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Article

The Economic Cost of Unsupplied Diesel Product in Korea Using Input-Output Analysis

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Abstract: Diesel is an essential factor in industrial production and development, and thus its stable supply is a crucial element for economic growth. The supply shortage of diesel has massive economic costs, namely supply shortage costs. This paper attempts to apply input-output (I-O) analysis to measuring the supply shortage cost of industrial diesel in Korea by finding an optimal way of allocating the limited diesel resources to different sectors according to the objective of maximizing overall value-added. To this end, a static I-O framework is presented using a recently published I-O table. The results indicate that the marginal cost of unsupplied diesel ranges from KRW 716 (USD 0.65) to KRW 113,376 (USD 103.07) per liter and these costs depend not only on the shortage rate of each non-diesel sector but also on the level of its own final demand. The quantitative results are useful for policy-makers to set economic reliability standards, develop optimum curtailment levels and priorities, and plan curtailment strategies for diesel supply and demand.

Keywords: diesel; supply shortage cost; marginal cost; input-output analysis; Korea

1. Introduction

Oil is widely accepted as a vital input to industrial development and economic growth. However, the prospects of future oil shortages have resulted in forecasts of continued high prices and even wars. Thus, the issue of oil risk has received increasing attention in both developed and developing countries. According to Energy Outlook 2030 [1], oil is expected to be a gradually growing fuel over the next two decades. Nevertheless, global oil consumption is likely to rise by 16.5 million barrels per day (Mb/d), exceeding 102 Mb/d by 2030. Furthermore, the growth of oil consumption comes exclusively from rapidly growing developing economies. Developing countries, rising by nearly 13 Mb/d, account for more than three quarters of the global increase. However, oil consumption in developed countries has been growing at a slower pace or even declining. Reynolds [2] emphasized that oil is the main energy source for the operation of mobile equipment and the main driver of economic growth. For example, some studies have showed that oil consumption causes economic growth [3,4].

This study pays particular attention to diesel. A stable supply of diesel is an important element to continuing industrial activities. Diesel supply shortages may bring massive economic losses [5–12]. If a diesel supply shortage happens, it will directly cause production disruptions, raw material supply shortages, and production and other processing problems, including equipment failures, and indirectly cause losses of production in related industries, unemployment, and inflation due to production disruptions. Korea's industrial structure is highly dependent on diesel consumption. Rapid economic growth has boosted the country's diesel demand in the past four decades. Furthermore, as the diesel price has been continuously increasing, the security of diesel supply has attracted a great deal of attention in recent years. These situations require the researcher to provide energy policy-makers with accessible and reliable information on the reliability of diesel supply. Diesel supply reliability can be characterized almost exclusively by shortage costs.

There are four well-known approaches to the measurement of the shortage cost of diesel, that is, the economic cost of unsupplied diesel: the willingness-to-pay approach, the production factor approach, the customer survey approach, and the input-output (I-O) approach.

First, the willingness-to-pay approach involves the valuation of specific changes from the *status quo* by using the stated preference technique [13]. Second, the production factor approach estimates the economic loss associated with reduced productive activity (for firms) or lost time (for households) as a result of idle resources, spoiled materials, and damaged equipment [14,15]. The approach enables us to infer the marginal cost of a diesel cut. Third, the customer survey approach lists the effects of an actual supply interruption and then monetizes them [16]. Finally, the I-O approach, which addresses the impact of supply shortages on the whole economy by recognizing the interdependence of all sectors of the economy, has been applied in the energy shortage context. For example, Bernstein and Hegazy [17] employed the I-O approach to examine the effect of electricity shortages in Egypt. Chen and Vella [18] used the Leontief I-O framework to account for the average economic impact of short-term diesel shortages in all industrial sectors. The approach assumes that diesel supply shortage brings about supply problems in heavy industries which will lead to huge production reduction of the whole industries.

Each has its own merits. This study uses the I-O methodology of Chen and Vella [18], because both the government and diesel sector can measure the macro-economic impacts of unsupplied diesel in the existing economy. This approach can also provide the information of decision-making related to which sectors should be cut off in the case of diesel shortages. Thus, the purpose of this paper is to measure the supply shortage cost of diesel in the Korean economy in order to obtain an indication of the impact of diesel supply shortages in other sectors. In this study, national economic impacts caused by supply shortages of diesel product will be calculated using the I-O analysis. In particular, diesel products commonly used by commercial vehicles and manufacturing activities will be studied. This supply will show specifically how much macroscopic social cost will be when we encounter diesel supply shortage. In addition, benefits from establishing a stable supply of diesel products can be estimated indirectly.

The remainder of the paper is organized as follows: Section 2 presents an overview of the methodology and the empirical model adopted here. Section 3 describes the data and some assumptions. Section 4 reports the empirical findings. Some concluding remarks are made in the final section.

2. Methodology and Empirical Model

2.1. Methodology: I-O Analysis

I-O analysis, an analytical framework developed by Wassily Leontief [19]. Leontief, has become well known in the energy and environmental fields in recent decades [20]. I-O analysis is very useful for analyzing diesel-related issues in the economic context at the national level because it recognizes the interdependence of all sectors of the economy and their diesel consumption, which is embodied in their sectoral output. The I-O model is a linear and inter-sectoral model that shows the relationship among various productive sectors of an economic system. In an economy composed of n sectors, the inter-relationship among those sectors can be represented as:

$$X_i = \sum_{j=1}^{n} Z_{ij} + F_i = \sum_{j=1}^{n} a_{ij} X_j + F_i \tag{1}$$

where X_i is the total gross output of sector $i = 1, \ldots, n$; Z_{ij} is the inter-industry purchases of producing sector i from supply sector j; F_i is the final demand for products of sector i; and a_{ij} is the direct input coefficient which divide Z_{ij} by total gross output in sector j (X_j). Considering imports (M), Equation (1) can be rewritten in an abbreviated matrix form:

$$(I - A)X = F - M \tag{2}$$

The following theoretical background is based on Chen and Vella [18]. To clearly demonstrate the effect of diesel supply on the economy, we move the items referring to the diesel sector to the nth sector. Using partitioning, Equation (2) becomes:

$$\begin{bmatrix} (I - \widehat{A}) & -\alpha \\ -d & 1-f \end{bmatrix} \begin{bmatrix} \widehat{X} \\ D \end{bmatrix} = \begin{bmatrix} \widehat{F} \\ F_D \end{bmatrix} - \begin{bmatrix} \widehat{M} \\ M_D \end{bmatrix} \tag{3}$$

where I is an $(n - 1) \times (n - 1)$ identity matrix; $\widehat{A}$ is an $(n - 1) \times (n - 1)$ technical coefficient matrix of non-diesel sectors; α is the diesel column of non- diesel sectors; d is the diesel row of non-diesel sectors; f is the self-use-ratio of the diesel sector; D is diesel supply; $\widehat{X}$ is non-diesel outputs; $\widehat{F}$ is the final demand of non-diesel products; F_D is the final demand of diesel; $\widehat{M}$ is the import by non-diesel sectors; and M_D is the import by diesel sector.

We are interested in knowing how diesel shortages impose extra cost on all sectors. Thus, the items of D are isolated on the right-hand side of the equations to enable the investigation of its relation to other sectors. Rewriting Equation (3) gives us:

$$(I-\widehat{A})\widehat{X} = \alpha D + (\widehat{F} - \widehat{M}) \tag{4a}$$

$$-d\hat{X} - F_D = (f-1)D - M_D \tag{4b}$$

2.2. Empirical Model

The optimal allocation of limited diesel resources to various sectors can be achieved by solving overall value-added maximization problem. This can be specified as maximizing the total benefit (*TB*):

$$TB = \widehat{V}\widehat{X} + V_D D \tag{5}$$

subject to:

$$(I-\widehat{A})^{-1}\widehat{X} = \alpha D + (\widehat{F} - \widehat{M})$$

$$-d\hat{X} - F_D = (f-1)D - M_D$$

$$0 \le \widehat{F} \le \widehat{F}^0$$

$$0 \le \widehat{X} \le \widehat{X}^0$$

$$D = (1-S)D^0$$

$$0 \le F_D \le F_D^0$$

where $\widehat{V}$ is the row vector of value-added coefficients for non-diesel sectors; V_D is the value-added coefficient for the diesel sector; D^0, $\widehat{X}^0$, $\widehat{F}^0$, and F_D^0 are D, $\widehat{X}$, $\widehat{F}$, and F_D under an adequate condition, respectively; and S is the unsupplied diesel as a proportion of diesel demand (D^0). Thus, D, D^0, and SD^0 are the amount of diesel actually supplied, the amount of diesel supplied under the condition of no shortage, the amount of diesel unsupplied in shortage situations, respectively. Maximizing Equation (5) under the six constraints implies that curtailment of the diesel will be performed to reduce the final demand of the sector with the lowest value-added multiplier as the shortage percentage increases.

We define five matrices as follows:

$$B = \begin{bmatrix} (I-\widehat{A}) & 0 \\ -d & -1 \end{bmatrix},\ X^* = \begin{bmatrix} \widehat{X} \\ F_D \end{bmatrix},\ \alpha^* = \begin{bmatrix} \alpha \\ f-1 \end{bmatrix},\ F^* = \begin{bmatrix} \hat{F} \\ 0 \end{bmatrix}, \text{and } M^* = \begin{bmatrix} \hat{M} \\ M_D \end{bmatrix} \tag{6}$$

Equation (4b) can be re-written as:

$$BX^* = \alpha^* D + F^* - M^* \tag{7}$$

The solution of X^* can be derived as:

$$X^* = B^{-1}\alpha^* D + B^{-1}(F^* - M^*) \tag{8}$$

From Equation (6), B^{-1} can be:

$$B^{-1} = \begin{bmatrix} (I-\hat{A})^{-1} & 0 \\ -d(I-\hat{A})^{-1} & -1 \end{bmatrix} \tag{9}$$

Equation (4a,b) can be re-written as:

$$\hat{X} = (I-\hat{A})^{-1}\alpha D + (I-\hat{A})^{-1}(\hat{F}-\hat{M}) \tag{10a}$$

$$F_D = [1 - f - d(I-\hat{A})^{-1}\alpha]D - d(I-\hat{A})^{-1}(\hat{F}-\hat{M}) + M_D \tag{10b}$$

For brevity, let $K = (I-\hat{A})^{-1}\alpha$, $\varepsilon = -d(I-\hat{A})^{-1}$, θ = $1-f$ − $\varepsilon\alpha$, and $C_D = M_D - \varepsilon\hat{M}$. Thus, Equation (10a,b) become:

$$\hat{X} = KD + (I-\hat{A})^{-1}(\hat{F}-\hat{M}) \tag{11a}$$

$$F_D = \theta D + C_D + \varepsilon\hat{F} \tag{11b}$$

Substituting Equation (11a) for $\hat{X}$ in Equation (5) gives us:

$$\hat{V}\hat{X} + V_D D = (\hat{V}K + V_D)D + \hat{V}(I-\hat{A})^{-1}(\hat{F}-\hat{M}) \tag{12}$$

Therefore, Equation (5) can be:

$$TB = \hat{V}\hat{X} + V_D D = w\hat{F} + QD - C_M \tag{13}$$

where $w = \hat{V}(I-\hat{A})^{-1}$, $C_M = w\hat{M}$, and $Q = \hat{V}K + V_D = w\alpha + V_D$.

If the diesel shortage occurs in such a short time that due to the limited capacities of import facilities and other factors the amount of imports $\hat{M}$ cannot be changed, then C_M is assumed to be constant. Since $w = [w_j]$ is a constant vector, and Q constant as well, the optimal benefit of an economy is dominated by the product of w and $\hat{F}$. w_j is the value-added multiplier of sector j. The final demand of a sector which has the highest value-added multiplier will induce the largest amount of total value-added. Hence, when facing difficulties of satisfying all the demand, the diesel-providing industry will first cut down supply to those sectors which have lower value-added multipliers based on economic aspect. In order to find the optimal solution, we can sort the value-added multipliers into ascending order. The best allocation policy is to cut down the final demands one by one in ascending order of value-added multipliers, until the diesel supply is sufficient to accommodate the new production configuration of the whole economy.

The amount of diesel supply is fixed at its upper limit in shortage situations. Therefore the direct value-added generated by the diesel sector is fixed at $V_D D$, no matter how the diesel-providing industry allocates its diesel supply. Because the final demand for diesel consumes goods but does not induce value-added products, supplying diesel to its final-demand consumers does not induce any value-added effects. Hence, if the economic aspect is only considered, the final demand users will be the first to suffer curtailment.

2.3. Economic Consideration

The consumers in final demand will be the first target for diesel cuts if we want to maximize total value-added. Without loss of generality, the sectors would be considered in ascending order of multiplier. From Equation (11b):

$$F_D = \theta D^0(1-S) + \sum_{k=1}^{n-1} \varepsilon_k F_k + C_D$$

This can be re-expressed as:

$$S = 1 - \frac{F_D}{\theta D^0} + \frac{C_D}{\theta D^0} + \sum_{k=1}^{n-1} \frac{\varepsilon_k F_k}{\theta D^0} \tag{14}$$

Under adequate conditions, the final demand of various sectors is denoted as F_D^0, F_{n-1}^0, F_{n-2}^0, …, F_1^0. If S = 0, then $F_D = F_D^0$ and $F_k = F_k^0$ (k = 1, 2, …, n − 1). F_D^0 and F_k^0 in Equation (15) are the final demands of diesel sector and non-diesel k th sector, respectively, under adequate conditions. Thus:

$$\frac{F_D{}^0}{\theta D^0} - \frac{C_D}{\theta D^0} - \sum_{k=1}^{n-1} \frac{\varepsilon_k F_k^0}{\theta D^0} = 1 \tag{15}$$

Let $r_D = \frac{1}{\theta D^0}$ and $r_k = \frac{\varepsilon_k}{\theta D^0}$ for k = 1, 2, …, n − 1. Replacing Equation (14) with Equation (15) gives us the following relation between shortage percentage and final demand:

$$S = r_D(F_D^0 - F_D) - \left[\sum_{k=1}^{n-1} r_k (F_k^0 - F_k) \right] \tag{16}$$

The shortage percentage in Equation (16) is S that means the unsupplied diesel as a proportion of diesel demand (D^0). As the shortage percentage increases, the diesel sector first reduces its diesel supply to its final-demand consumers to maximize the total value-added. Theoretically, this first curtailment measure can last until F_D = 0. Then, if diesel demand is still greater than the supply, the second curtailment will be performed to reduce the final demand of the sector with the lowest value-added multiplier. These steps are:

$$S_D = r_D F_D^0,$$

$$S_1 = r_D F_D^0 - r_1 F_1^0,$$

$$S_t = r_D F_D^0 - \sum_{k=1}^{t} r_k F_k^0,$$

$$S_{n-1} = r_D F_D^0 - \sum_{k=1}^{n-1} r_k F_k^0$$

where t means the curtailment stage. At stage t, the optimal solution for F is:

$$\begin{cases} F_k = 0 & \text{for } k \le t \\ \quad\; = F_k^0 & \text{for } k > t \end{cases}$$

From Equation (11a), the elements of $(I - \hat{A})^{-1}$ and $(I - \hat{A})^{-1}\hat{M}$ are represented as β's and m's. The output of sector *i* at stage *t* is:

$$X_i^t = K_i D - m_i + \sum_{k=1}^{n-1} \beta_{ik} F_k$$
$$= K_i (1 - S_t) D^0 - m_i + \sum_{k=t+1}^{n-1} \beta_{ik} F_k^0$$

for $i = 1, 2, \ldots, n - 1$ and $x_i \geq 0$. From Equation (13) the total benefit at stage *i* is:

$$TB_t = TB^0 - \sum_{k=1}^{t} w_k F_k^0 - Q\Delta D$$

The decrements of sector production, diesel, and total benefit from stage $t - 1$ to *t* are:

$$\Delta X_i^t = K_i \Delta D_t - \beta_{it} F_t^0 \quad \text{for} \quad i = 1, 2, \ldots, n - 1$$
$$\Delta D_t = (S_{t-1} - S_t) D^0 = r F_t^0 D^0 = \frac{\varepsilon_t F_t^0}{\theta}$$
$$\Delta TB_t = Q r_t F_t^0 D^0 - w_t F_t^0 = -F_t^0 (w_t - Q r_t D^0)$$

Based on the assumption of fixed input coefficients, the diesel supply to sector *i* for producing X_i will be $d_i X_i$, and the optimal curtailment policy in stage *t* will be $d_i (X_i^0 - X_i)$. Under such a policy the marginal production and the marginal benefit (cost) of diesel shortage can be derived as:

$$MX_i^t = \frac{\Delta X_i^t}{\Delta D_t} = K_i - \frac{\theta \beta_{it}}{\varepsilon_t}$$

and:

$$MB_t = \frac{\Delta TB_t}{\Delta D_t} = Q - \frac{\theta w_t}{\varepsilon_t}, \tag{17}$$

respectively.

3. Data and Some Assumptions

3.1. Data

For the diesel-based I-O analysis, we used the original 2009 benchmark I-O table for Korea [21]. The original benchmark I-O table was composed of 403 sectors. To avoid the arbitrariness of aggregation and minimize sectoral bias, we used the Bank of Korea's 28-sector classification method. Sector 7 was originally petroleum and coal products sector, but for the I-O analysis, we divided this sector into two sectors (diesel sector and non-diesel petroleum and coal products sector). Therefore, we considered a total of 29 sectors. Sectors 1 to 28 are non-diesel sectors; Sector 29 is the diesel sector. Section classification adopted in this study is described in Table 1.

Table 1. Sector classification in this study.

Code	Name of Sector
1	Agriculture, forestry and fishing
2	Mining and quarrying
3	Food, beverages and tobacco products
4	Textile and apparel
5	Wood and paper products
6	Printing and reproduction of recorded media
7	Non-diesel petroleum and coal products
8	Chemicals, drugs and medicines
9	Non-metallic mineral products
10	Basic metal products
11	Fabricated metal products except machinery and furniture
12	General machinery and equipment
13	Electronic and electrical equipment
14	Precision instruments
15	Transportation equipment
16	Furniture and other manufactured products
17	Electricity, gas, steam and water supply
18	Construction
19	Wholesale and retail trade
20	Accommodation and food services
21	Transportation
22	Communications and broadcasting
23	Finance and insurance
24	Real estate and business services
25	Public administration and defense
26	Education, health and social work
27	Other services
28	Dummy (miscellaneous) sectors
29	Diesel products

3.2. Some Assumptions

To determine an optimal solution from the empirical model, first of all, we have to sort the value-added multipliers into ascending order. In general, the optimal allocation policy involves the reduction of the final demand one by one in the ascending order of value-added multipliers until the diesel supply can accommodate the new production configuration of the whole economy. Moreover, the best allocation policies are typically achieved by maximizing the overall social economic benefit with respect to various supply shortage situations.

Next, to analyze the influence of such policies on the cost of unsupplied diesel in the Korean economy, we determined whether the diesel sector could reduce its supply to its final-demand consumers based on economic considerations and to what extent the sectoral supply to final-demand consumers could be curtailed. Optimal allocation policy assuming the allocation is maximizing the total social benefit for each supply shortage situations. However, it is important whether we can restrict the supply of the product to the end user and by how far we can reduce sectoral supply to the end user.

We assume that the diesel-providing industry can cut diesel to final demand consumers based on economic considerations. Thus, the assumptions about supply reduction allocation policy are needed. We consider two cases. The maximum decrease percentages for sectoral supplies to final demand (σ) are assumed to be 20% or 30%.

For more realistic results, we made some modifications during the calculation procedure. Because the final demand of Sector 2 (mining and quarrying) was too small relative to other sectors, the proportion of real consumption to the final demand was also quite small, and thus, the sector's σ was set to zero. Furthermore, the economic cost of unsupplied diesel is expressed as KRW per liter for a better understanding. The average price of diesel per liter was KRW 967 (USD 0.88) during 2009 [22].

4. Results

The value-added multipliers of all the non-diesel sectors are shown in Table 2. Sector 23, "finance and insurance", has the highest value-added multiplier at 0.9920, which means that this sector will generate more value-added than any other sectors to the Korean national economy. Sector 21, 'transportation', has the lowest value-added multiplier at 0.8770.

Table 2. Value-added multipliers for non-diesel sectors in Korea.

Name of Sectors	Sector Codes	Value-Added Multipliers
Transportation	21	0.8770
Mining and quarrying	2	0.9155
Non-diesel petroleum and coal products	7	0.9303
Non-metallic mineral products	9	0.9450
Electricity, gas, steam and water supply	17	0.9504
Basic metal products	10	0.9601
Chemicals, drugs and medicines	8	0.9649
Agriculture, forestry and fishing	1	0.9650
Construction	18	0.9666
Fabricated metal products except machinery and furniture	11	0.9705
Food, beverages and tobacco products	3	0.9718
Wood and paper products	5	0.9735
Wholesale and retail trade	19	0.9736
Furniture and other manufactured products	16	0.9746
General machinery and equipment	12	0.9764
Dummy (miscellaneous) sectors	28	0.9772
Transportation equipment	15	0.9777
Textile and apparel	4	0.9778
Electronic and electrical equipment	13	0.9792
Accommodation and food services	20	0.9797
Precision instruments	14	0.9797
Printing and reproduction of recorded media	6	0.9804
Other services	27	0.9826
Education, health and social work	26	0.9833
Public administration and defense	25	0.9868
Communications and broadcasting	22	0.9872
Real estate and business services	24	0.9906
Finance and insurance	23	0.9920

In order to deal with the matrix calculations, a GAUSS program was written and EXCEL was used for computing this input-output framework. The program was applied to estimating the diesel shortage costs of Korea in 2009. Table 3 presents the marginal shortage costs, and average shortage costs of unsupplied diesel under different shortage percentages. The marginal shortage costs are independent of shortage percentages. Therefore, they are the same under different shortage percentages.

Table 3. Average and marginal shortage costs of unsupplied diesel.

		Case 1 (σ = 20%)			Case 2 (σ = 30%)			
Stage	**Name of Sectors**	**Shortage %**	**Total Benefit [a]**	**Average Shortage cost [b]**	**Shortage %**	**Total Benefit [a]**	**Average Shortage Cost [b]**	**Marginal Shortage Cost [b]**
1	Diesel product	0.0850	1,045,788	2,116	0.1275	1,044,730	3,175	716
2	Transportation	0.1296	1,034,277	11,511	0.1943	1,027,462	17,267	7,420
3	Non-diesel petroleum and coal products	0.1423	1,028,477	5,799	0.2134	1,018,763	8,699	13,099
4	Non-metallic mineral products	0.1429	1,028,149	327	0.2143	1,018,271	491	16,608
5	Electricity, gas, steam and water supply	0.1479	1,024,939	3,209	0.2218	1,013,456	4,814	18,409
6	Basic metal products	0.1525	1,021,243	3,696	0.2288	1,007,912	5,544	22,902
7	Chemicals, drugs and medicines	0.1653	1,009,683	11,559	0.2479	990,572	17,339	25,991
8	Agriculture, forestry and fishing	0.1688	1,006,449	3,234	0.2533	985,721	4,851	26,087
9	Construction	0.2074	970,873	35,575	0.3111	932,357	53,363	26,508
10	Fabricated metal products except machinery and furniture	0.2102	967,907	2,966	0.3152	927,907	4,449	30,984
11	Food, beverages and tobacco products	0.2201	956,707	11,199	0.3301	911,108	16,799	32,393
12	Wood and paper products	0.2205	956,170	536	0.3308	910,303	805	34,395
13	Wholesale and retail trade	0.2318	942,679	13,491	0.3477	890,066	20,236	34,551
14	Furniture and other manufactured products	0.2335	940,468	2,210	0.3503	886,750	3,315	35,893
15	General machinery and equipment	0.2441	926,331	14,137	0.3661	865,544	21,205	38,633
16	Dummy (miscellaneous) sectors	0.2441	926,279	52	0.3661	865,466	78	40,103
17	Transportation equipment	0.2631	899,203	27,076	0.3947	824,851	40,614	40,852
18	Textile and apparel	0.2688	891,125	8,078	0.4032	812,734	12,117	41,147
19	Electronic and electrical equipment	0.2938	852,868	38,256	0.4407	755,350	57,384	43,922
20	Accommodation and food services	0.3009	841,804	11,063	0.4513	738,754	16,595	44,896
21	Precision instruments	0.3027	839,036	2,768	0.4540	734,601	4,152	44,983
22	Printing and reproduction of recorded media	0.3027	838,923	112	0.4541	734,432	169	46,561
23	Other services	0.3091	827,363	11,559	0.4636	717,092	17,339	52,345
24	Education, health and social work	0.3259	795,383	31,980	0.4888	669,121	47,970	54,674
25	Public administration and defense	0.3336	776,919	18,464	0.5004	641,425	27,696	68,969
26	Communications and broadcasting	0.3355	772,097	4,821	0.5033	634,193	7,232	71,129
27	Real estate and business services	0.3433	746,074	26,022	0.5149	595,159	39,034	96,796
28	Finance and insurance	0.3458	736,120	9,954	0.5187	580,227	14,931	113,376

[a] Total benefits are in billion Korean won; [b] Average and marginal shortage costs are expressed in Korean won per liter.

Total benefit in Korean national economy calculated using Equation (17) is KRW 1,047,905 billion (USD 953 billion). Marginal shortage cost of unsupplied diesel incurred by society is as low as KRW 716 (USD 0.65) per liter, which is 74% of the sales price, in case that the diesel sector initially opts to curtail its supply to final demand consumers. This is based on the fact that the final demand users only consume goods and do not add any values nor do they indirectly contribute to any value-added effects.

Next to that, transportation sector will be the target to have reduced diesel supply because they have the lowest value-added multiplier. Its marginal cost of the shortage is KRW 7,420 (USD 6.75) per liter. The third target will be non-diesel petroleum and coal products sector and its marginal cost of the shortage will be KRW 13,099 (USD 11.91) per liter. When the supply of diesel exceeds its demand and it leads to a continuous supply shortage and ends up with targeting the final supply reduction target, finance and insurance sector, the marginal cost of the shortage is analyzed to be reaching KRW 113,376 (USD 103.07) per liter. The marginal costs of unsupplied diesel increase from KRW 716 (USD 0.65) to KRW 113,376 (USD 103.07) per liter as the stage goes from 0 to 29, which means that opportunity costs increase as value-added multipliers get higher.

Without loss of generality, the stage of each sector has already determined by ascending order of value-added multiplier. Therefore, sector 21, "transportation", would be the second target for curtailment, due to its lower value-added multiplier. According to the ascending order of value-added multiplier (see Table 2), sector 7, "non-diesel petroleum and coal products", would be the third target, and so on.

5. Concluding Remarks

Korea has been highly reliant on diesel consumption. Timely and unceasing supply of diesel could be a cornerstone of its modern economy. Ensuring reliable diesel supply has been and will continue to be one of the most important considerations in decision-making about the industrial policy of the diesel sector. Recently, the industrial development has made diesel supply reliability a critical part of any policy for a sustainable future. These situations require researchers to provide energy policy-makers with accessible and reliable information on the reliability of diesel supply. In this regard, this study employed I-O analysis to estimate the economic cost of unsupplied diesel for all sectors in Korea by determining the optimal way in which limited diesel product resources can be allocated to various sectors while maximizing the total value-added. The results indicate that the marginal cost of unsupplied diesel ranged from KRW 716 (USD 0.65) to KRW 113,376 (USD 103.07) per liter and that these total costs depended not only on the shortage percentage of each non-diesel sector but also on the level of its final demand. This exercise provides important insights into both policy and research.

For policy purposes, the results are useful starting points in understanding the possible implications of the role of diesel supply in Korea. The overall results indicate that diesel product shortages have a big influence on the industrial production and standard of living. The data on the economic cost of diesel supply shortages, which is obtained from our study, may provide valuable information for planners in various ways. First, it can be used in setting economic reliability standards in diesel production and distribution planning and diesel system optimization. The social optimal service quality level is determined at the minimum of the sum of supply costs and shortage costs [23]. Second, it can be employed in determining pricing and load management strategies. Finally, it can be applied in developing shortage management strategies, optimum curtailment levels and priorities. The data can help in assessing a more economically sound way of allocating the available diesel during a period of shortage. A policy dealing with limited diesel being provided for sectors in which shortage costs are relatively high could be considered.

Judging from a review of the literature, there are only several studies in which the I-O model was used for analyzing diesel-related issues. The advantage of I-O analysis lies in the use of data from the latest I-O table produced by the government [21]. Thus, this method helps to simplify the estimation and ensure more reliable results. For research purposes, beyond the intrinsic interest of the results in relation to the diesel policy, this case study has demonstrated the feasibility of extending the use of the I-O analysis at least to diesel-providing industry. It could provide one prerequisite for helping diesel-related policy-making, but the extension of the present framework needs to be undertaken in a future study as a second phase of the work. The extension can be made in three aspects.

First, the next study has to focus the multi-regional I-O model. This study focused on the national I-O model. The multi-regional I-O model reflecting the peculiarities of a regional problem could improve understanding of diesel-providing industry.

Second, dynamic consideration can be useful in the demand-driven I-O model. Actually, some input goods contribute to the production process but are not immediately used up during that production. Therefore, dynamic I-O analysis, which allows the changing of input coefficients over time, will significantly increase the precision of analytical results.

Third, in deriving the shortage costs of energy supply, the supply-driven model can be more useful than the demand-driven model adopted here. The demand-driven I-O approach assesses the economic cost of unsupplied diesel product dealing with diesel as a raw material for the production of other sectors. The demand-driven I-O approach has been widely used in computing the forward linkage effect [24]. The demand-driven I-O model, which depends on the assumption of fixed input coefficients and a perfectly elastic supply of inputs, concentrates on analyzing the impacts stemming from the final demand, or backward linkage, and output orientation of activities [25,26]. However, the model may not be appropriate for dealing with the impact from the primary supply, or forward linkage, and the input orientation of activities. Therefore, the supply-driven I-O model has been developed to deal with the direct and indirect impacts of natural resource supply restrictions [27]. Thus, it is appropriate to assume that allocation coefficients are fixed during supply restriction in primary inputs [28]. According to Equation (13), TB is the only function of $\hat{F}$, indicating any non-diesel value-added sectors may not directly affect those non-diesel industries total outputs. Similarly, the equation is not explaining how the V_D affects other non-diesel industries; it only assumes non-diesel final demands may be the first affected factors. Thus, the framework of our paper should be extended to the supply-driven I-O approach as a second stage of the study.

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