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Structural Changes to Nuclear Energy Industries and the Economic Effects Resulting from Energy Transition Policies in South Korea

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Abstract: The world's aging fleet of nuclear power reactors faces decommissioning. Because decommissioning is implemented through a series of procedures, and this process changes the links between some industries, its economic impact needs to be investigated. This study compared the economic impacts of three nuclear industry sectors—nuclear generation, nuclear power construction, and nuclear decommissioning—using input-output analysis in South Korea, the first Asian country that has declared a nuclear phaseout. The study also traced changes in the structure of the nuclear industry during the Korean nuclear phaseout and the consequent economic impacts. The study found that the implementation of the nuclear phaseout will lead to a decrease in the induced outputs and the value added of nuclear industries in South Korea; however, this would be offset by deploying more renewable energy. In addition, the temporal impacts on individual sectors vary depending on changes in the number of reactors being decommissioned and the expenditure profile of the nuclear decommissioning sector. The findings call for policy measures that support a soft landing for nuclear industry sectors and related stakeholders, timely development of necessary technologies, and transparency in public communication. This study provides a methodological approach and input structure that can be used for studies in other countries.

Keywords: nuclear phaseout; decommissioning; industry structural change; economic impacts; input-output analysis

1. Introduction

Nuclear power plants that permanently stop operating must go through a decommissioning process: cleaning up their radioactive waste, dismantling the facility, and restoring the site [1]. As of July 2018, 173 nuclear reactors, with a capacity of 73.5 GW, had been permanently shut down globally. Of these, only 19 reactors with a capacity of 6 GW had been fully decommissioned, and only 10 of those 19 reactor sites had been restored [2]. Assuming an average reactor lifespan of 40 years, Schneider and Froggatt [2] estimated that 327 reactors would shut down by 2057 and that the size of the global decommissioning market would approach USD 1 trillion by 2050. Closing down the many old nuclear reactors in the world will have significant economic impacts. Based on analysis of this effect, appropriate policy measures, such as aid or compensation for the loss of jobs and other adverse effects on related industries, should be implemented [3].

Nuclear power plants may be permanently shut down because of serious accidents or political decisions, but often they are closed because they are regarded as no longer economical or because they have reached their design lifetime. One of these was South Korea's first nuclear power reactor, Kori-1, which had a capacity of 576 GW and operated from 1977 to 2017. It was permanently shut down because it was no longer economical to operate [1].

Controversies about energy transition continue in South Korea, which was the first Asian country that declared a nuclear phaseout. However, the economic impact of nuclear phaseout has rarely been analyzed. Park and Kim [4] investigated the economic impact of closing a single nuclear power plant, Kori-1, which was the first commercial-scale nuclear power plant in South Korea and had a capacity much smaller than other reactors. The economic impact of the consecutive decommissioning of nuclear power reactors under South Korea's energy transition policy needs to be analyzed in order to determine the policy implications of implementing the planned phaseout. This study evaluates the economic impact of structural changes in nuclear industry sectors during nuclear phaseout and analyzes temporal changes in the economic impact of nuclear phaseout. To achieve these goals, this study constructed an input-output table that included three nuclear industry sectors: nuclear generation, nuclear power construction, and nuclear decommissioning. The input-output table was based on a survey of the input and distribution structures of these industry sectors. Additionally, this study conducted an input-output analysis that considered temporally different profiles for expenditures on decommissioning and for the progression of nuclear phaseout and renewable energy deployment.

This paper is organized as follows. The background section briefly outlines energy transition policies, with a focus on nuclear phaseout in South Korea; it also surveys and defines the processes involved in decommissioning nuclear reactors. The literature review section investigates and analyzes studies that look into the impact of nuclear phaseout. The methodology and data section describes the data used to organize the input-output table into 35 sectors, including the three nuclear industry sectors, and specifies the input-output analysis. The results section compares the economic impacts on the three nuclear industry sectors and analyzes temporal changes in the impact of a changed nuclear power industry following the implementation of nuclear phaseout. This section then deepens the results and draws some policy implications. The conclusion presents the contributions and limitations of this study.

2. Background

2.1. Energy Transition Policies and Nuclear Industry Sectors in South Korea

In South Korea, nuclear power was introduced in 1978 to meet electricity demand, which was increasing in line with rapid economic growth. Nuclear power was promoted as an important pillar of South Korean energy policy, along with coal-fired power [5]. At the end of 2018, there were 24 nuclear plants operating in South Korea; they had a total capacity of 22.5 GW [6].

Despite the importance of nuclear power, its sustainability has been questioned because of nuclear waste and safety issues. The cost of radioactive waste treatment seems to be much higher in South Korea than in other countries. The cost for treating low- and intermediate-level radioactive waste in South Korea was estimated to be KRW 66.5 million (equivalent to about USD 63,000)/m^2, which is about 2.7 times the cost in the United States. This can be attributed to the long conflict regarding the siting of low- and intermediate-level radioactive waste disposal facilities [7].

The Moon Jae-in administration strongly advocated for a low-carbon and sustainable energy transition and announced a plan for stepwise nuclear phaseout [8]. The Public Deliberation Committee on Shin Kori Nuclear Reactors 5 and 6 concluded that the construction of those reactors should resume, but the committee supported reducing dependence on nuclear power [9]. Even with continued political controversies regarding nuclear phaseout, an eco-friendly and safe energy transition has been pursued [10]. Consequently, dependence on nuclear power is intended to decrease from 29.4% of the total power generated in 2017 to 23.9% in 2030 [11].

If nuclear power plants are closed down according to the government's plan, the nuclear power plants in operation would reach maximum capacity (27.45 GW and 27 units) in 2023 (see Figure 1). As of 2019, six reactors with a total capacity of 8400 MW were under construction and two reactors (Kori-1 and Wolsung-1) with a total capacity of 1266 MW had stopped operating [6]. The number and capacity, respectively, would steadily decrease to nine reactors and 11.4 GW in 2050. At the same time, the number of reactors under decommissioning would increase, peaking at 10 reactors in 2037 and 2038, before decreasing.

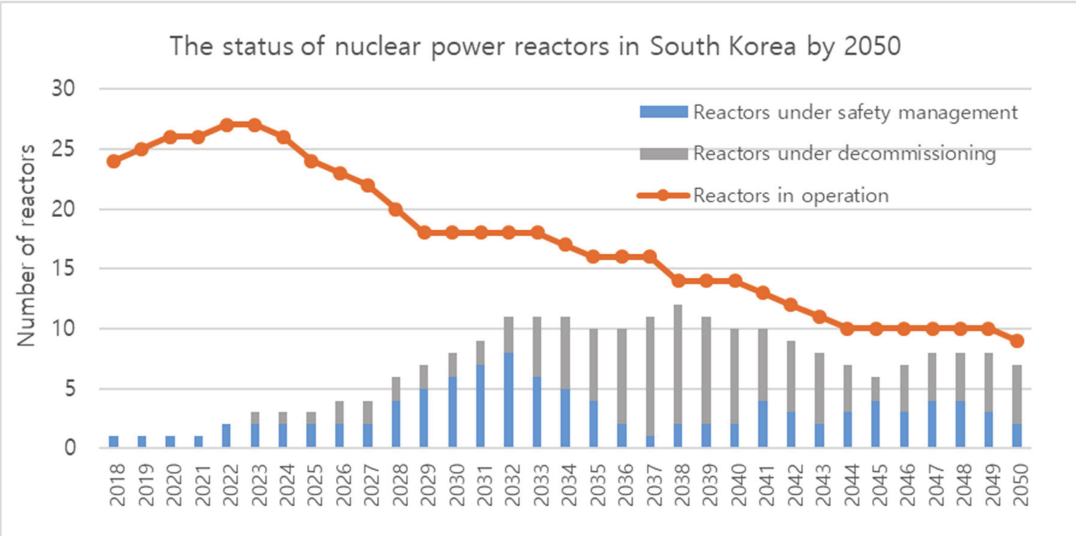

Figure 1. The status of nuclear power reactors in South Korea through 2050. Source: authors constructed this chart using [11,12].

With the domestication of the construction of nuclear power plants, the nuclear industry's impact on other industries, such as precision devices and heavy electric devices, has become significant [13]. As of 2017, there were 552 nuclear power-related organizations (2 power generators, 508 nuclear suppliers, 24 research institutes, and 18 universities). The total revenue of this industry was equivalent to KRW 23.9 trillion (USD 21.1 billion), of which nuclear power comprised the dominant portion (76.2%), followed by suppliers (19.7%) [14]. The structural changes, the decrease in nuclear power generation and construction, and the increase in decommissioning will significantly impact related industries and the overall economy.

2.2. Decommissioning of Nuclear Power

Decommissioning is a term that incorporates the "defueling, deconstruction, and dismantling of nuclear power plants [2]." This term often refers not only to dismantling the nuclear facilities but also to restoring the site [15]. Utilization of restored sites varies: some sites have been restored to greenfield, while others have been restored to brownfield so they can be used for fossil-fired power plants [16]. South Korean law defines the term more comprehensively. Article 2.24 of the Nuclear Safety Act defines decommissioning as all activities that would lead to nuclear facilities becoming exempt from the application of the Act through dismantling facilities and sites or by removing radioactive contamination after permanently suspending operation.

Decommissioning is carried out differently depending on when dismantling is commenced. Reactors can be dismantled as soon as they are permanently shut down, which is called Immediate Dismantling (ID), or reactors can be dismantled after a period of safe management, which is called Long-Term Enclosure (LTE) [2]. Decommissioning takes from 6 to 42 years, with about 19 years being the average. Decommissioning generally takes more time than planned [2]. Table 1 summarizes the planned activities for the Kori-1 reactor. Kori-1 will be decommissioned using the ID approach; this will take about 15.5 years, so it will be decommissioned by the end of 2032 [16].

Table 1. Decommissioning schedule for Kori-1 [16].

Due	Activities
Jun 2022	Development and approval of the decommissioning plan
Dec 2025	Cooling and moving spent fuels - Cooling spent fuels underwater - Temporary storage of spent fuels in on-site dry casks - Moving spent fuels to high radioactive waste disposal facilities
Dec 2030	Dismantling contaminated facility and radioactive waste treatment - Dismantling turbine and generators - Cutting and volume reduction of the dismantled system and waste - Installation of waste treatment facilities
Dec 2032	Site restoration

3. Literature Review

Many studies have been conducted on the decommissioning of nuclear power. Some evaluate the institutional or financing systems [17,18], others investigate and compare strategies and options for handling the nuclear waste that is generated during decommissioning [19,20], and others estimate the cost of decommissioning [21–23]. Additionally, Mulholland et al. [24] tried to define social value in an analysis of nuclear decommissioning cases in the UK.

Other studies have tried to quantify the economic impacts of nuclear phaseout. The International Atomic Energy Agency (IAEA) [25] identified socioeconomic impacts of decommissioning nuclear power plants. It pointed out that nuclear facilities are generally located in remote areas, where they often are the main source of income of the local community. Thus, the socioeconomic effects of decommissioning of nuclear power plants can be significant [3,25,26]. In addition to the economic impacts, the IAEA [25] pointed out that decommissioning could induce demographic changes, such as the emigration of young persons to seek work elsewhere, which could affect the level of local services like transportation.

Because of the significance of decommissioning for local economies, its impact on communities has also been quantitatively measured and estimated. D. Fuentes-Saguar, A. Vega-Cervera and Cardenete [3] analyzed the socioeconomic impacts of decommissioning the Almaraz nuclear power plant, which had been generating a quarter of Spain's nuclear power output, using a regional social accounting matrix model. The results showed negative impacts on regional outputs (EUR 115 million) and employment (about 1951 jobs). In the studied region, the energy sector was most adversely impacted in terms of output and the other services sector was most affected in terms of employment.

Using a computable general equilibrium model, Bretschger et al. [27] simulated the economic impact of nuclear phaseout until the middle of the 2030s in Switzerland, where more than one-third of electricity is generated using nuclear power. They found that the impacts would not be very large—a decrease of consumer welfare of only 0.4%—and they predicted that the shift could result in innovative changes to the energy mix and investment. In a more recent study, Bretschger and Zhang [28] reaffirmed that the adverse impacts of nuclear phaseout would not be very large even in the presence of stringent carbon policies in Switzerland. Marcucci and Turton [29] attributed the small economic impact of nuclear phaseout to accessible electricity generated in other EU countries. In contrast, they found that the impact of nuclear phaseout on the Japanese economy would be much more significant.

Haller, Haines and Yamamoto [26] investigated the impact of decommissioning on population growth, per capita income, and employment at the county level in the United States by conducting panel data analysis. Contrary to their a priori expectations and the findings of other studies, they found a positive impact of nuclear decommissioning on employment and income during and even after decommissioning, using empirical data from 1975 to 2014.

Recently, Park and Kim [4] analyzed the national and regional economic impacts of decommissioning the Kori-1 nuclear reactor using input-output analysis. They assumed that the cost of deconstruction and dismantling would have more impact on the regional economy and that R&D and design related to the decommissioning process would have more impact on the national economy.

In South Korea, where uranium extraction and fuel fabrication are not conducted, the lifecycle of nuclear power reactors consists of construction, electricity generation, and decommissioning. The handful of studies on the economic impact of decommissioning nuclear power reactors have analyzed a single stage of a nuclear power reactor's lifecycle. Therefore, these existing studies are limited in what they can say about the comprehensive implications of changes in the nuclear energy industry because of South Korea's energy transition policy. Although Park and Kim [4] analyzed the economic impact of decommissioning a nuclear reactor, this was limited to a single nuclear reactor.

In reality, nuclear power reactors will be consecutively decommissioned, with 10 expected to be decommissioned in addition to Kori-1. Therefore, methodological approaches need to be designed so the comprehensive implications of structural changes in the nuclear energy industry can be discussed when considering the timeline of the overall nuclear phaseout. This approach will be helpful to other countries that anticipate consecutively decommissioning old nuclear reactors.

4. Methodology and Data

4.1. Construction of Input-Output Table

This study organized the 384 industry sectors of the 2014 input-output (IO) table [30] into 35 sectors, as presented in Table 2. These sectors included nuclear generation, nuclear power construction, and nuclear decommissioning. Because the nuclear power construction and nuclear decommissioning sectors were not in the original IO table, this study established those two sectors based on a survey of the input structure and the distribution of products across the sectors.

Table 2. Sector classification of input-output table.

ID	Sectors	ID	Sectors
1	Agriculture, forestry, and fisheries	**19**	Other power
2	Mining	**20**	Water, waste, and recycling service
3	Food, beverage, and tobacco	**21**	Nuclear power construction
4	Textile and leather	**22**	Nuclear power decommissioning
5	Timber, paper, printing, and copy	**23**	Other construction
6	Coal and petroleum	**24**	Wholesale and retail
7	Chemicals	**25**	Transportation
8	Nonmetal products	**26**	Restaurant and accommodation
9	Primary metal products	**27**	ICT and broadcasting
10	Metal products	**28**	Finance and insurance
11	Machinery and devices	**29**	Real estate and rental
12	Electric and electronic devices	**30**	Professional, scientific, and technological services
13	Precision devices	**31**	Business supporting services
14	Transportation equipment	**32**	Public administration and national defense
15	Other products	**33**	Educational services
16	Nuclear generation	**34**	Public health and social welfare services
17	Renewable power	**35**	Culture and other services
18	Fossil fuel fired power		

For its input structure, this study assumed that the nuclear power construction sector mirrors the other electric facility construction sector. The total input to nuclear power construction was retrieved from the 2014 financial report of Korea Hydro & Nuclear Power Co., Ltd. (KHNP); this value was about USD 1.8 billion (the annual average exchange rate was applied).

For the input structure of the nuclear power decommissioning sector, this study established the profile of the cost of the associated tasks after consultation in August 2018 with nuclear decommissioning experts in South Korea. The cost profile of decommissioning a standard nuclear power reactor depends on these assumptions: 1) a nuclear power reactor with capacity of 1000 MW; 2) a lifetime of 40 years; 3) following ID procedures after closing down, which means safety management for 5 years and decommissioning for 8 years (safety management refers to system reclassification prior to actual decommissioning, and decommissioning includes site restoration for 2 years in addition to a dismantling period of 6 years); and 4) excluding the cost of managing spent fuel (according to the Radioactive Waste Management Act, charges for managing spent nuclear fuel are collected separately, along with a reserve for the cost of decommissioning nuclear power plants). The specifications for how the input structure of the nuclear power decommissioning sector was built are presented in the Appendix A (Tables A1 and A2).

4.2. *Analysis of Temporal Changes in the Impacts of Nuclear Phaseout*

Once the IO table was reorganized, this study analyzed temporal changes in economic impacts as nuclear phaseout progresses. Decommissioning of a nuclear power reactor is carried out according to a series of procedures, as mentioned earlier. For example, the design, production, and construction of the volume reduction facility needs to be completed before dismantling can begin.

This study differentiates the annual input structure of the nuclear power decommissioning sector according to how decommissioning is implemented. As presented in Figure 2, the most significant cost should be in the 11th year of the decommissioning process of a nuclear reactor, followed by the 6th, 7th, and 8th years. In general, water, waste, and recycling services related to decontamination and radioactive waste treatment accounted for the largest proportion of the total input to the nuclear power decommissioning sector. Given the decommissioning schedule of individual nuclear power reactors in South Korea and the annual input profile of decommissioning, the annual input profile can be estimated until 2050.

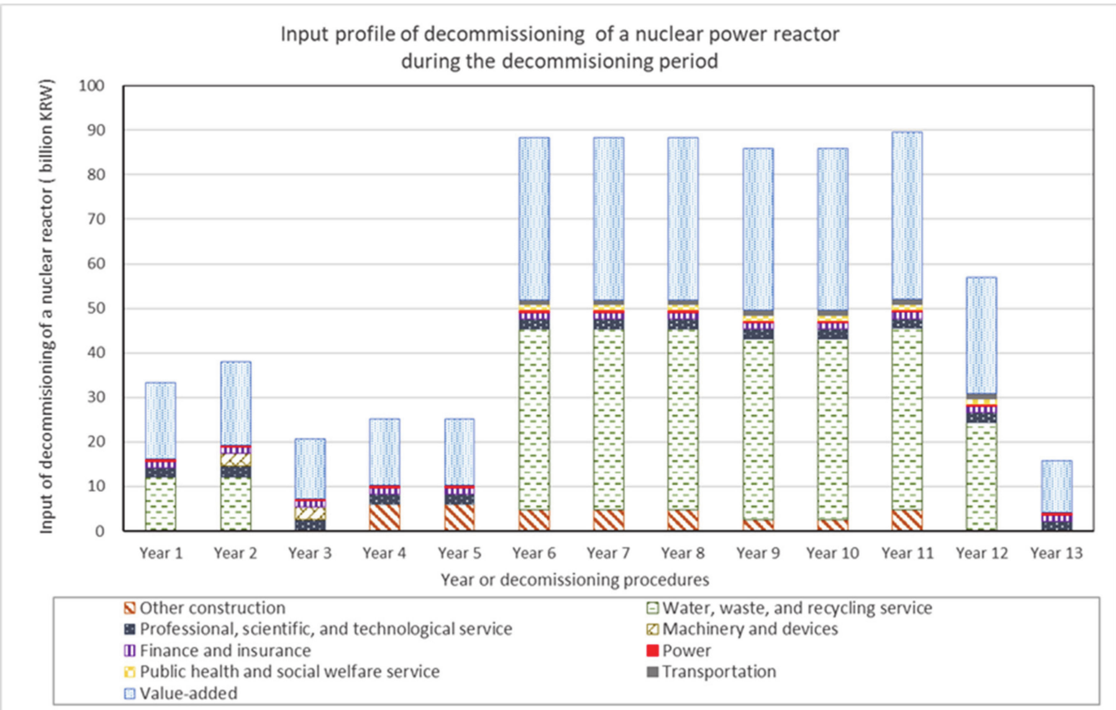

Figure 2. Input profile of decommissioning of a nuclear power reactor during the decommissioning period.

With consideration of the temporal input profiles and the nuclear fleet facing decommissioning, this study analyzed variations in the impact of nuclear power generation and nuclear decommissioning on outputs and value added. To analyze the impact on the domestic economy, this study used the input-output model that was developed by Leontief in 1936. The equations in Miller and Blair [31] were modified as follows. This study used a domestic transaction table that did not include imported goods. The following set of equations (Equation (1)) describes the interindustry flows of the produced output in the IO table. The total produced output (x_i) is distributed as final demand (f_i^d) and intermediate inputs ($a_{ii}^d x_i$). The intermediate inputs are used at a fixed proportion to total output, called technical input coefficients (a_{ii}^d). In this study, the number of sectors (n) is 35, so this system of equations consists of 35 equations. It can be simply stated in matrix algebra notation (Equation (2)), where X is a 35×1 vector of sectoral output (x_i), A^d is a 35×35 matrix of technical input coefficients (a_{ii}^d), and f^d is a 35×1 vector of sectoral final demand (f_i^d). When $\left(I - A^d\right)$ is not singular, X can be solved as in Equation (3). This equation illustrates how much output will be required in an economy to satisfy the total domestic final demand. Equation (4) describes the amount of output induced by changes in the final demand; this is called the total output inducement. In addition, the proportion of value added to total output (A^v) is fixed, similar to the technical input coefficients. Value added can be expressed as in Equation (6). Similarly, changes in final demand induce changes in value added; this is called the value-added inducement (Equation 7).

$$\begin{aligned} x_1 &= a_{11}^d x_1 + \cdots + a_{1i}^d x_i + \cdots a_{1n}^d x_n + f_1^d \\ &\vdots \\ x_i &= a_{i1}^d x_1 + \cdots + a_{ii}^d x_i + \cdots a_{in}^d x_n + f_i^d \\ &\vdots \\ x_n &= a_{n1}^d x_1 + \cdots + a_{ni}^d x_i + \cdots a_{nn}^d x_n + f_n^d \end{aligned} \tag{1}$$

$$x = A^d x + f^d \tag{2}$$

$$x = \left(I - A^d\right)^{-1} f^d \tag{3}$$

$$\Delta x = \left(I - A^d\right)^{-1} \Delta f^d \tag{4}$$

$$v = \hat{A}^v x \tag{5}$$

$$v = \hat{A}^v \left(I - A^d\right)^{-1} f^d \tag{6}$$

$$\Delta v = \hat{A}^v \left(I - A^d\right)^{-1} \Delta f^d \tag{7}$$

Additionally, the induced impacts of renewable energy deployment were analyzed based on the forecasted energy mix through 2050. This study estimated the annual energy mix until 2030 by interpolating the 2018 energy mix and the 2030 target provided by the 8th Electricity Supply and Demand Basic Plan [11] (see Table 3). Then, this study estimated the annual energy mix from 2031 to 2050 based on the following assumptions: 1) the policy orientations for nuclear phaseout will be kept; 2) the capacity factor of nuclear power plants will be the same beyond 2030; 3) the share of coal power plants will remain as it would be in 2030; and 4) new and renewable energy will be expanded to meet the electricity demand. The share of new and renewable energy will reach 30.5%, an increase from 20.0% in 2020, while the share of nuclear power is assumed to decrease to 13.4%. In addition to the changes in the shares of nuclear and renewable energy, this study considered their economic impact.

Table 3. Summary of electricity demand and energy mix.

Targeted Electricity Demand (TWh)							
2017	507.0						
2030	579.5						
The Share of Electricity to the Total Electricity Generation (%)							
	Nuclear	Coal	LNG	New & renewable	Oil	Pumped storage	Total
2017	30.3	45.4	16.9	6.2	0.6	0.7	100
2030	23.9	36.1	18.8	20.0	0.3	0.8	100

5. Results

5.1. Economic Impacts of Nuclear Power Industry Sectors

Figure 3 presents and compares the value of the total inducement coefficients and sectoral inducement effects on nuclear power industry sectors through graphs, where nodes are individual sectors. In the graphs, links describe how much output, value added, and employment are induced by a 1 unit increase in final demand for nuclear power industry sectors; the link width varies with the inducement effects. The length of links does not have any implication; rather, it is determined by the algorithm in order to better visualize the structure of the network.

The total inducement coefficients illustrate how much output, value added, and employment are induced in an economy to meet a unit increase in final demand for a certain sector [31]. Of the three sectors of the nuclear power industry, increased final demands for nuclear power construction lead to the largest output effect on the South Korean economy (2.2595). A unit increase in final demand for nuclear power construction induces the largest output in electric and electronic devices (Sector ID 12), followed by primary metal products (Sector ID 9) and metal products (Sector ID 10), which are used as machinery and devices for nuclear power plants.

The total output inducement coefficients of nuclear decommissioning are less than those of the nuclear power construction sector alone. The sectoral output effects are also quite different from those of nuclear power construction. A unit increase of final demand for nuclear decommissioning induces the largest output in water, waste, and recycling services (Sector ID 20) because decommissioning consists of decontamination, dismantling, and radioactive waste treatment.

While the total output inducement coefficient of the increased final demand was larger for the nuclear construction sector, the value-added and employment inducement coefficients show quite different results. The total value added induced by a unit increase of final demand is the largest for nuclear decommissioning (0.8793), followed by nuclear power construction (0.7175) and nuclear generation (0.6953). Among sectors, the value added induced by the increased final demand for nuclear decommissioning is the largest in water, waste, and recycling services (Sector ID 20), but the final demands for other nuclear industry sectors induce much less value added in that sector.

Total employment inducement is most significant for nuclear decommissioning (13.1483 persons/thousand USD), followed by nuclear generation (10.6551 persons/thousand USD) and construction (4.8779 persons/thousand USD). Sectoral inducement impacts across the nuclear industry sectors are generally more substantial in professional, scientific, and technological services (Sector ID 30), business supporting services (Sector ID 31), finance and insurance (Sector ID 28), wholesale and retail (Sector ID 24), and transportation (Sector ID 25). Larger employment is induced in professional, scientific, and technological services (Sector ID 30) to satisfy the additional demand for nuclear power construction and decommissioning, beyond that needed for nuclear generation. In addition, employment induced by the increased final demand for decommissioning is much larger in water, waste, and recycling services (Sector ID 20) than in other nuclear industry sectors (detailed values of sectoral output, value-added, and employment inducements can be found in Table A3).

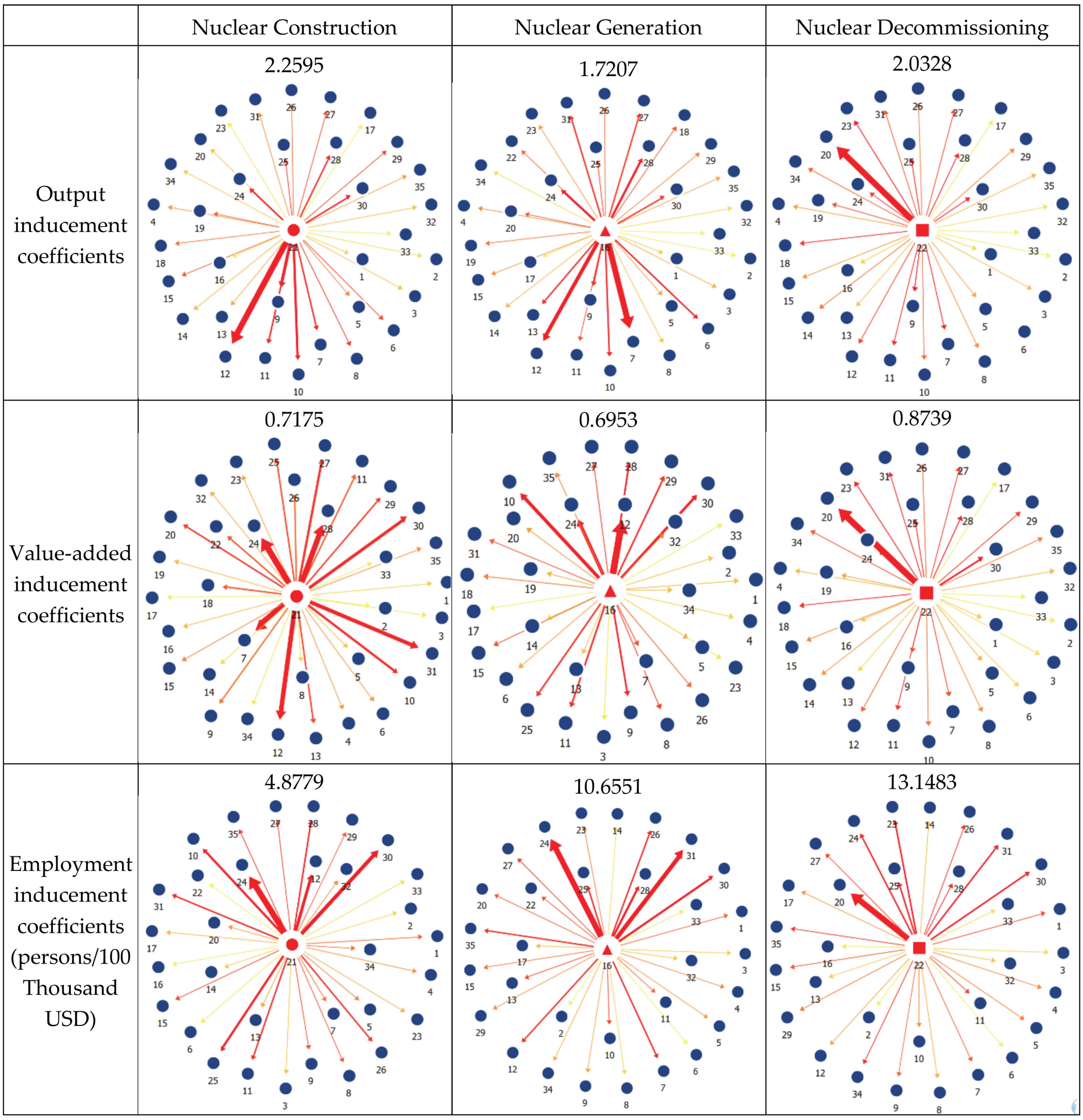

Figure 3. Output, value-added, and employment inducement coefficients by nuclear power industry sector. (Note: Node numbers nodes refer to sectoral IDs. The links illustrate the relative effects of a unit increase of final demand for nuclear power industry sectors. The links are differentiated by width and color: when the increased final demand has a stronger effect, the link is thicker and bright red-colored.).

5.2. Temporal Changes in the Impact of Nuclear Phaseout

Considering the input profile of decommissioning nuclear power reactors during this period (Figure 2) and the planned schedule of closing down nuclear power reactors (Figure 1), this study estimated temporal changes in the economic impacts of nuclear decommissioning and presents results for every 5 years from 2025 to 2050. The total output inducement effects vary with the number of reactors under decommissioning and the progression of the decommissioning process (see Figure 4). Based on the larger number of reactors being decommissioned, the total induced output increases up to 2035, then decreases to 2045, and finally increases slightly afterwards. The temporal variance in the total output inducement is closely related to the number of nuclear power reactors under decommissioning and the stage and corresponding input profile of nuclear power plants under decommissioning. Again, when more nuclear power reactors are in the 6th to 11th year of the decommissioning process (see Figure 2), a larger output will be induced.

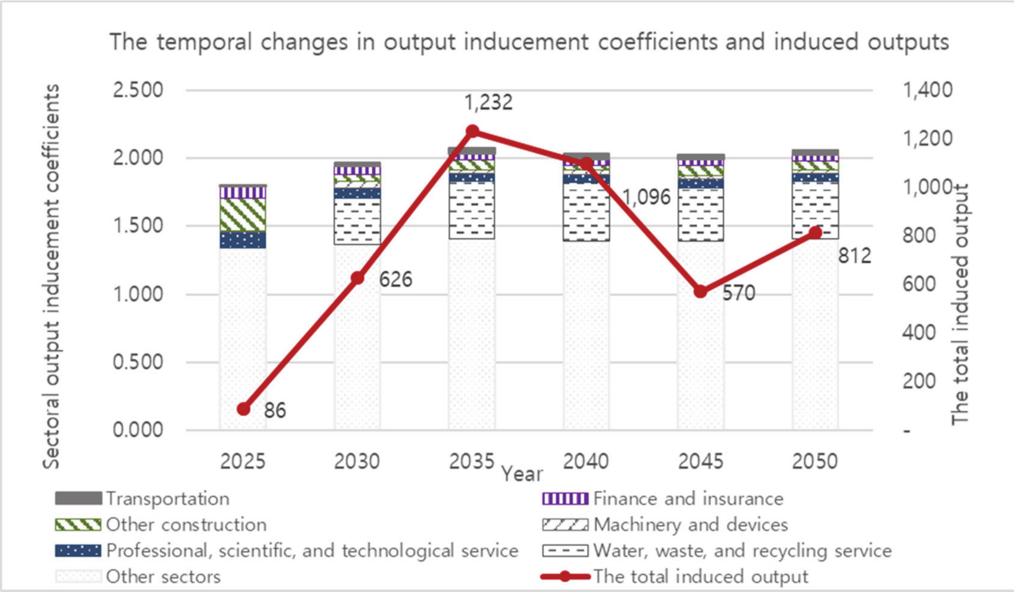

Figure 4. The total and sectoral output inducement coefficients of nuclear decommissioning. (Note: This figure presents the sectoral output inducement coefficients of some industries that have larger effects. The effect on industries beyond these six sectors is combined into "Other sectors.").

The sectoral output inducement effects are different across the analysis period. Initially, nuclear phaseout has the largest influence on other construction (Sector ID 23), followed by professional, scientific, and technological services (Sector ID 30). As dismantling begins and nuclear waste is delivered from the reactors to treatment facilities, the output inducement effect on water, waste, and recycling services (Sector ID 20) becomes the largest and the effect on transportation (Sector ID 25) becomes relatively larger.

Similar patterns are found in the temporal changes to value-added inducement coefficients, as presented in Figure 5. Although the total value-added inducement coefficients slightly decrease, the total induced value added increases significantly by 2035, then decreases to 2045, and finally increases slightly afterwards. In 2025, nuclear decommissioning has a larger effect on professional, scientific, and technological services (Sector ID 30), which are related to tasks at the initial stage of decommissioning, such as designing volume reduction facilities and R&D. The value-added effect on this sector becomes smaller and remains relatively constant as dismantling progresses and these engineering tasks reach a certain level. The value-added inducement effect on water, waste, and recycling services (Sector ID 20) is large after the 2030s, as the dismantling process progresses.

Figure 6 presents the economic impact of energy transition, with a focus on temporal changes in nuclear decommissioning, nuclear power construction, and renewable energy expansion. The total induced output of the nuclear energy industry decreases from about USD 14.3 billion in 2025 to USD 8.1 billion in 2050 because the effect of nuclear power generation exceeds that of nuclear decommissioning even with the rapid increase in the total inducement output of nuclear decommissioning by 2035, as presented in Figure 4. The total induced value added of the nuclear energy industry shows a similar pattern of continuous decrease from USD 5.8 billion in 2025 to USD 3.3 billion in 2050. Simultaneously, the total induced output of renewable energy deployment continuously increases from about USD 16.0 billion in 2025 to USD 37.0 billion in 2050; its scale is larger than that of the nuclear industry.

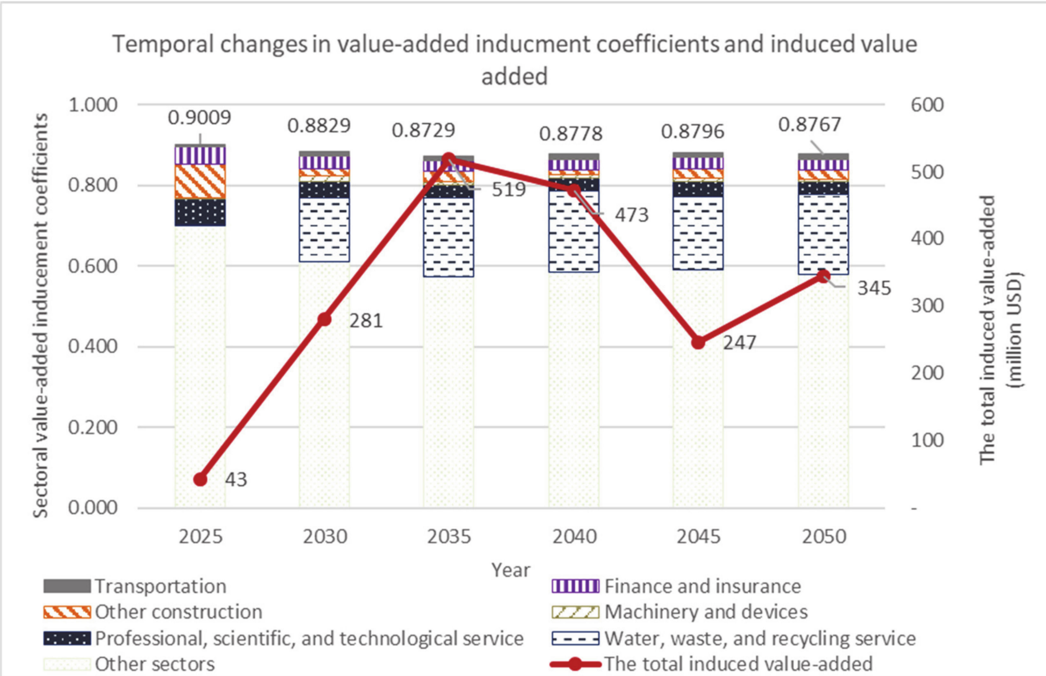

Figure 5. The total and sectoral value-added inducement coefficients of nuclear decommissioning. (Note: This figure presents the sectoral output inducement coefficients of some industries that have larger effects. The effect on industries beyond these six sectors is combined into "Other sectors.").

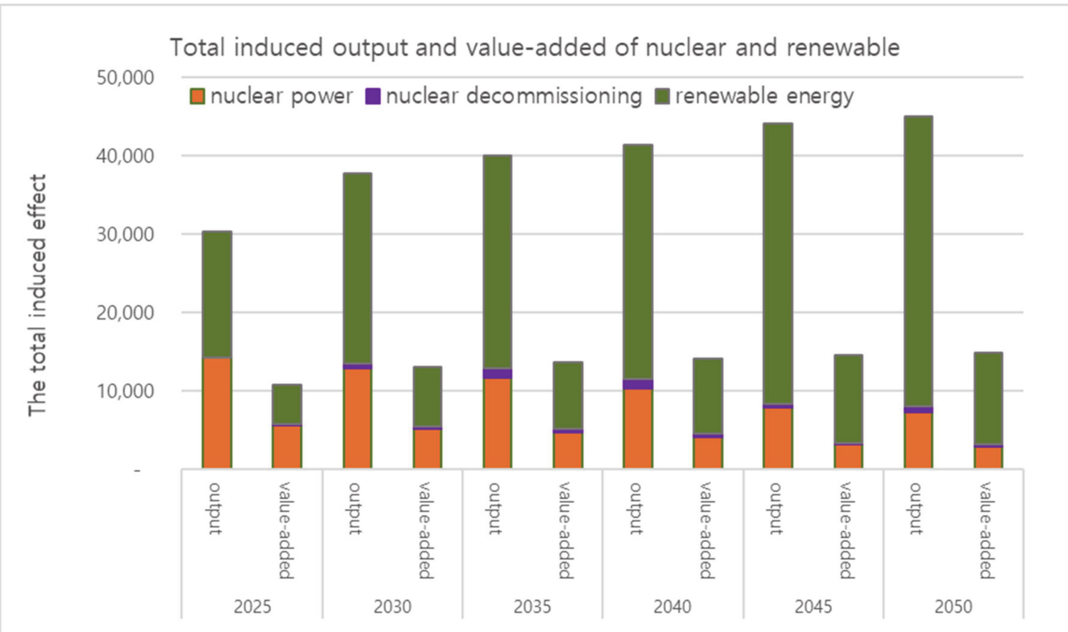

Figure 6. Total induced output and value added of nuclear phaseout and renewable power promotion. (Note: Because no more nuclear power reactors will be built, the nuclear power construction sector was not included.).

5.3. Discussion

This study used input-output analysis to trace changes in the structure of the nuclear industry during the progression of nuclear phaseout in South Korea and the economic impacts of those changes. The nuclear phaseout has temporally different impacts on industries and the economy.

Even with increases in output and value added from nuclear decommissioning, as seen in Figure 6, the overall decreases in economic impacts from nuclear phaseout are much more noticeable. As Bretschger, Ramer and Zhang [27] pointed out, positive effects of nuclear phaseout, such as the promotion of renewable energy, could offset the decreased output or value added resulting from changes in the Swiss nuclear industry. These decreases could be harsh on regions near the nuclear power plants, as found in one Spanish study [3]. No transition to a new system is easy, because society, economics, and technologies have been shaped around the existing energy system. In particular, Seto, et al. [32] pointed out that existing infrastructure, such as roads and power plants, which last for decades, lead to significant greenhouse gas emissions. Institutions also sustain these so-called locked-in effects [33]. Unless these locked-in effects are untangled effectively, the shift to a safe and environmentally friendly energy system can be delayed. In addition, the economic impact of nuclear phaseout depends on related institutional arrangements [28].

To tackle the locked-in effects, government policy measures that support a soft landing for nuclear industry sectors and relevant stakeholders are significant. For Korea, although the effects look positive in terms of the whole economy, there is a clear divide between the winner (the renewable sector) and the loser (the nuclear industry). Without proper policy measures that account for job losses and adverse impacts on relevant industries, the energy transition will be challenged.

In addition, the economic impacts of nuclear phaseout will unfold differently over time. Initially, the largest output inducement would be for the other construction sector. As dismantling begins, the water, waste, and recycling services sector would increase quickly. To facilitate this shift, relevant techniques and technologies should be developed in South Korea—for example, cutting and demolition technologies, remote and robotic operation technologies, and site remediation techniques [34]. Securing this domestic technology will also have positive economic impacts.

South Korea has not yet experienced the decommissioning of a commercial-scale nuclear power plant, and 10 of the 38 technologies required for decommissioning nuclear power plants have not yet been developed. The government aims to develop these technologies by 2021 [35]. Together with technology development, demands for human resources related to nuclear decommissioning are expected to grow. The government needs to proactively support training programs for skilled personnel and promote enhanced curriculum at universities.

With the recognition of this issue, the 3rd Energy Basic Plan [10] includes new content regarding strategies to enable a soft landing for nuclear industry sectors. It incorporates measures to support the nuclear construction and generation sectors, with a focus on nuclear power plant export and safety management. The plan also incorporates basic orientations to support technology development and the development of human resources in the decommissioning sector. To proceed with decommissioning as planned, problems such as the construction of interim and final storage facilities need to be solved. Interim storage is being constructed on-site where nuclear power reactor fleets are located, and their cost is lower than that of final storage facilities. However, residents' concerns about the addition of interim storage facilities could delay the process [36], which could then increase the cost of decommissioning [37]. Therefore, the South Korean government needs to delve into the issues by communicating with local residents and sharing the relevant information in a transparent manner.

6. Conclusions

This study compared the economic impacts of three nuclear industry sectors: generation, construction, and decommissioning. It also used input-output analysis to trace changes in the structure of the nuclear industry and its economic impact during the progression of nuclear phaseout in South Korea using input-output analysis.

This study found that the implementation of nuclear phaseout leads to a decrease in the economic impacts of nuclear industry sectors in South Korea. At the level of the whole economy, these economic effects can be offset by the deployment of renewable energy. The clear divide between nuclear and renewable energy industries, however, could inhibit expedited progress towards energy transition. In addition, the impacts on individual sectors are temporally different based on the number of reactors under decommissioning at any point of time, and the expenditure profile of nuclear decommissioning changes during its progression.

This divide between the energy industries and the temporally different economic impacts call for appropriate policy measures. First, the government needs to provide appropriate support for a soft landing of nuclear industry sectors and related stakeholders, and to base that support on the temporally different impacts of nuclear phaseout. Second, the techniques and technologies required for decommissioning need to be developed in a timely manner that takes into account the temporally different impacts of nuclear phaseout. Third, public acceptance is pivotal to facilitating this shift, so transparency needs to be pursued in communication with residents and stakeholders.

This study investigated the impact of nuclear phaseout based on an empirical survey of input structure; however, it has some limitations. The decrease in the nuclear industry may have an adverse effect on exports in the long term; in turn, it is likely to influence the domestic economy. Because the priority of this study was to investigate the effect of structural changes in nuclear industry sectors under South Korea's energy transition policy, the effect of diminished exports was not included. In addition, technological developments during the process of nuclear phaseout may change the total expense of decommissioning per reactor unit and the input profile. However, this study did not delve into that decrease in costs because the data were unavailable.

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Appendix A

The appendix specifies the profile of nuclear decommissioning by sector and the allocation of the decommissioning cost items in the IO table. As presented in Table A1, decontamination and dismantling accounts for about 30% of the total decommissioning cost. According to the Korean Standard Industry Classification (KSIC), the decontamination and dismantling of a structure is classified as construction, while that of devices and systems is categorized as water, waste, and recycling services. The cost for decontamination and dismantling of structures was 85% of the total, with devices and systems accounting for the remaining 15%. The reserve is the cost that would be incurred if additional radioactive waste were generated due to unexpected events. This cost was driven by estimating the additional costs for treatment, community support, and transport, assuming 30% of the waste generated was in this category.

This study used KRW 751.5 billion, the reserve cost for nuclear decommissioning that was recently announced by the Ministry of Trade, Industry, and Energy (MOTIE), as the total decommissioning cost of a nuclear reactor. It allocated the costs with consideration of the cost profile of relevant sectors in the IO table and derived the input structure shown in Table A2.

Table A1. The profile of nuclear decommissioning by task.

Category	Cost items		Share of Costs (%)
Containment and dismantling	Decommissioning project cost	Labor	16.6
		Dismantling	21.1
		Decontamination	8.7
	Volume reduction facility [a)]	Construction	2.5
		Facility establishment	1.2
		Decommissioning	0.5
		Design	0.2
	Others	Insurance	4.0
		Regulation compliance	3.7
		R&D	1.1
		Utility	1.4
Treatment of radioactive waste		Treatment	27.4
		Community support [b)]	1.4
		Transport	1.2
		Reserve	9.0
Total			100.0

Note: [a)] Generally, six nuclear power reactors can use a single volume reduction facility. To determine the portion of the decommissioning cost of one nuclear reactor, the cost of one volume reduction facility was divided by six and that proportion of the estimated cost was allocated. [b)] According to the Special Act on Assistance to the Locations of Facilities for Disposal of Low and Intermediate Level Radioactive Waste, a certain amount of money per drum of radioactive waste should be used for community support.

Table A2. Allocation of the decommissioning cost items to corresponding IO sectors and estimated costs.

Unit: billion KRW		
Cost items	Corresponding sectors in IO sectors	Estimated costs
Decommissioning labor	Nuclear decommissioning	124.6
Structure decontamination and dismantling	Construction	33.6
Devices, systems decontamination, and dismantling	Water, waste, and recycling services	190.6
Volume reduction facility construction and decommissioning	Construction	22.7
Volume reduction facility design	Professional, scientific, and technological services	1.4
Volume reduction facility establishment	Machinery and devices	8.4
Insurance	Finance and insurance	30.1
R&D	Professional, scientific, and technological services	35.9
Utility	Electricity	10.8
Radioactive waste treatment	Water, waste, and recycling services	267.7
Community support	Public health and social welfare services	14.0
Transport	Transportation	11.7
Total		751.5

Decommissioning takes time. In the case of Kori-1, it is expected to take 15.5 years. Other decommissionings will take less time because Kori-1 is the first decommissioning of a commercial-scale nuclear power plant. This study assumes that the decommissioning of a standard nuclear power plant will take 13 years (safety management for 5 years, dismantling for 6 years, and site restoration for 2 years). In addition, because the total decommissioning cost of KRW 751.5 billion is a consumer price, we adjusted from consumer prices to basic prices by excluding the wholesale and retail profit and net production taxes.

Table A3. Output, value added, and employment inducements of three nuclear industry sectors.

	Output inducement			**Value added inducement**			**Employment inducement(Unit: persons/100 million KRW)**		
	Construction	**Generation**	**Decommissioning**	**Construction**	**Generation**	**Decommissioning**	**Construction**	**Generation**	**Decommissioning**
Agriculture, forestry, and fishery	0.0036	0.0028	0.0029	0.0016	0.0020	0.0016	0.0886	0.0701	0.0725
Mining	0.0034	0.0006	0.0011	0.0003	0.0019	0.0006	0.0108	0.0018	0.0034
Food, beverage, and tobacco	0.0063	0.0059	0.0057	0.0009	0.0010	0.0009	0.0189	0.0177	0.0169
Textile and leather	0.0078	0.0103	0.0088	0.0024	0.0018	0.0020	0.0344	0.0456	0.0389
Timber, paper, printing and copy	0.0113	0.0068	0.0087	0.0018	0.0031	0.0023	0.0547	0.0326	0.0417
Coal and petroleum	0.0371	0.0374	0.0239	0.0024	0.0024	0.0015	0.0031	0.0031	0.0019
Chemicals	0.0545	0.1382	0.0419	0.0273	0.0108	0.0081	0.0762	0.1929	0.0581
Non-metal products	0.0403	0.0043	0.0110	0.0012	0.0112	0.0030	0.1004	0.0108	0.0274
Primary metal products	0.1501	0.0326	0.0529	0.0045	0.0206	0.0072	0.1252	0.0271	0.0440
Metal products	0.1380	0.0370	0.0151	0.0112	0.0420	0.0045	0.3561	0.0952	0.0386
Machinery and devices	0.0706	0.0195	0.0314	0.0056	0.0201	0.0087	0.2378	0.0657	0.1054
Electric and electronic devices	0.3320	0.0815	0.0191	0.0223	0.0908	0.0052	0.5385	0.1321	0.0307
Precision devices	0.0066	0.0264	0.0053	0.0076	0.0019	0.0015	0.0238	0.0951	0.0188
Transportation equipment	0.0065	0.0054	0.0132	0.0012	0.0014	0.0029	0.0127	0.0107	0.0258
Other products	0.0179	0.0091	0.0095	0.0039	0.0076	0.0039	0.1270	0.0645	0.0667
Nuclear power generation	0.0029	1.0041	0.0042	0.0019	0.0013	0.0019	0.0024	0.8343	0.0035
Renewable power	0.0008	0.0014	0.0018	0.0004	0.0002	0.0005			
Fossil fuel-fired power	0.0126	0.0183	0.0294	0.0064	0.0044	0.0101	0.0205	0.0224	0.0343
Other power	0.0139	0.0116	0.0171	0.0019	0.0022	0.0027			
Water, waste, and recycling services	0.0063	0.0174	0.4312	0.0081	0.0029	0.1958	0.0301	0.0835	2.0661
Nuclear power construction	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	4.6459	0.0000	0.0000
Nuclear decommissioning	0.0000	0.0139	1.0001	0.0064	0.0000	0.0000	0.0003	0.0921	6.6483
Other construction	0.0029	0.0068	0.0504	0.0023	0.0010	0.0172	0.0233	0.0553	0.4107
Wholesale and retail	0.0855	0.0562	0.0276	0.0285	0.0433	0.0138	1.1991	0.7864	0.3837
Transportation	0.0394	0.0199	0.0359	0.0071	0.0141	0.0125	0.4279	0.2158	0.3878
Restaurant and accommodation	0.0134	0.0124	0.0121	0.0047	0.0050	0.0046	0.2273	0.2109	0.2042
ICT and broadcasting	0.0254	0.0204	0.0188	0.0090	0.0111	0.0084	0.1406	0.1130	0.1034
Finance and insurance	0.0489	0.0491	0.0485	0.0261	0.0260	0.0252	0.2630	0.2642	0.2601
Real estate and rental	0.0259	0.0108	0.0115	0.0080	0.0193	0.0085	0.0946	0.0394	0.0419
Professional, scientific, and technological service	0.0674	0.0235	0.0502	0.0133	0.0384	0.0328	0.7296	0.2528	0.5419
Business supporting services	0.0103	0.0259	0.0166	0.0174	0.0069	0.0110	0.2483	0.6239	0.3974
Public administration and national defense	0.0063	0.0027	0.0028	0.0020	0.0047	0.0020	0.0498	0.0214	0.0216
Educational services	0.0004	0.0005	0.0003	0.0004	0.0003	0.0002	0.0055	0.0076	0.0041
Public health and social welfare services	0.0040	0.0017	0.0154	0.0009	0.0020	0.0058	0.0576	0.0247	0.2213
Culture and other services	0.0075	0.0062	0.0086	0.0031	0.0037	0.0042	0.1418	0.1184	0.1618
Total	2.2595	1.7207	2.0328	0.2420	0.4054	0.4111	10.1159	4.6311	12.4830

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