be measured by the distance *NF*. There are only two methods to improve the production possibility frontier *OACDE*. First, when a DMU can learn from another group of DMU *Q*, its potential to increase its efficiency becomes as large as IF, which is called technical efficiency (EC), based on the learning effect from the benchmark DMU on the general production possibility frontier *OGKL*. Another way of enhancing potential efficiency is through innovation. Over time, new technology sets can be larger, such as *OGKL* and this potential increase in efficiency comes from innovation, which is called technical change (TC). Therefore, in this research, we discuss the enhanced efficiency potential for distance IF from the perspectives of time-fixed EC and dynamic TC.

3.2.3. Global Non-Radial Luenberger Productivity Indicator

A new green productivity GNLPI was provided to assess the change in the GNLPI of electric utility firms from period t to t + 1, solving the problem of slack variables and infeasible solutions by integrating the GLPI (Guo et al., 2024 [23]) and NDDF. The definition is:

$$GNLPI_n^{t,t+1} = \overrightarrow{D_n^G}(L^t, E^t, K^t, Y^t, C^t; g^t) - \overrightarrow{D_n^G}(L^{t+1}, E^{t+1}, K^{t+1}, Y^{t+1}, C^{t+1}; g^{t+1}) \quad (5)$$

Based on Equation (5), we further decomposed the GNLPI into efficiency and technological changes, as shown below:

$$\begin{aligned} GNLPI_n^{t,t+1} &= \overrightarrow{D_n^G}(.^t) - \overrightarrow{D_n^G}(.^{t+1}) \\ &= [\overrightarrow{D_n^t}(.^t) - \overrightarrow{D_n^{t+1}}(.^{t+1})] + [(\overrightarrow{D_n^G}(.^t) - \overrightarrow{D_n^t}(.^t)) - (\overrightarrow{D_n^G}(.^{t+1}) - \overrightarrow{D_n^{t+1}}(.^{t+1}))] \\ &= EC_n^{t,t+1} + TC_n^{t,t+1} \end{aligned} \quad (6)$$

In Equation (6), $EC_n^{t,t+1}$. is the change in the relative efficiency of each electric utility firm between t and t + 1, which demonstrates the distance between them and the frontiers of best practice production. If $EC_n^{t,t+1} < 0$, it will be less efficient, if $EC_n^{t,t+1} < 0$, it means the efficiency gets better. $TC_n^{t,t+1}$ denotes the change in technology from period t to period t + 1 for each firm, it shows the level of technological frontier or backwardness. So, when $TC_n^{t,t+1} < 0$, it means technological backwardness; instead, it means the company completes the technological enhancement.

In our study, to better understand the intrinsic drivers affecting CTFP and capture the specific factor contributions of EC and TC according to the nature of the Luenberger productivity index (Färe et al.,1994 [17]; Lin & Sai, 2021 [24]), we can decompose the factors as indicated below:

$$\begin{aligned} GNLPI^{t,t+1} &= CTFP_L^{t,t+1} + CTFP_E^{t,t+1} + CTFP_K^{t,t+1} + CTFP_Y^{t,t+1} + CTFP_C^{t,t+1} \\ EC^{t,t+1} &= EC_L^{t,t+1} + EC_E^{t,t+1} + EC_K^{t,t+1} + EC_Y^{t,t+1} + EC_C^{t,t+1} \\ TC^{t,t+1} &= TC_L^{t,t+1} + TC_E^{t,t+1} + TC_K^{t,t+1} + TC_Y^{t,t+1} + TC_C^{t,t+1} \end{aligned} \quad (7)$$

In Equation (7), the values for each represent the effect of specialized input or output factors on matching CTFP, EC, and TC.

4. Empirical Results

4.1. Decomposition of Total Factor Productivity

The evaluation of TFP in the electric utility industry shows contrasting results for each region. In this subsection, we delve further into the different performances of the local utilities in each region. To determine the governance mechanism of this differential performance, we decomposed the dynamic changes in TFP over time into technical efficiency (EC) and technical change (TC). As previously explained, EC implies the learning

effect from other benchmark cases within the same technology and fixed production possibility frontier, whereas TC evaluates the innovation effect with the change in the overall productivity frontier.

First, from Figure 5 and Table 4, Jeolla Province was found to play a leading role in enhancing EC during the pilot project period, however, it experienced a significant decrease in technical change (TC) as well. This rapid fluctuating trend can be explained in several ways.

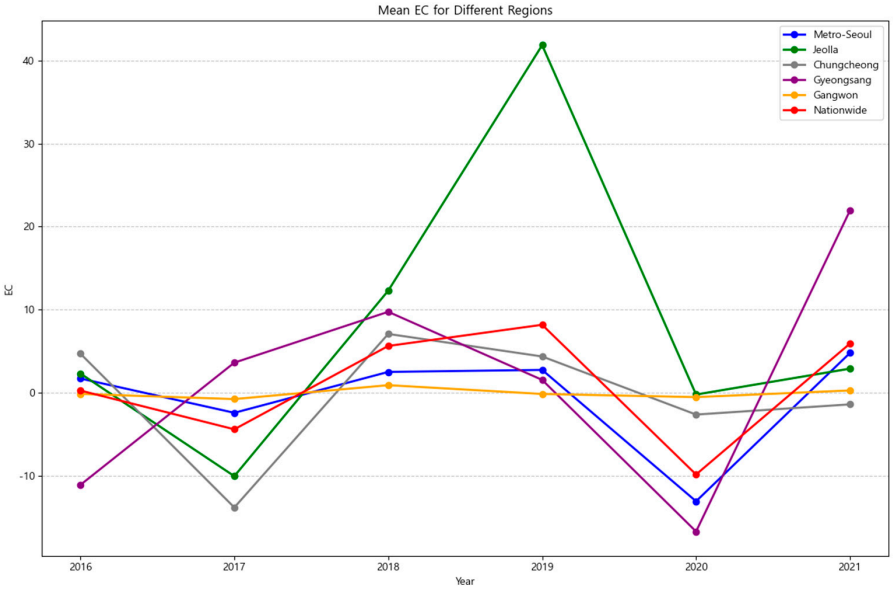


Figure 5. EC for Different Regions.

Table 4. Values of EC for Different Regions for Each Year.

	Metro-Seoul	Jeolla	Chungcheong	Gyeongsang	Gangwon	Nationwide
2016	1.7004	2.3000	4.6934	−11.1057	−0.1519	0.2513
2017	−2.4272	−10.0575	−13.8262	3.6127	−0.7748	−4.4145
2018	2.4964	12.2819	7.0698	9.7355	0.9007	5.6230
2019	2.7392	41.8388	4.3554	1.5361	−0.1587	8.1721
2020	−13.0805	−0.2292	−2.6393	−16.7191	−0.5373	−9.8544
2021	4.7834	2.8937	−1.4101	21.9332	0.2654	5.9112

During the period from 2017 to 2019, Jeolla Province vigorously developed several new large-scale energy projects, including wind farms and solar power plants. The construction of these projects boosted the technical efficiency (EC) of electric utilities in the region as new facilities and technologies were built to utilize resources more efficiently and improve production processes. However, technical change (TC) declined during this phase, possibly because, while infrastructure and technological conditions improved, technological innovation did not keep pace. In other words, the pace of technological progress and innovation has lagged in relative terms despite overall improvements in the efficiency of resource utilization.

As shown in Figure 6 and Table 5, the situation changed significantly from 2019. At this point, the technical efficiency (EC) in Jeolla Province began to decline, while technological change (TC) rose significantly. This shift may be related to the continued promotion of new energy projects in Jeolla Province since 2019, particularly the introduction and application of new technologies. The introduction of new technologies and equipment accelerated technological change (TC), that is, the pace of technological innovation and

the level of technology, as shown in Figure 7 and Table 6. However, in this process, technical efficiency (EC) may be negatively affected in the short term because the application of new technologies requires time for optimization and integration. This implies that, despite the accelerated pace of technological innovation, the actual application of new technologies has not been fully optimized for resource utilization yet, leading to a decline in technical efficiency.

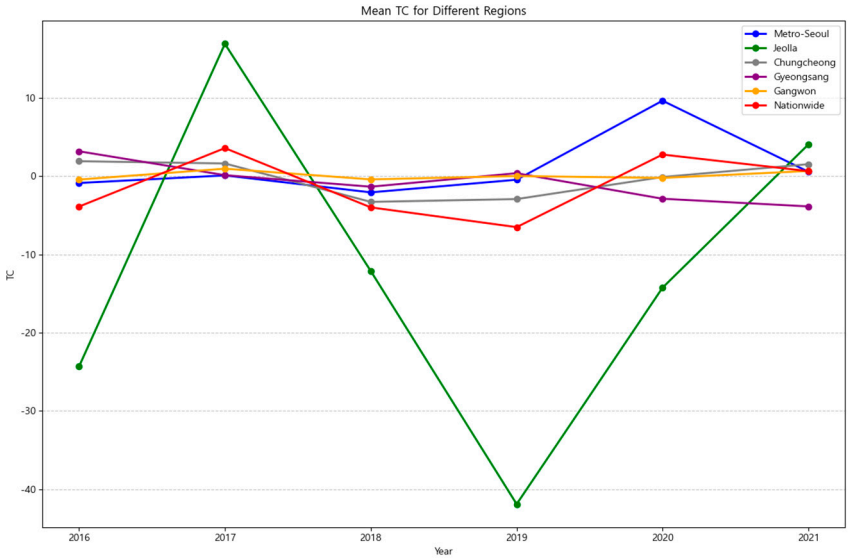


Figure 6. TC for Different Regions.

Table 5. Values of TC for Different Regions for Each Year.

	Metro-Seoul	Jeolla	Chungcheong	Gyeongsang	Gangwon	Nationwide
2016	−0.8833	−24.3267	1.8981	3.1672	−0.4455	−3.8946
2017	0.0870	16.8856	1.6105	0.1172	0.9453	3.5737
2018	−2.0818	−12.1282	−3.2949	−1.3570	−0.4241	−3.9974
2019	−0.4653	−41.8948	−2.9360	0.3676	0.0053	−6.5203
2020	9.6288	−14.2544	−0.1205	−2.8927	−0.2355	2.7503
2021	0.5475	4.0431	1.5206	−3.8737	0.6513	0.6299

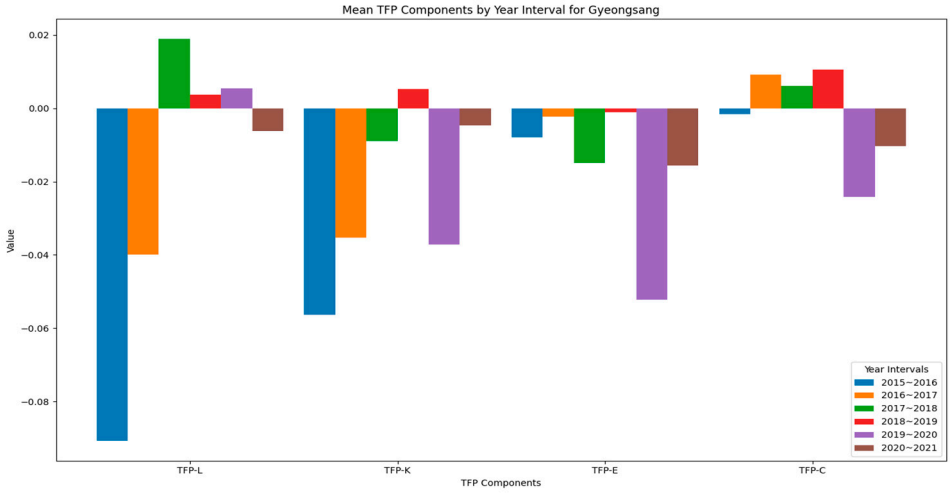
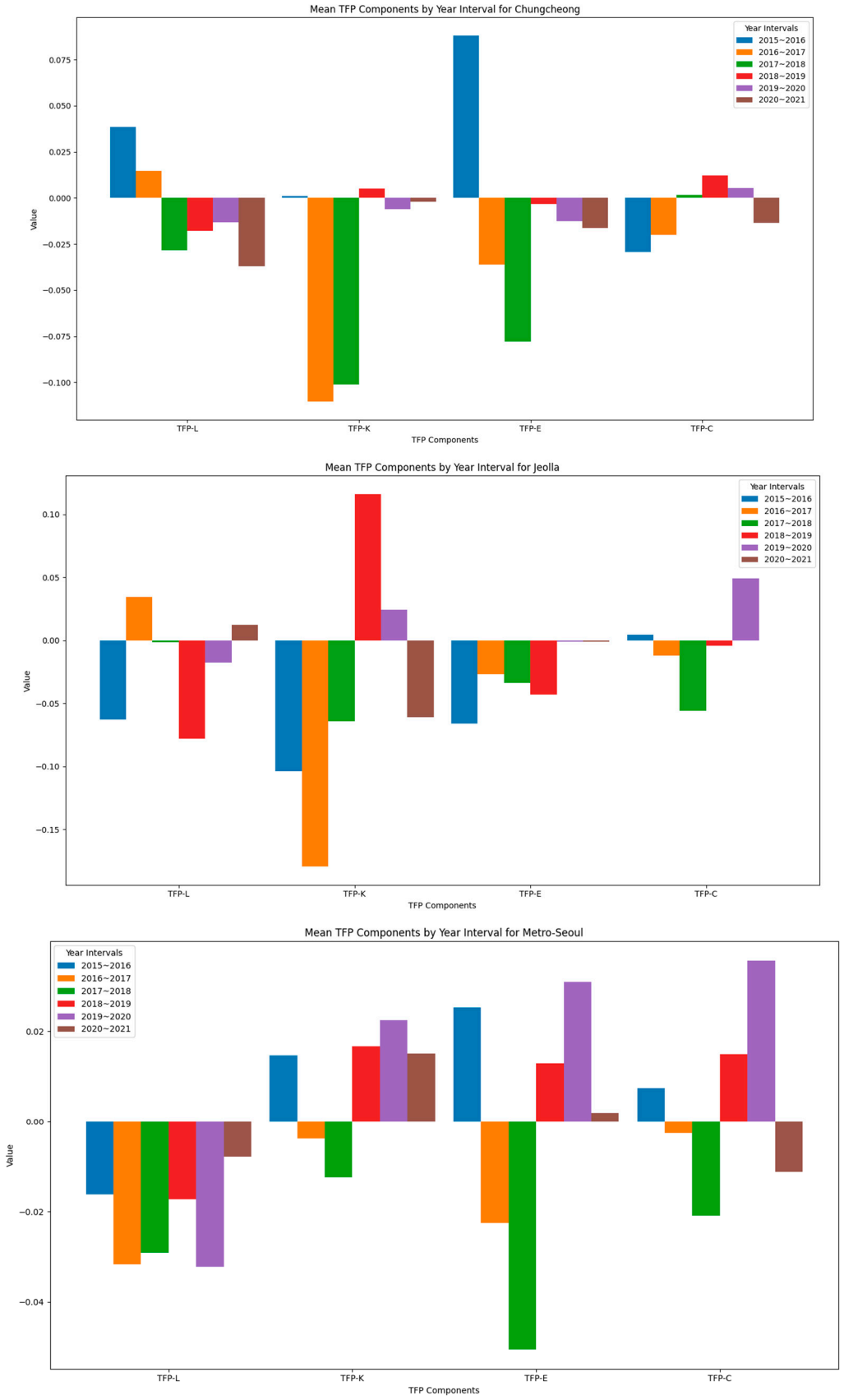


Figure 7. *Cont.*



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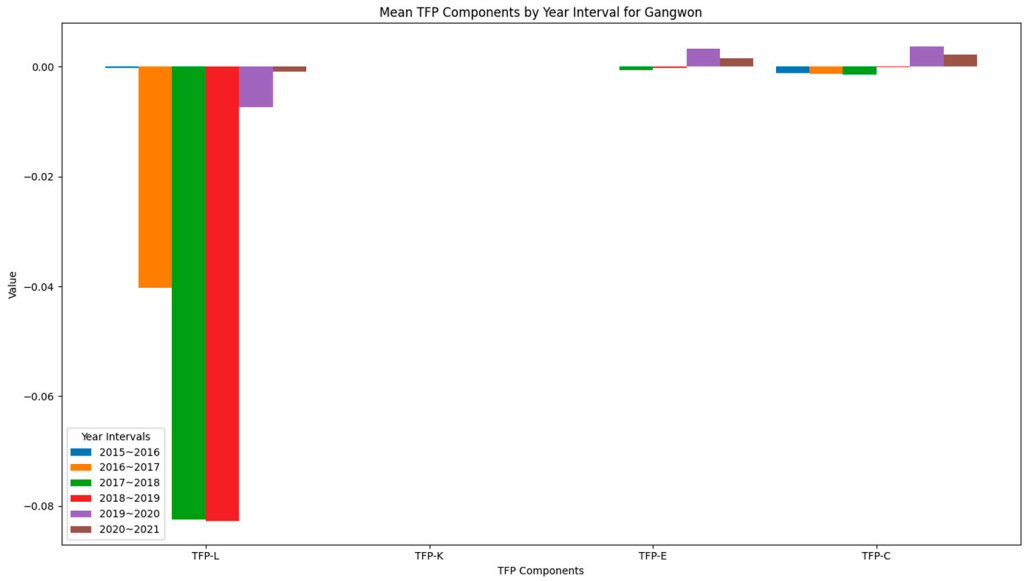

Figure 7. Trend of the driving factors by region.

Table 6. Values of TFP for Different Regions for Each Year.

	Metro-Seoul	Jeolla	Chungcheong	Gyeongsang	Gangwon	Nationwide
2016	0.8171	−22.0267	6.5915	−7.9384	−0.5974	−3.6433
2017	−2.3402	6.8281	−12.2156	3.7299	0.1705	−0.8408
2018	0.4147	0.1537	3.7749	8.3785	0.4766	1.6256
2019	2.2739	−0.4567	1.4195	1.9037	−0.1533	1.5376
2020	−3.4517	−11.4593	−2.7597	−19.6118	−0.7728	−6.8051
2021	5.3309	9.2273	0.1105	18.0595	0.9168	6.9852

Additionally, the relocation of the headquarters of the Korea Electric Power Corporation (KEPCO), South Korea's largest state-owned electric utility, to Jeolla in 2014 may have played an important role in this structural change in the industry. The company's relocation strengthened the power infrastructure and technology R&D capabilities of Jeolla Province, generating more technological resources and innovation opportunities for the region. However, in the early stages of technology introduction and adoption, overcoming efficiency losses and adapting to new technologies may take some time, leading to short-term declines in technological efficiency. However, since 2019, it has played a leading role in enhancing TC with the strong support of KEPCO for technological innovation in renewable energy.

To examine the factor drivers in each region, we used the nature of the summation of the Luhnberg indices and further disaggregated the factor contributions in each region. Because output $\boldsymbol{Y}$ plays a key role in these factors, to distinguish and analyze the differences in drivers across regions in more detail, we extracted output $\boldsymbol{Y}$ separately and conducted an in-depth analysis of the performance of the other factors in the five regions. In particular, the Gangwon region is sparsely populated; therefore, the labor force mentioned here refers mainly to that in the electricity production sector. In Figure 7, we observe that the labor force is a particularly prominent driver of enhanced TFP in the Gangwon region, and creates a significant difference, as compared with other regions.

The reason the labor force is so prominent in the Gangwon region can be attributed mainly to its unique regional economic characteristics and demographic structures. Although South Korea is a developed country, the economy of Gangwon, a relatively remote

mountain city, is highly dependent on the power and energy sectors, which provide significant local employment opportunities, thus making labor one of the core drivers of local economic development. Compared to other regions, Gangwon's labor force performs well in electric utilities, not only in terms of the number of jobs, but also in terms of the efficiency and contribution of the labor force due to the geopolitical emphasis on the environmental protection of the region, which further increases its environmental performance in the electric utility industry.

Additionally, the socioeconomic conditions and demographics of the Gangwon region play an important role in driving the labor force. Due to the low population density, socioeconomic development is more concentrated in the power and energy sectors, which means that the local labor market is largely dominated by these industries. Not only is Gangwon-do's labor force significantly higher than in other regions, but it also has a higher level of skills and focus, resulting in a solid foundation for electric utility development. Together, these factors have led to the development of significant regional characteristics in Gangwon region, making it a key differentiating element from other regions.

In summary, Gangwon's regional labor force performance in electric utility reflects not only the uniqueness of its economic structure, but also the significant regional advantage in terms of the labor force drive. This implies that private participation with behavioral change could play a leading role in enhancing TFP. Most developing countries, such as Korea, emphasize the importance of government-led regulatory policies, as the Porter hypothesis argues, but this study also found a unique feature of the labor force in terms of the geopolitical background, that favors a clean and green Gangwon.

4.2. Environmental Total Factor Productivity

This study utilized total factor productivity (TFP) data for five different regions and the country as a whole for the period 2015–2021. The five regions were Metro-Seoul, Jeolla, Chungcheong, Gyeongsang, and Gangwon. The charts show the TFP trend for each region, providing a picture of the environmental efficiency of different regions for visual comparison. This study examines the trend and fluctuation of TFP in various regions through time-series analysis. The results show that although the TFP of some regions has increased slightly, the whole country shows a fluctuating trend. By comparing the changes in TFP across regions, the differences in environmental efficiency can be shown more clearly.

As shown in Figure 8, nationwide TFP fluctuated less between 2015 and 2021, indicating that overall productivity was relatively stable. However, there were significant differences between regions. The TFP in the Seoul metropolitan area remained relatively stable, while the Jeolla region experienced significant jumps and falls. The Chungcheong region showed a significant decline in 2016, but a gradual recovery thereafter. The Gyeongsang region fluctuated significantly between 2020 and 2021, reaching its highest point in 2021. In contrast, the Gangwon region showed a steady upward trend, with little overall fluctuation. The global outbreak of COVID-19 affected TFP to varying degrees in each region (Huang et al., 2022 [25]). These regional differences prompted a more in-depth analysis to explore the causes and effects of differentiated policies.

Table 6 reveals surprising results that the most significant differences were between Jeolla and Gyeongsang. The TFP in Jeolla declined between 2015 and 2016 and then quickly rebounded to a positive figure between 2016 and 2017. This phenomenon may be related to the strong solar energy development in the Jeolla region in 2016. In the short term, the development of renewable energy sources, such as solar energy, led to a decline in TFP, mainly due to initial investment and technology transition costs, as well as increased operational complexity. Initial investment in the introduction of new technologies and infrastructure development depresses regional TFP, while not generating commensurate output in the short term. Additionally, the intermittent and volatile nature of solar energy increases the complexity of power system scheduling and management, which may lead to a short-term decline in TFP. Nonetheless, in the long ssrun, as technological advances and

scale effects become apparent, the gradual reduction in solar energy costs and increased efficiency may increase regional TFP. The development of renewable energy sources may lead to new market opportunities and competitive advantage. Therefore, the fluctuations in TFP in the Jeolla region not only reflect the challenges of the initial development of renewable energy, but also foreshadow its potential long-term benefits.



Figure 8. TFP for Different Regions.

Comparing these two regions, rather than demonstrate a significant leading role, Metro-Seoul area revealed a lower performance in enhancing nationwide TFP, as shown in Figure 5. In particular, it was much lower than nationwide TFP when the latter increased from 2015 to 2018. When nationwide TFP recovers from COVID 19 between 2020 and 2021, it shows a lower performance than the nationwide TFP. Figure 5 shows that despite Seoul's excellent economic performance, its environmental efficiency does not stand out. The poor performance of the Seoul region may be due to the complexity and uncertainty of its emission reduction policy. Many studies have emphasized that market-oriented economic support for highly developed areas, such as Seoul and Shanghai, may provide easier access to resources and better opportunities for innovation toward sustainable development, resulting in much higher TFP performance. However, this cannot be true in our context because Metro-Seoul has experienced an arbitrary expansion of the green belt for the industrial zone or a new habitat. The surrounding areas of Metro-Seoul have lost much of their environmental heritage from the greenbelt landscape. Moreover, it uses more resources to produce its output because of the abundantly accessible resource concentration resulting from rapidly growing urbanization. Many developing countries may exhibit similar conditions by aggravating the undesirable outputs of urbanization, such as water and atmospheric pollution, and lucrative business strategies. Instead of reducing carbon emission, many companies choose a penalty based on the rather low arbitrary price of KAU, which is much lower than its abatement cost (shadow price). These metropolitan areas even export their environmental burden to other regions. Metro-Seoul is heavily dependent on the Chungcheong region for its electricity supply. Therefore, the Chungcheong region experiences more pressure for emission abatement. COVID-19 caused more significant economic shocks due to the high share of heavy industry in the region, especially the dependence on energy-intensive industries, such as refining and chemicals. This has not only led to a decline in productivity, but has also exacerbated the region's challenges in maintaining a balance between environment and economics, potentially creating additional social problems for the local self-sufficient economic model.

The TFP of electric utilities in the Gyeongsang region declined most significantly between 2019 and 2020, mainly because of the overlap of several key factors. First, the permanent closure of the Wolseong-1 nuclear power plant led to a significant reduction in electricity supply, which increased operating costs and overall production difficulties for the local economic landscape. Second, the multiple Energy Storage System (ESS) fire incidences in solar energy facilities raised safety concerns and prompted local governments to implement stricter regulatory measures, further inhibiting the productivity of related industries. Additionally, the COVID-19 outbreak, particularly in Gyeongsang Province, led to a sharp drop in electricity demand and disruptions in the supply chain, which reduced TFP. Because the Gyeongsang region is the base of national heavy industries, such as oil refineries and chemical industries, the effect of COVID-19 on the region was the largest, resulting in a decline in TFP. However, by 2020–2021, as the outbreak was controlled, legal issues arising from the closure of the nuclear power plant were gradually resolved, security measures at the ESS were strengthened, electric utilities regained productivity, and the TFP rebounded.

5. Conclusions

This study provides a detailed analysis of the total factor productivity (TFP) in five regions of South Korea from 2015 to 2021, with the aim of assessing the policy performance of local governments on carbon-neutral transition in the electric utility industry. In the National Emissions Trading System (ETS) pilot program launched in 2015, the South Korean government adopted different strategies in different regions to achieve its carbon reduction targets. These strategies reflected the unique economic structures and energy dependence of each region. The results revealed significant differences in environmental efficiency and TFP among the regions, especially between metropolitan areas (Metro-Seoul) and Jeolla Province (Jeolla). Although Metro-Seoul is considered the economic center of Korea, its relatively poor environmental performance is mainly related to weak governance, arbitrary greenbelt reduction, and unrestricted land development. Similar factors are observed in many developing countries that face climate adaptation challenges. In contrast, the Jeolla and Gangwon regions show relatively better performance, especially because of new energy innovation and its resulting technological efficiency, driven by the promotion of new energy projects and geopolitical characteristics.

Based on the factor decomposition of TFP, the Gangwon region showed particularly strong labor-driven performance, with its unique regional economic characteristics and geographies that make labor a key driver of the landscape of local economic development. This implies that private participation through behavioral change during the climate crisis could be an effective step leading toward a carbon-zero economy. According to the Porter hypothesis, many developing countries with government-led economic policies argue that regulatory policies are crucial for a carbon-zero economy. However, the regulatory policies in Korea did not perform well in its pilot project phase of ETS from 2015 to 2020 due to flickable quotas among the new administrations, resulting in a lack of governance and a much lower market price of ETS compared to its potential shadow price, resulting in a moral hazard for the participating companies [3]. This study explains why this lack of governance occurred; it was because the government did not make adequate efforts for the private sector to change its behavioral habits. Since the Gangwon region is famous for its outstanding natural heritage, most local people are sensitive to climate challenges; thus, their efforts have promoted the enhancement of the TFP.

Therefore, we recommend that relevant authorities strengthen regional governance and field-oriented planning. Experience in the Seoul Metropolitan Area shows that relying solely on market forces is not sufficient to solve environmental efficiency problems. The government should strengthen local governance and curb unnecessary development through strict land use planning and environmental regulations. Simultaneously, greenspace protection policies need to be revisited to ensure their prioritization in urban development to avoid further deterioration in environmental efficiency. The economic structures and

geopolitical characteristics of the regions differ significantly, thus requiring policies tailored to local contexts. For regions, such as Gangwon, whose economies depend on the power and energy sectors, technological innovation and skill upgradation should be further promoted to strengthen competitiveness in the new energy sector. For regions with slower technological efficiency improvements, such as Jeolla Province, the government should provide more technical support and incentives to promote the effective application of new technologies.

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Conflicts of Interest: The authors declare no conflict of interest.

Notes

[1] In this context, "geopolitical" refers to how geographical and economic conditions within regions influence their environmental and energy policies, rather than geopolitics in the traditional sense of international relations.

[2] Figure 1 is the explanation of slack-bias.

[3] If $\vec{D}(L, E, K, Y, C; g) = 0$, it implies that the evaluated DMU is positioned on the optimal frontier of the g-vector, considering the slack variables.

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