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An Effect of Carbon Dioxide and Energy Reduction on Production Efficiency and Economic Growth: Application of Carbon Neutrality in Korea

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Abstract: Global interest in climate change and carbon neutrality is hot. According to the Intergovernmental Panel on Climate Change, achieving carbon neutrality is the solution to avoiding climate change. Carbon neutrality is a global challenge for sustainable economic growth. In response, Korea declared 2050 carbon neutrality in 2021. However, for Korea to be carbon neutral, an incredible transformation in terms of an energy revolution is required. In this context, this study aims to diagnose the current situation to achieve carbon neutrality in Korea and to explore the direction of minimizing the national economic burden in the implementation process. To this end, we use the data envelopment analysis (DEA) directional distance function based on the material balance flow approach to examine changes in production efficiency and GDP due to carbon dioxide reduction and energy conversion. The empirical analysis results are as follows. First, in the analysis, according to the type of reduction, when only 1% of CO_2 was reduced, GDP decreased by about 0.1%. Still, when reduced simultaneously with fossil energy, GDP fell by about 0.3% or more. Secondly, based on the scenario of the 2050 carbon-neutral plan, as a result of estimating the efficiency and GDP change caused by Korea's energy transition, Korea is a country with a significant increase in inefficiency due to the energy transition and a substantial loss of GDP. Therefore, the government should establish a Korean carbon-neutral policy at a level that the national economy can afford.

Keywords: carbon neutral; energy transformation; economic growth; GDP

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1. Introduction

After the 2015 Paris Climate Agreement, the Intergovernmental Panel on Climate Change (IPCC) requested a national action plan (NDC). IPCC said if the global temperature rose by 1.5 degrees compared to preindustrial levels, global disasters would result. In response, major developed countries, such as the U.K., Germany, and France, declared carbon neutrality by 2050, prepared reduction targets and action plans, and began submitting them to the IPCC. Carbon neutrality refers to a state in which net emissions are zero. It is achieved by reducing greenhouse gas emissions and absorbing or removing excess emissions (forests, carbon capture, etc.). Korea also submitted a midterm goal of reducing 170 million tons by 2030 to the U.N. Climate Change Secretariat, but the reduction goal was raised as it was judged to be insufficient.

The government installed the Presidential Carbon Neutrality Committee in 2021 and announced the enhanced carbon neutrality scenario 2050 in October 2021. Accordingly, the Carbon Neutrality Committee prepared two carbon-neutral scenarios (A and B) in which domestic net emissions would be zero in 2050 and announced a plan to raise the national greenhouse gas reduction target (NDC) by 2030 to 40% compared to 2018 (ref. [1]). The main point of these two proposals is to drastically reduce fossil energy, which causes greenhouse gas emissions, and convert it to new and renewable energy, including electricity and hydrogen, by 60.9% (plan A) and 70.8% (plan B), respectively. Both plans plan to reduce existing nuclear power generation from 29% of existing power generation to about 6% by 2050.

Carbon neutrality is a global trend and must be achieved for sustainable economic growth. However, greenhouse gas reduction and energy conversion are a considerable burden and challenge for Korea. In particular, in the energy-conversion plan, coal is eliminated as fossil energy, oil is drastically reduced, and nuclear energy is scrapped at the end of its lifespan. It is evaluated as a great transition corresponding to the energy revolution. Compared to other countries, major developed countries such as the UK, France, and Germany have steadily reduced greenhouse gas emissions since the early 1990s, and the 2050 carbon-neutral implementation period is about 50 to 60 years. On the other hand, Korea achieved economic growth relatively late, and the carbon-neutral transition period is about 30 years. Rapid change hits the economy hard.

So far, each country, including developed countries, has established and reported a 2050 carbon-neutral plan, but it is not known exactly how much the cost of carbon reduction is. Korea's 2050 Carbon Neutral Plan was only planned, and the economic burden was not accurately presented. In fact, it is not too much to say that the conditions for achieving carbon neutrality depend on the economic costs that the national economy can bear. If the economic burden is too great, it is difficult for the carbon-neutral plan to be promoted as planned.

In this study, the actual economic burden of each country's carbon reduction is measured by production efficiency and GDP change. Estimating this economic burden can confirm whether the carbon-neutral action plan is realistically achievable. It is very important to empirically confirm the feasibility of this achievement for the revision of the carbon-neutral plan and the search for alternatives.

Therefore, the purpose of this study is to measure the level of GDP reduction due to carbon and energy reduction by using data from 166 countries and to further measure the change in production efficiency and GDP due to carbon reduction and energy conversion.

To explore the impact of the transition to carbon neutrality on economic growth, various methods, such as the use of macroeconomic models and panel data analysis can be used (refs. [2–7]). In this study, the data envelopment analysis (DEA) directional distance function of the material balance flow approach is utilized with a focus on production efficiency. In detail, we will examine changes in production efficiency and GDP due to carbon dioxide reduction and energy conversion.

The research hypothesis of this study is as follows. First, when only carbon dioxide is reduced (B), when both carbon dioxide and fossil energy are reduced simultaneously (C), and when carbon dioxide, fossil energy, and nuclear energy are reduced simultaneously (D), changes in production efficiency and GDP change will be different. Secondly, production efficiency and GDP changes due to greenhouse gas reduction and energy conversion will differ by country.

The analysis performed for this purpose can be divided into two major categories. First, 166 countries are classified by income group, the current situation (A1) is diagnosed, and changes in production efficiency and GDP according to the three reduction types (B1, C1, and D1) mentioned above are analyzed. Secondly, the current situation is diagnosed for only 30 countries using nuclear energy (A2), and production efficiency and GDP changes according to three energy conversion types (B2, C2, D2) are examined.

The difference between this study and previous studies is that this study uses DEA to analyze the impact of CO_2 reduction and energy conversion on Korea's economic growth and review carbon-neutrality measures suitable for the Korean situation. At this point, when carbon neutrality and energy transition are desperately needed, analysis based on the 2050 carbon neutral plan will be able to suggest Korea's policy direction. To the best of our knowledge, no previous studies have measured the impact of carbon neutrality and energy transition on economic growth, with a focus on Korea's 2050 carbon-neutral plan.

This study is structured as follows. In Section 2, previous studies are reviewed. In Section 3, the theoretical model is examined. In Section 4, data are explained, and empirical analysis results are presented. Section 5 discusses in detail the results of the empirical analysis. Finally, Chapter 6 presents conclusions, policy implications, and limitations.

2. Literature Review

Previous studies can be divided into three criteria. First, based on the main variables, it can be divided into the relationship between energy consumption and economic growth, the relationship between economic growth and CO_2 emission, and the analysis of the impact of changes in the energy mix on economic growth. Secondly, similar to this study, it is a study on the path to estimating the impact of carbon neutrality on the economy or achieving carbon neutrality. Finally, from a methodological point of view, this is a study using DEA or SFA.

2.1. Energy Consumption, CO_2 Emission, Energy Mix, and Economic Growth

First, most studies examining the direction of the causal relationship between energy consumption and economic growth suggest a two-way causal relationship (refs. [8–10]). On the other hand, some results showed that the relationship was unclear (refs. [11,12]).

Secondly, research on the relationship between economic growth and CO_2 emissions was also inconclusive. In the case of developing countries, a negative relationship was found (ref. [13]). In the case of 10 OECD countries, a positive relationship was found (ref. [14]). On the other hand, no causal relationship was found (ref. [15]). Regarding Korea, as a result of analyzing the relationship between energy and economic growth for the period 1970–1999, energy had a one-way causal relationship affecting economic growth in the short term. In the long term, it showed a two-way causal relationship (ref. [16]).

Thirdly, there are studies on the effects of energy conversion and the expansion of renewable energy on economic growth. Ref. [2] analyzed the relationship between Korea's CO_2 emissions, economic growth, and energy mix. As a result, the energy mix significantly contributed to domestic greenhouse gas reduction. Specifically, nuclear energy significantly reduced CO_2 emissions compared to other energy sources, but renewable energy did not. It is interpreted that this is because Korea's proportion of renewable energy is deficient. Ref. [3] analyzed the impact of nuclear energy consumption on GDP growth and CO_2 emissions in 30 nuclear energy-consuming countries. The results show that nuclear energy consumption contributes to GDP growth without affecting CO_2 emissions. Ref. [4] analyzed the relationship between renewable energy consumption and economic growth in 25 European countries. As a result, there was a higher correlation between the energy consumption of renewable energy storage (RES) and economic growth in countries with high GDP than in countries with low GDP. Ref. [5] analyzed the threshold effect in the transition to new energy by using a panel threshold model for countries with high energy consumption (the United States, China, Japan, Canada, Korea, Germany, and France) from 1997 to 2016. As a result, it was found to have a nonlinear effect on economic growth. That means it harms economic growth initially but turns into a positive effect after a certain point. Influencing factors include R&D level, economic development, and dependence on traditional energy. Ref. [17] conducted panel data analysis on the impact and determinants of the energy paradigm shift on the economic growth of the European Union. Thirty European countries (EU member states, Iceland, and Norway) were targeted. The nine economic variables (energy dependence, energy intensity, environmental tax revenue, etc.) used in the analysis affected the energy paradigm shift.

2.2. Carbon Neutrality and Economic Growth

Studies that estimated the impact of carbon neutrality on the economy or explored an efficient path are as follows. Ref. [7] estimated the cost of climate change mitigation policies based on Japan's 2050 GHG reduction scenario. In this case, a macroeconomic model was used. As a result of comparing the existing independent CGE model and the new integrated CGE model that reflects energy system information, the former showed a loss of about 2.5% of GDP in 2050, and the latter showed a low loss of about 1.2%. Ref. [18] established a roadmap to carbon neutrality in 2050 in the United States by using the energy pathways (EP) and RIO models and explored multiple pathways toward it. All pathways are based on energy efficiency, decarbonization, electrification, and carbon capture strategies. The analysis showed that a primary energy system with 100% renewable energy is possible, but at an increased cost. It was also noted that biomass use and renewable land could be limited, requiring nuclear power to compensate. The study found that the U.S.'s cost of a 2050 carbon-neutral transition is not very high. However, it highlights the need to consider tradeoffs. Ref. [19] discussed the economic aspects of the U.S. energy transition. In the United States, the economic costs of switching from fossil fuels to renewables in power generation are estimated to be lower than the benefits. However, decarbonization means replacing electricity throughout the site; for this, the price of electricity must be close to the marginal cost. That has been pointed out as a big problem. Ref. [20] analyzed the impact of Korea's climate change response policies on GDP by using the macromodel dynamic stochastic general equilibrium (DSGE). The emission cost, according to carbon dioxide emission, was reflected as the carbon tax increase, and the emission-removal effect, according to carbon capture, utilization, storage (CCUS) technology, was assumed to be the carbon tax cut effect, which was analyzed. As a result of the analysis, it was found that from 2020 to 2050, the average annual decline was 0.08–0.32%. The case in which the global average temperature increase is suppressed by 2 °C rises compared to preindustrialization is 0.08%, and the case where 1.5 °C rises suppress the increase is 0.32%.

2.3. Studies with DEA and SFA

Lastly, these studies used DEA or SFA to study the relationship between efficiency and economic growth. Ref. [21] divided 63 countries into income groups from 1981 to 2005 and examined the relationship between adopting the Kyoto Protocol and environmental efficiency. A stochastic metafrontier analysis was used. It was estimated that the production technology was different between the groups. It was also found that countries that ratified the Kyoto Protocol tended to be more efficient. Ref. [22] compared the difference in production efficiency between the traditional and material flow approaches using the directional distance function. In addition, the impact of pollution control on economic growth was estimated. As a result, when Korea's CO_2 emissions were reduced by 3%, the reduction in economic growth rate was 1%, which was higher than the OECD average. Ref. [23] estimated the impact of economic growth on environmental efficiency over the period 1980–2010 by using a stochastic directional distance function for 99 countries. Ref. [6] used a stochastic frontier analysis (SFA) to estimate GDP loss due to reduced energy consumption and the expansion of renewable energy. According to the empirical results, GDP losses are projected to be about $3.155 billion, $9.384 billion, and $16.692 billion in 2025, 2030, and 2035, respectively. Compared to the 2015 GDP, these figures correspond to 0.2%, 0.7%, and 1.3%, respectively.

In summary, from the results of previous studies, it can be expected that GDP loss will inevitably occur due to greenhouse gas reduction and energy conversion policies. In addition, the impact of the transition to renewable energy on economic growth differed depending on the country's existing energy generation characteristics. It is in line with what we want to confirm in this study.

3. Theoretical Model

3.1. Model

This study estimates the optimal GDP and production efficiency using the DEA method. DEA is a linear programming method that does not assume a specific function and is a method to find an optimized value by applying conditions. It is a method of finding the most efficient decision-making unit (DMU) and measuring the relative distance based on this to obtain efficiency. In this study, the DEA directional distance function is used. It is widely used to maximize desirable outputs and minimize undesirable pollutants by assuming free disposal (strong disposal) of a large number of inputs and outputs.

Material flow balance, our approach, refers to the fact that inputs to a production process produce equal amounts of desirable outputs and pollutants (refs. [24–30]). In other words, it refers to estimating efficiency by activating not only outputs and pollution but also inputs closely related to them.

Consider two outputs (y, b). y is the desired output and b is the pollutant. They are produced with four inputs (k, l, ff, nf). In this equation, it is assumed that ne (nuclear energy) is included in nf (nonfossil energy) to explain the principle simply. It can also be separated. Specifically, y is real GDP, b is CO_2, ff is fossil energy consumption, nf is nonfossil energy consumption, k is capital stock, and l is labor. Assume that there are two productive sets of production as follows:

$$\begin{aligned} T_1 &= \{(k,l,ff,nf) : (k,l,ff,nf)\ produce\ y\} \\ T_2 &= \{(ff,b) : (ff)\ produce\ b\}. \end{aligned} \quad (1)$$

In T_1, the desired output and four inputs are assumed to be free disposition. However, in T_2, only a pair of inputs and outputs (ff, b) is assumed to be a weak disposition. At this time, free disposition (strong disposition) means not being restricted, and weak disposition means being restricted. The detailed description of this weak disposal is as follows:

$$\begin{aligned} (ff,b) \in T_2 &\Rightarrow (k \cdot ff, k \cdot b) \in T_2, 0 \le k \le 1 \\ but\ not\ (ff, k \cdot b) \in T_2, 0 \le k &\le 1\ or\ (k \cdot ff, b) \in T_2, k > 1. \end{aligned} \quad (2)$$

It is assumed that b (CO_2) and ff (fossil fuel) are in a material flow relationship. Increased use of fossil fuels changes pollution levels. In other words, if the use of fossil fuels is increased in a certain state of technology, the level of pollution will inevitably increase. T_1 and T_2 have a convex relationship. Therefore, the entire product set is expressed as Equation (3) below. This expresses that the technology of production consists of two technological structures that combine general production technology and environmental technology. This reflects the close connection between fossil fuels and pollutants among the inputs. We have

$$T = \{(k,l,ff,nf;y,b) : (k,l,ff,nf;y) \in T_1, (ff,b) \in T_2\}. \quad (3)$$

As described above, this study introduces a set of descriptions of fossil energy, pollutants, and outputs based on this material balance approach. In order to define the direction distance function by linking fossil energy, pollutants, and outputs in this way, let the direction vector be $g = (+g_y, -g_b, -g_{ff}, -g_{nf}, -g_{ne})$. The direction distance function can be expressed as Equation (4). Equation (5) also includes the case in which a direction vector is given by adjusting new and renewable energy. β is the value of the direction distance function and β has a value greater than zero. If $\beta = 0$, it is most efficient to reach the frontier, and if $\beta > 0$, it is located inside the frontier and is inefficient. We have

$$\begin{aligned} &\overrightarrow{D}_1(y,k,l,b,ff,nf,ne : +g_y, -g_b, -g_{ff}, -g_{ne}) \\ &= max\{y : (y + g_y\beta, b - g_b\beta, ff - g_{ff}\beta, ne - g_{ne}\beta)\} \end{aligned} \quad (4)$$

$$\begin{aligned} &\overrightarrow{D}_1(y,k,l,b,ff,nf,ne : +g_y, -g_b, -g_{ff}, -g_{nf}, -g_{ne}) \\ &= max\{y : (y + g_y\beta, b - g_b\beta, ff - g_{ff}\beta, nf - g_{nf}\beta, ne - g_{ne}\beta)\}. \end{aligned} \quad (5)$$

3.2. Analysis Scenarios

3.2.1. Scenario model

In this study, two analyses are performed. The first analysis is to estimate Equation (6) based on the directional distance function of Equation (4). It is to confirm the change in economic growth according to the type of energy reduction. The second analysis is to estimate Equation (7) based on the directional distance function of Equation (5). It is to see changes in efficiency and GDP according to energy conversion based on Korea's 2050 carbon-neutral plan. In other words, it is to measure the directional efficiency when converting fossil energy and nuclear energy into new and renewable energy.

In the direction distance function estimation, λ is a nonnegative intensity vector $(k * 1)$ that forms a frontier by achieving the maximum and minimum amounts of the observed inputs and outputs. In the equation, the equal sign means weak disposal, and the inequality sign means free disposability, the state that can be controlled without restriction. μ denotes the level of the reduction target. When a reduction target value (μ) is given, the maximum achievable output and directional efficiency are derived.

Specifically, Equation (6)-(A1) is a current direction efficiency estimation equation that simultaneously minimizes CO_2, fossil energy, and nuclear energy and maximizes output. Equations (6)-(B1) represent the case where only CO_2 emissions are reduced (3%). Equation (6)-(C1) means that the reduction target (μ) for both fossil energy consumption and CO_2 is assigned at the same time. Equation (6)-(D1) means the case of simultaneously reducing CO_2, fossil energy consumption, and nuclear power consumption for the reduction target (μ). We have

$$
\begin{array}{ll}
Max \quad y & Max \quad y \\
s.t.: & s.t.: \\
\sum\lambda \cdot y \geqslant (1+\beta)\cdot y_0 & \sum\lambda \cdot y \geqslant (1+\beta)\cdot y_0 \\
\sum\lambda \cdot b = (1-\beta)\cdot b_0 & \sum\lambda \cdot b = (1-\beta-\mu)\cdot b_0 \\
\sum\lambda \cdot ff = (1-\beta)\cdot ff_0 & \sum\lambda \cdot ff = (1-\beta)\cdot ff_0 \\
\sum\lambda \cdot nf \leq nf_0 & \sum\lambda \cdot nf \leq nf_0 \\
\sum\lambda \cdot ne = (1-\beta)\cdot ne_0 & \sum\lambda \cdot ne = (1-\beta)\cdot ne_0 \\
\sum\lambda \cdot k \leq k_0 & \sum\lambda \cdot k \leq k_0 \\
\sum\lambda \cdot l \leq l_0 & \sum\lambda \cdot l \leq l_0 \\
\lambda \geqslant 0 & \lambda \geqslant 0 \\
(A1) & (B1) \\
Max \quad y & Max \quad y \\
s.t.: & s.t.: \\
\sum\lambda \cdot y \geqslant (1+\beta)\cdot y_0 & \sum\lambda \cdot y \geqslant (1+\beta)\cdot y_0 \\
\sum\lambda \cdot b = (1-\beta-\mu)\cdot b_0 & \sum\lambda \cdot b = (1-\beta-\mu)\cdot b_0 \\
\sum\lambda \cdot ff = (1-\beta-\mu)\cdot ff_0 & \sum\lambda \cdot ff = (1-\beta-\mu)\cdot ff_0 \\
\sum\lambda \cdot nf \leq nf_0 & \sum\lambda \cdot nf \leq nf_0 \\
\sum\lambda \cdot ne = (1-\beta)\cdot ne_0 & \sum\lambda \cdot ne = (1-\beta-\mu)\cdot ne_0 \\
\sum\lambda \cdot k \leq k_0 & \sum\lambda \cdot k \leq k_0 \\
\sum\lambda \cdot l \leq l_0 & \sum\lambda \cdot l \leq l_0 \\
\lambda \geqslant 0 & \lambda \geqslant 0 \\
(C1) & (D1)
\end{array}
\tag{6}
$$

Equation (7) measures the deterioration or improvement of directional efficiency and GDP due to carbon reduction and energy conversion. Specifically, Equation (7)-(A2) are for measuring the current direction efficiency. In order to apply energy conversion, desirable outputs, pollutants, fossil energy, nonfossil energy, and nuclear energy are all set to an adjustable state. Equation (7)-(B2) means the case where nonfossil energy plus fossil energy consumption reduction (δ) are added. Equation (7)-(C2) means the addition of the reduction in nuclear energy consumption (ρ) to the nonfossil energy (renewable energy) consumption.

Equation (7)-(D2) means the addition of both fossil energy consumption reduction (δ) and nuclear energy consumption reduction (ρ) to nonfossil energy consumption. We have

$$
\begin{array}{ll}
\begin{aligned}
& Max \quad \beta \\
& s.t.: \\
& \sum \lambda \cdot y \geqslant (1+\beta) \cdot y_0 \\
& \sum \lambda \cdot b = (1-\beta) \cdot b_0 \\
& \sum \lambda \cdot ff = (1-\beta) \cdot ff_0 \\
& \sum \lambda \cdot nf = (1-\beta) \cdot nf_0 \\
& \sum \lambda \cdot ne = (1-\beta) \cdot ne_0 \\
& \sum \lambda \cdot k \leq k_0 \\
& \sum \lambda \cdot l \leq l_0 \\
& \lambda \geqslant 0 \\
& (A2)
\end{aligned}
&
\begin{aligned}
& Max \quad \beta \\
& s.t.: \\
& \sum \lambda \cdot y \geqslant (1+\beta) \cdot y_0 \\
& \sum \lambda \cdot b = (1-\beta) \cdot b_0 \\
& \sum \lambda \cdot ff = (1-\beta) \cdot ff_0 - \delta \\
& \sum \lambda \cdot nf = (1-\beta) \cdot nf_0 + \delta \\
& \sum \lambda \cdot ne = (1-\beta) \cdot ne_0 \\
& \sum \lambda \cdot k \leq k_0 \\
& \sum \lambda \cdot l \leq l_0 \\
& \lambda \geqslant 0 \\
& (B2)
\end{aligned}
\\
\begin{aligned}
& Max \quad \beta \\
& s.t.: \\
& \sum \lambda \cdot y \geqslant (1+\beta) \cdot y_0 \\
& \sum \lambda \cdot b = (1-\beta) \cdot b_0 \\
& \sum \lambda \cdot ff = (1-\beta) \cdot ff_0 \\
& \sum \lambda \cdot nf = (1-\beta) \cdot nf_0 + \rho \\
& \sum \lambda \cdot ne = (1-\beta) \cdot ne_0 - \rho \\
& \sum \lambda \cdot k \leq k_0 \\
& \sum \lambda \cdot l \leq l_0 \\
& \lambda \geqslant 0 \\
& (C2)
\end{aligned}
&
\begin{aligned}
& Max \quad \beta \\
& s.t.: \\
& \sum \lambda \cdot y \geqslant (1+\beta) \cdot y_0 \\
& \sum \lambda \cdot b = (1-\beta) \cdot b_0 \\
& \sum \lambda \cdot ff = (1-\beta) \cdot ff_0 - \delta \\
& \sum \lambda \cdot nf = (1-\beta) \cdot nf_0 + \delta + \rho \\
& \sum \lambda \cdot ne = (1-\beta) \cdot ne_0 - \rho \\
& \sum \lambda \cdot k \leq k_0 \\
& \sum \lambda \cdot l \leq l_0 \\
& \lambda \geqslant 0 \\
& (D2)
\end{aligned}
\end{array}
\tag{7}
$$

In addition, reductions of one year, five years, and ten years will be applied and analyzed. The reason for applying this is to roughly determine whether and when an inflection point in efficiency due to energy conversion occurs. Table 1 below shows the overall scenario composition of this study.

Table 1. Scenario structure.

	1: Energy Reduction Type				2: Energy Transition									
Analysis Target	166 countries				30 countries (using nuclear power energy)									
Analysis Model	Equation (4)				Equation (5)									
Scenario Model	Equation (6)				Equation (7)									
Type	current	$CO_2\downarrow$	$CO_2\downarrow$, $ff\downarrow$	$CO_2\downarrow$, $ff\downarrow$, $ne\downarrow$	current	$-ff(\delta)$, $+nf(\delta)$			$-ne(\rho)$, $+nf(\rho)$			$-ff(\delta), -ne(\rho)$, $+nf(\delta+\rho)$		
Amounts Year	-	-	-	-	-	1	5	10	1	5	10	1	5	10
Scenario Name	A1	B1	C1	D1	A2	B2			C2			D2		

Note 1. ff = fossil energy, nf = non-fossil energy, ne = nuclear energy.

3.2.2. Applied Scenarios

In this section, we examine the specific data values applied to the analysis scenario of this study. Table 2 below shows the target CO_2 emissions, energy consumption, expected GDP growth rate, and real GDP according to A and B of Korea's 2050 carbon-neutral scenario.

Table 2. Korea's 2050 carbon neutrality scenario goals.

Type	Emission (10 Thousand tons CO_2eq)	Energy consumption (10 Thousand TOE)	GDP Growth Rate	Real GDP (millions US$)
2018	68,630	17,740	0.027	2,149,301
2050 Plan A	Total: 8040, Net: 0	3360	2018–2040 GDP growth rate 1.9%/year, 2040–2050 GDP growth rate 1.0%/year	3,592,055
2050 Plan B	Total: 11,730, Net: 0	3320		

Note 1. The 2050 GDP value is the value applied by the predicted growth rate by KDI (Korea Development Institute).

As of 2018, Korea's final energy consumption was 177.4 million TOE (coal 32.5 million TOE, oil 116.3 million TOE, city gas 28.6 million TOE). According to the Carbon Neutral Reduction Plans A and B, in 2050, 33.6 million TOE of fossil energy (26.7 million TOE of oil +6.9 million TOE of city gas) and 33.2 million TOE (26.3 million TOE of oil +6.9 million TOE of city gas) will remain, respectively. In other words, Korea must reduce fossil energy by 144.2 to 143.8 million TOE over the next 30 years.

First, we look at the application of scenario 1 (type of energy reduction). Suppose the total reduction for 30 years is converted into an annual reduction based on Korea's carbon-neutral plan. In that case, the annual reduction of fossil and nuclear energy converges to approximately 3% of the current consumption, and CO_2 emissions exceed about 4%. In view of this, it was applied uniformly at 3%.

Next, we look at the dataset in scenario 2 (energy transition). Dividing the total amount of fossil energy reduction by 30 years yields 4,793,000 to 4,807,000 TOE per year. Therefore, in this study, the annual reduction of fossil energy is set at an average of 4.8 million TOE. Likewise, Korea's nuclear energy consumption in 2018 was 36.06 million TOE. According to the government's nuclear power reduction plan, the remaining nuclear power in 2050 is about 7.46 million TOE. Therefore, Korea needs to reduce by approximately 28.6 million TOE over the next 30 years. The annual nuclear power reduction is about 0.953 million TOE.

Additionally, because most international statistics are published in TCE (a ton of coal equivalent), the TOE unit is changed to TCE (1 TOE = 1.43 TCE, 1 TWh = 0.122917 million TCE). By applying this, fossil and nuclear energy reduction can be converted into TOE and TCE. One year, five years, and 10 years are calculated and applied, respectively.

4. Data and Empirical Results

4.1. Data

In the empirical study, we estimate the maximum GDP and carbon emission efficiency of production under constraints such as outputs, pollutants, and inputs by using cross-sectional data in 2018 (the most recent year at the time of the survey) for 166 countries. The output GDP (y) and the input capital stock (k) values are constant in 2017 national prices. Labor (l) is the number of persons engaged in the country. All these three data are from the Penn World Table 10.0 version (ref. [31]). The fossil and nonfossil energy consumption data come from the U.S. Energy Information Administration (EIA) (ref. [32]). Fossil energy includes coal, natural gas, oil, and other liquids. Nonfossil energy includes hydro, geothermal, wind, solar energy, etc. At the same time, EIA provides separate data on nuclear energy, which helps us to analyze the nuclear energy policy in Korea's carbon-neutrality policy. The Our World in Data database (ref. [33]) provides CO_2 data, the annual total production-base emission value that excludes emissions related to land-use change. Table 3 below listed the sources and descriptions of the variables.

Table 3. Variables description and source.

	Variables (Notation)	Description	Source
Output	Value added (y)	Real GDP	Penn World 10.0
Input	Capital (k)	Capital	
	Labor (l)	The number of workers	
	Fossil energy (ff)	Petroleum, natural gas, coal, etc	Energy Information of Administration of U.S. (EIA)
	Nonfossil energy (nf)	Renewable energy, etc	
	Nuclear energy (ne)	Extraction from the composition of non-fossil energy	
Pollutants	CO_2 (b)	CO_2	Our World in Data

The classification criteria for the five country groups is the income level (based on fiscal year 2018) according to the World Bank classification (ref. [34]). G1 is 38 OECD countries, G2 is 20 non-OECD member countries (GNI per capita: 12,375 US$ or more), G3 is 43 non-OECD upper-middle-income countries (GNI per capita: 3996–12,375 US$), G4 is 39 Low-middle-income countries (GNI per capita: US$ 1026–3995), G5 consists of 26 low-income countries (GNI per capita: less than US$ 1025).

Table 4 below shows the basic statistics of real GDP, CO_2 emissions, capital stock, labor, fossil energy consumption, nonfossil energy consumption, and nuclear energy consumption by country group. All price variables (GDP, capital stock) were converted to constant prices in U.S. dollars in 2017. In addition, the unit of energy consumption provided by EIA is quad BTU (quadrillion British thermal unit). This was converted to TCE (a ton of coal equivalent) and divided by 10^6 to convert millions TCE (1 TCE = 2.406×10^7 BTU).

The average of real GDP, CO_2 emissions, capital, and fossil energy consumption is the highest in the order of G1, G3, G4, G2, and G5. The average labor is the highest in the order of G4, G3, G1, G5, and G2. Nonfossil energy consumption follows the order of G1, G3, G4, G5, and G2. The minimum value of G2 in nonfossil energy consumption is 0, indicating that there are countries without nonfossil energy facilities. In some cases, the minimum value in the raw data is negative (-) because it was calculated by reflecting imports and exports. In the actual analysis, it was changed to 0 and estimated. Moreover, G2 and G5 countries do not have nuclear energy, so the maximum value is 0, and only 30 countries consume nuclear energy.

We calculated the following two models by using the above data by combining the material balance approach and DEA methods. In the first model (A1-D1), we divide 166 countries into five groups and compare their sensitivity to efficiency and economic changes caused by policy changes, by using Korea's carbon-neutral policy as a criterion. In the second model (A2-D2), we use the Korean carbon neutral policy as the standard to determine GDP and efficiency changes before and after the energy transition for 30 nuclear-powered countries. These two methods are built to pinpoint the issues with Korea's carbon neutrality program.

Table 4. Basic statistics (in 2018).

Group	Variables	Obs.	Mean	Std.Dev	Min.	Max.
G1	Real GDP (million US$)	38	1,546,430	3,332,687	17,303	20,100,000
G2		20	216,663	380,559	2329	1,644,060
G3		43	839,849	3,064,869	1162	19,800,000
G4		39	520,687	1,464,879	867	8,791,310
G5		26	47,371	51,036	3604	230,360
G1	CO_2 (million tonnes)	38	334.84	885.09	3.68	5424.88
G2		20	63.00	130.39	0.61	576.76
G3		43	360.67	1526.06	0.26	9956.57
G4		39	128.38	419.91	0.13	2591.32
G5		26	5.35	6.03	0.30	25.88
G1	K (million US$)	38	7,057,008	12,100,000	92,958	68,000,000
G2		20	1,081,412	1,761,571	11,220	6,884,170
G3		43	3,826,109	14,500,000	6595	93,500,000
G4		39	2,029,555	5,928,514	3828	33,600,000
G5		26	153,654	166,506	6209	555,485
G1	L (millions)	38	16.75	28.29	0.19	156.68
G2		20	2.08	3.09	0.03	13.38
G3		43	28.07	121.77	0.04	799.31
G4		39	28.67	80.41	0.06	491.08
G5		26	9.18	11.42	0.67	56.12
G1	Fossil energy (millions TCE)	38	214.98	561.46	2.16	3439.72
G2		20	57.44	100.92	0.46	422.84
G3		43	207.62	826.53	0.14	5336.36
G4		39	63.47	192.37	0.09	1172.62
G5		26	2.97	4.01	0.20	19.63
G1	Nonfossil energy (millions TCE)	38	33.25	70.76	0.00	415.87
G2		20	0.82	1.59	0.00	5.20
G3		43	25.42	106.83	0.00	680.85
G4		39	6.44	17.84	0.00	108.01
G5		26	1.10	1.88	0.00	6.56
G1	Nuclear (millions TCE)	38	21.18	62.17	0.00	350.71
G2		20	0.00	0.00	0.00	0.00
G3		43	5.30	21.33	0.00	115.82
G4		39	1.49	6.43	0.00	36.39
G5		26	0.00	0.00	0.00	0.00

Note 1. G1, OECD (38 countries); G2, high income (20 countries); G3, upper middle income (43 countries); G4, lower middle income (39 countries); G5, low income (26 countries).

4.2. Empirical Results

4.2.1. Changes in GDP and Efficiency (Reduction of CO_2, Fossil Energy and Nuclear Energy)

In this section, the results (3. theoretical model-estimation result of Equation (6)) according to the type of carbon dioxide and energy reduction are discussed. The results of the analysis of 166 countries are presented by income group. The original directional distance efficiency (A1) is compared with the efficiency and GDP estimation results in the other three cases (B1, C1, D1). B1 is a 3% reduction in CO_2 alone, C1 is a 3% reduction in both CO_2 and fossil energy, and D1 is a 3% reduction in CO_2, fossil energy, and nuclear energy respectively.

Table 5 below shows this. By group, the efficiency of G4 was the highest at 0.206, and the efficiency of G3 was the lowest at 0.274. By scenario type, the efficiency increases monotonically as the original state changes to B1, C1, and D1. Although the directional efficiencies of C1 and D1 are the same, the growth rates are strictly different because they are the rounded values of the actual raw data. The efficiencies of C1 and D1 were almost identical. The efficiency improvement rate of the five groups was 2.024% for B1 and 5.246%

for C1, more than twice as high. However, there was little difference between C1 and D1. This is because only 30 out of 166 countries use nuclear energy, which does not significantly affect the average.

Table 5. Efficiency change and growth rate of reduction of CO_2, fossil energy, and nuclear energy (in 2018).

Group	A Type	B Type	C Type	D Type	Growth Rate1 (%)	Growth Rate2 (%)	Growth Rate3 (%)
G1	0.243	0.237	0.230	0.230	2.626	5.213	5.272
G2	0.238	0.225	0.225	0.225	5.679	5.442	5.442
G3	0.274	0.270	0.261	0.261	1.460	4.719	4.723
G4	0.206	0.203	0.194	0.194	1.482	6.057	6.057
G5	0.253	0.250	0.239	0.239	1.154	5.226	5.226
average	0.244	0.239	0.231	0.231	2.024	5.246	5.261

Note 1. G1, OECD; G2, high income; G3, upper middle income; G4, lower middle income; G5, low income. Note 2. A type: efficiency by applying the direction distance function to CO_2, fossil energy, and nuclear energy; B type: directional efficiency when CO_2 is reduced by 3%; C type: directional efficiency when CO_2 and fossil energy are reduced by 3% each; D type, directional efficiency when reducing CO_2, fossil energy, and nuclear energy by 3% each. Note 3. Growth rate 1%: efficiency growth rate of B with respect to A; growth rate 2%: efficiency growth rate of C with respect to A; growth rate 3%: efficiency growth rate of D with respect to A Note 4. If the value of directional efficiency is greater than 0, it is inefficient. Note 4. If the value of directional efficiency is greater than 0, it is inefficient.

Table 6 below shows the country's GDP and growth rate changes for these three cases (B1, C1, D1). From the original state (A1) to B1, C1, and D1, the maximum GDP decreased monotonically. The growth rate change was the largest in D1, with an average of −1.012. On the other hand, the difference between C1 and D1 was not significant. Comparing B1 and C1, B1 has a 0.380% drop in GDP, but C1, which simultaneously reduces CO_2 and fossil energy, has a GDP drop of about 1.009%. In other words, simultaneous cuts had a much more significant impact on GDP than single cuts.

Table 6. GDP and growth rate due to reduction of CO_2, fossil energy, and nuclear energy (in 2018).

Group	Maximum GDP-A	Maximum GDP-B	Maximum GDP-C	Maximum GDP-D	Growth Rate1 (%)	Growth Rate2 (%)	Growth Rate3 (%)
G1	1,644,100	1,630,050	1,627,106	1,626,774	−0.502	−1.004	−1.015
G2	154,723	153,267	153,384	153,384	−1.051	−1.006	−1.006
G3	1,691,630	1,690,714	1,675,348	1,675,314	−0.273	−0.978	−0.978
G4	879,391	880,204	871,553	871,553	−0.276	−1.031	−1.031
G5	66,779	66,726	66,095	66,095	−0.20	−1.039	−1.039
average	1,096,780	1,093,265	1,086,101	1,086,013	−0.380	−1.009	−1.012

Note 1. A, directional distance function for CO_2, fossil energy, and nuclear energy; B, 3% reduction in CO_2; C, 3% reduction in CO_2 and fossil energy each; D, 3% reduction in CO_2, fossil energy, and nuclear energy each. Note 2. Growth rate 1, growth rate of B with respect to A; growth rate 2, growth rate of C with respect to A; growth rate 3, growth rate of D with respect to A. Note 3. The unit of GDP is one million dollars.

4.2.2. Directional Efficiency and GDP Changes by Country due to Energy Transition

In this section, changes in efficiency and GDP by country according to energy conversion types are discussed (3. theoretical model-estimated result of Equation (7)). Korea's 2050 carbon neutral scenario was applied, and only 30 countries using nuclear energy were targeted. In the results of Table 7, there was little effect of additional nuclear energy reduction. It is because most countries, except for 30 countries, do not possess nuclear power, and countries that include nuclear power show no significant change, only a 3% decrease.

The original directional distance efficiency (A2) is compared with the efficiency and GDP estimation results in the other three cases (B2, C2, D2). B2 is renewables plus annual fossil energy reductions, C2 is renewables plus annual nuclear energy reductions, and D2 is renewables plus annual fossil and nuclear energy reductions. In addition, the analysis results of 10 items can be confirmed by applying reductions of one year, five years, and 10 years, respectively. The point at which efficiency improves first is an approximate inflection point, shaded. Because the efficiency improves monotonically after the inflection point, the number of cells in the shade is at most one in one type (B2, C2, D2). The absence of a shaded cell means the inflection point of efficiency is not reached even after up to 10 years.

The energy transition can have different results depending on the energy-oriented economic structure of each country. In other words, the energy transition will show different results depending on the economy dependent on fossil energy, nuclear energy, and renewable energy.

The main results are as follows. First, the U.S. and Switzerland are best-practice countries. America has reached the frontier in every case. At this time, it is essential to note that it is not entirely efficient just because the U.S. has reached the frontier. The efficiency measurement of the DEA method is to estimate the relative efficiency based on sample data, which means that it is the most efficient among DMUs. Switzerland consumes less energy, so reducing it to five years makes the estimate meaningless.

Secondly, in the case of countries with low energy consumption (e.g., Armenia, Slovenia, etc.), energy consumption becomes negative due to the application of the reduction scenario, so the meaning of the estimation is lost. On the other hand, there was no significant change in efficiency in countries with very high energy consumption (e.g., China and Canada). It is likely because the country's actual energy consumption is so large that it does not significantly impact relatively small reduction scenarios.

Thirdly, Korea has a large efficiency gap due to fossil energy reduction; the inflection point was the 10-year reduction point. Therefore, it was found that the economic burden of energy transition was greater than that of other countries. In the 10-year reduction, inefficiency (0.360) when energy conversion was implemented was significantly higher than that when energy conversion was not attempted (0.288). In particular, in the case of converting the savings in nuclear energy consumption to new and renewable energy (C2), efficiency improvement can only be expected after 10 years of reduction. This category includes China, India, and Russia.

Fourth, countries that have been preparing for energy transition for a long time (such as Germany, Spain, Sweden, and the United Kingdom) immediately improved efficiency in the first year, and even if it deteriorated, the degree was not large. In particular, Germany is a country that maintains a nuclear power plant policy, and the difference between C2 and D2, which reflects nuclear power plant reduction, was not large. In other words, as a country that has already undergone a significant energy transition, it shows that Germany has a renewable energy-oriented economic structure. On the other hand, France is highly dependent on nuclear energy, so it has yet to reach the inflection point in C2. In other words, as nuclear energy decreases, inefficiency increases.

Table 7. Directional efficiency changes by country due to energy transition.

Country	Direction Efficiency	1-Year Reduction			5-Year Reduction			10-Year Reduction		
	A	B	C	D	B	C	D	B	C	D
Argentina	0.214	0.233	0.216	0.235	0.051	-	-	-	-	-
Armenia	0.061	-	-	-	-	-	-	-	-	-
Belgium	0.381	0.451	0.397	0.438	0.000	0.354	0.000	-	-	-
Brazil	0.317	0.317	0.314	0.314	0.271	-	-	0.123	-	-
Bulgaria	0.249	0.000	0.262	0.000	-	-	-	-	-	-
Canada	0.387	0.387	0.387	0.387	0.382	0.387	0.382	0.324	0.387	0.324
China	0.619	0.625	0.620	0.626	0.643	0.623	0.643	0.637	0.627	0.638
Czechia	0.151	0.350	0.296	0.350	-	0.435	-	-	-	-
Finland	0.358	0.036	0.358	0.036	-	0.192	-	-	-	-
France	0.145	0.177	0.149	0.181	0.117	0.166	0.117	0.000	0.186	0.000
Germany	0.342	0.335	0.342	0.335	0.262	0.343	0.262	0.168	0.343	0.156
Hungary	0.297	0.185	0.369	0.185	-	-	-	-	-	-
India	0.320	0.344	0.323	0.347	0.400	0.337	0.400	0.354	0.156	0.156
Iran	0.611	0.740	0.446	0.446	0.676	-	-	0.541	-	-
Japan	0.374	0.413	0.380	0.418	0.392	0.402	0.389	0.320	0.271	0.271
Mexico	0.283	0.364	0.295	0.368	0.288	-	-	0.120	-	-
Netherlands	0.236	0.334	0.000	0.000	0.189	-	-	0.000	-	-
Pakistan	0.066	0.024	0.066	0.024	0.000	-	-	0.000	-	-
Romania	0.116	0.012	0.120	0.012	-	-	-	-	-	-
Russia	0.511	0.549	0.516	0.554	0.584	0.535	0.585	0.559	0.559	0.559
Slovakia	0.422	0.000	0.453	0.000	-	-	-	-	-	-
Slovenia	0.408	-	0.345	-	-	-	-	-	-	-
South Africa	0.366	0.472	0.403	0.474	0.301	-	-	0.039	-	-
South Korea	0.288	0.416	0.307	0.428	0.466	0.378	0.466	0.360	0.441	0.360
Spain	0.294	0.310	0.300	0.306	0.121	0.290	0.101	0.000	0.262	0.000
Sweden	0.115	0.000	0.115	0.000	-	0.115	-	-	0.115	-
Switzerland	0.000	0.000	0.000	0.000	-	-	-	-	-	-
Ukraine	0.439	0.539	0.488	0.547	0.092	0.609	0.092	-	0.588	-
The U.K.	0.216	0.243	0.220	0.239	0.168	0.224	0.155	0.006	0.205	0.000
The U.S.	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Note 1. A, GDP, CO_2, and energy all give direction; B, Addition of fossil energy reduction to nonfossil energy; C, Addition of nuclear energy reduction to nonfossil energy; D, Addition of both fossil and nuclear reductions to non-fossil energy. Note 2. Amounts of the reduction are based on Korea's carbon-neutral plan. Note 3. The '-' mark means that the energy consumption becomes negative after applying the energy reduction according to the Korean standard. That is, there is no meaning to estimate.

Table 8 below shows GDP losses and improvements due to the energy transition in 30 countries by using nuclear energy. The GDP is multiplied by the A benchmark efficiency minus the B2, C2, and D2 efficiencies first. GDP loss or improvement according to the change in efficiency was calculated. For each type, the first GDP improvement is shaded. It is almost similar to the shading notation in Table 7, but there is a caveat. Even if the efficiency is improved, GDP becomes negative if it is greater than the efficiency of Type A.

In particular, in the case of Korea, efficiency improvement is achieved in B and D of Table 7, but it is still much higher than A, so GDP shows a negative sign.

In general, countries with improved GDP in the case of the energy transition are Brazil, Bulgaria, Finland, Germany, Hungary, Romania, and Sweden. On the other hand, Korea, Russia, and China's GDP declined. In other words, these countries have a heavy economic burden due to energy saving and conversion.

Table 8. GDP Loss and improvement by country due to efficiency changes in energy transition.

Country	1-Year Reduction			5-Year Reduction			10-Year Reduction		
	A–B	A–C	A–D	A–B	A–C	A–D	A–B	A–C	A–D
Argentina	−19,454	−2166	−21,620	162,602	-	-	-	-	-
Armenia	-	-	-	-	-	-	-	-	-
Belgium	−37,178	−8785	−30,197	199,820	13,811	199,820	-	-	-
Brazil	733	8713	9445	138,967	-	-	583,739	-	-
Bulgaria	35,735	−1891	35,735	-	-	-	-	-	-
Canada	−380	0	−380	9182	0	9182	115,028	0	115,028
China	−119,717	−17,243	−136,961	−470,965	−86,216	−478,238	−362,627	−172,432	−377,174
Czechia	−77,664	−56,688	−77,664	-	−111,134	-	-	-	-
Finland	79,085	0	79,085	-	40,632	-	-	-	-
France	−94,367	−12,136	−106,503	82,464	−60,681	82,464	422,825	−121,363	422,825
Germany	31,116	−1363	31,116	342,033	−3306	342,033	747,327	−5735	797,310
Hungary	30,906	−19,757	30,906	-	-	-	-	-	-
India	−212,214	−30,442	−240,476	−703,867	−152,210	−704,081	−302,837	1,443,402	1,443,402
Iran	−138,041	177,051	177,051	−68,981	-	-	74,916	-	-
Japan	−196,140	−28,382	−223,602	−90,438	−139,107	−76,921	274,913	524,166	524,598
Mexico	−194,343	−27,553	−203,692	−10,605	-	-	394,525	-	-
Netherlands	−92,041	223,405	223,405	45,201	-	-	223,405	-	-
Pakistan	43,432	0	43,432	68,649	-	-	68,649	-	-
Romania	54,079	−2212	54,079	-	-	-	-	-	-
Russia	−151,565	−19,097	−170,661	−291,279	−95,484	−293,377	−190,831	−190,969	−190,831
Slovakia	63,129	−4608	63,129	-	-	-	-	-	-
Slovenia	-	4326	-	-	-	-	-	-	-
South Africa	−77,697	−26,848	−79,170	47,718	-	-	239,608	-	-
South Korea	−275,009	−42,104	−301,591	−383,097	−194,860	−383,097	−155,751	−329,858	−155,751
Spain	−29,096	−10,026	−21,650	323,031	8299	360,258	547,398	59,689	547,398
Sweden	60,292	0	60,292	-	0	-	-	0	-
Switzerland	0	0	0	-	-	-	-	-	-
Ukraine	−55,595	−27,274	−60,133	192,662	−94,931	192,662	-	−83,026	-
The U.K.	−80,501	−11,142	−69,103	143,602	−24,742	182,819	627,156	32,245	644,056
The U.S.	0	0	0	0	0	0	0	0	0

Note 1. Unit is one million dollars. Note 2. Loss or improvement of GDP due to efficiency change is measured as (A–B) ∗ GDP. A–C and A–D are the same. Note 3. The '-' mark means that the energy consumption becomes negative after applying the energy.

5. Discussion

In this study, we tried to minimize the national economic burden of implementing carbon neutrality in response to climate change. In 2021, the Korean government announced a scenario for 2050 carbon neutrality. In line with this plan, we analyzed changes in production efficiency and GDP due to carbon dioxide reduction and energy conversion.

The main findings of this study are summarized as follows. First, if only CO_2 was reduced by 1%, GDP would decrease by about 0.1%. On the other hand, if CO_2 and fossil energy were reduced simultaneously, GDP would fall by about 0.3% or more. In other words, simultaneous reductions resulted in a threefold drop in GDP compared to single reductions.

Secondly, as a result of estimating the impact of Korea's carbon-neutral transition based on the 2050 carbon-neutral plan scenario, Korea's production inefficiency increased significantly, and GDP fell. The transition from fossil and nuclear energy to renewable energy significantly increased inefficiency, and the point of improvement in efficiency was at the 10-year mark.

The implications of these results are as follows. First, in the case of concurrent restrictions, the resulting economic loss is more severe than in the case of single restrictions in policy. It could be taken into account when implementing regulations. It can be expected that the economic burden will be much more significant when several fields are converted at the same time.

Secondly, to achieve carbon neutrality in Korea, it is necessary to utilize the existing infrastructure actively. For example, suppose coal, oil, and nuclear power plants are immediately stopped, and new renewable energy plants are built. In that case, the capital invested in existing fossil power plants becomes a deadweight asset. It will soon burden the national economy, so that a rapid transition can be dangerous.

Differences between countries in energy-transition scenarios are due to different technological levels, industrial structures, energy-use patterns, carbon emissions, and policies in each country. In Korea's industrial structure, manufacturing accounts for about 30%, which is higher than that of developed countries, which is 10–20%. In addition, as it consists of energy-intensive industries, the intensity of greenhouse gas emissions relative to GDP is very high. The share of renewable energy in Korea's total energy consumption currently exceeds approximately 2%, so expanding it to approximately 50% within 30 years is a challenging goal. In particular, the land area is small, and the weather conditions for improving the economic feasibility of solar or wind power generation are poor.

The implementation of carbon neutrality causes economic losses even though the results differ slightly depending on the analysis model. Refs. [5–7,22] support this. In particular, ref. [5] analyzed the effect of renewable energy conversion by using the panel threshold model. As a result, it had a negative effect on economic growth initially but a positive effect after a certain point. It is similar to the result of applying the CO_2 reduction and energy consumption reductions for one year, five years, and ten years in this study. At the time of energy conversion, it has a negative effect at the beginning but a positive effect after the inflection point. Ref. [6] used a stochastic frontier analysis (SFA) to estimate GDP loss due to reduced energy consumption and the expansion of renewable energy. According to the empirical results, the GDP loss due to energy reduction and expansion of renewable energy is estimated to be 0.2% to 1.3% compared to 2015. Ref. [20] analyzed the impact of Korea's climate change response policies on GDP by using the macromodel DSGE. As a result of the analysis, it was found that from 2020 to 2050, the average annual decline was 0.08–0.32%. The case in which the global average temperature increase is suppressed by 2 °C rises compared to preindustrialization is 0.08%, and the case where 1.5 °C rises suppress the increase is 0.32%.

According to the results of this study, the GDP loss for each energy transition scenario showed a change in GPD of −12.80% (B2), −1.96% (C2), and −14.03% (D2) compared to 2018 according to each scenario in the case of one-year reduction. Refs. [6,20] commonly occurred in GDP loss compared to the estimated results. However, the degree of loss was much greater in the results of this study.

It is due to differences in detailed scenario composition, the presence or absence of various assumptions, the separation of stochastic errors, and estimation targets. Specifically, previous studies simply converted the cost of reducing carbon emissions into GDP. However, this study covers all costs of stranded assets related to overall production efficiency, including energy structure conversion during the production process. In other words, the estimation of this study is a comprehensive estimate of the cost of implementing carbon neutrality without any assumptions.

In this study, DEA, which minimizes assumptions, was also used. Furthermore, analysis using SFA, which is complementary to DEA, is also possible. Although DEA cannot distinguish between stochastic error and technical inefficiency error, SFA has the advantage of being able to distinguish stochastic error. Although we conducted SFA, the estimation was not converged to the assumed function due to the problem of considerable variation among countries. It could be improved and analyzed in future studies.

6. Conclusions

In this study, the effect of greenhouse gas and energy transition on the production efficiency and GDP of the national economy was examined. The focus of this study is not on estimating the benefits obtained from greenhouse gas reduction, but rather on the economic impact of changes in GDP and the efficiency of the national economy.

This study provides timely information in that it analyzes the impact of carbon neutrality on economic growth in line with Korea's carbon-neutral scenario plan. It is differentiated in that, as far as we know, no study has analyzed the impact of carbon neutralization by using the DEA directional distance function. In the case of using a macroeconomic model, there are limitations associated with various assumptions. However, the DEA methodology has an advantage in that it can minimize assumptions and diagnose the state of reality.

The results of this study can be divided into two categories based on the subject.

First of all, it is an implication for Korea. The economic cost of energy transition under Korea's 2050 carbon-neutral plan scenario is very high, and the impact on the efficiency of the national economy is severe. Compared to major developed countries such as the United States, Germany, and the United Kingdom, Korea has many difficulties implementing carbon neutrality due to differences in industrial structure and energy-use patterns. The carbon-neutrality committee's plan to reduce fossil and nuclear energy simultaneously does not properly reflect the economic ripple effect. One alternative is to temporarily use nuclear energy or natural gas to further reduce the burden of carbon neutrality in the Korean economy, which relies heavily on energy-intensive industries. Because South Korea is an economy dependent on nuclear and fossil energy, it is not desirable to reduce nuclear energy, as reducing it will continue to reduce efficiency. Nuclear power plants need to play a role as a supplementary means of energy conversion for the time being.

Furthermore, this raises the question of fairness in achieving the international goal of carbon neutrality. The weight of carbon neutrality accepted by countries that have built economic development and ecofriendly energy production infrastructure early differs from those that have not. It confirms the legitimacy of creating an international fund for carbon neutrality.

This study has limitations in not reflecting technological innovation, energy demand, and GDP changes. In addition, analysis using SFA is left as a future task.

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