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Impact and Challenges of Reducing Petroleum Consumption for Decarbonization

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Abstract: This study aimed to identify the impact of achieving the 1.5 °C target on the petroleum supply chain in Japan, and discuss the feasibility and challenges of decarbonization. First, a national material flow was established for the petroleum supply chain in Japan, including processes for crude petroleum refining, petroleum product manufacturing, plastic resin and product manufacturing, and by-product manufacturing. In particular, by-product manufacturing processes, such as hydrogen, gaseous carbon dioxide, and sulfur, were selected because they are utilized in other industries. Next, the outlook for the production of plastic resin, hydrogen, dry ice produced from carbon dioxide gas, and sulfur until 2050 was estimated for reducing petroleum consumption required to achieve the 1.5 °C target. As a result, national petroleum treatment is expected to reduce from 177,048.00 thousand kl in 2019 to 126,643.00 thousand kl in 2030 if the reduction in petroleum consumption is established. Along with this decrease, plastic resin production is expected to decrease from 10,500.00 thousand ton in 2019 to 7511.00 thousand ton by 2030. Conversely, the plastic market is expected to grow steadily, and the estimated plastic resin production in 2030 is expected to be 20,079.00 thousand ton. This result indicates that there is a large output gap between plastic supply and demand. To mitigate this gap, strongly promoting the recycling of waste plastics and making the price competitiveness of biomass plastics equal to that of petroleum-derived plastics are necessary.

Keywords: decarbonization; 1.5 °C target; petroleum consumption; plastics; by-products of petroleum refinery

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1. Introduction

The Paris Agreement is an international framework that focuses on reducing greenhouse gas emissions after 2020 and making efforts to limit the temperature rise from the Industrial Revolution to 2100 to less than 2 °C and to 1.5 °C [1]. The Glasgow Agreement was adopted at the 26th session of the Conference of the Parties (COP26) held in the United Kingdom in 2021. This agreement states that all countries should pursue efforts to restrict the temperature rise from before the Industrial Revolution to within 1.5 °C, while gradually reducing coal-fired power plants [2]. The background to the promotion of the "1.5 °C target" is a special report published by the Intergovernmental Panel on Climate Change (IPCC) [3] in 2018. The report states that curbing global warming to 1.5 °C can be achieved with global goals other than climate change, such as achieving sustainable development, and eradicating poverty [3]. This report also states that CO_2 emissions should be reduced by 45% by 2030 and reach net zero by 2050 to achieve this goal [3]. Based on this trend, the Japanese government has claimed that it will set a national goal of achieving carbon neutrality by 2050 [4]. According to the IPCC's AR5 WG1 report, 65.3% of the world's CO_2 emissions, as of 2010, came from fossil fuels [5]. Considering this situation, reducing fossil fuel consumption for achieving the 1.5 °C target is inevitable. From this perspective, the trend of fossil fuel reduction is rapidly progressing worldwide.

As examples of efforts to reduce fossil fuel consumption, divestment of fossil fuels such as petroleum and coal has been actively increasing from the perspectives of environmental, social, and governance investment. The international initiative "RE100" aims to cover 100% of the power consumption related to product manufacturing and business operations with renewable energy, with more than 300 companies participating [6]. Focusing on plastics, the European Union (EU) suggests the increased use of recycled plastics in its circular economy action plan [7]. The EU also applied the "Directive on single-use plastics" from July 2021, which stipulates the prohibition of the distribution of disposable plastic products such as straws and forks [8]. In Japan, the "Plastic Resource Circulation Act," which stipulates the reduction of disposable plastic product usage and the promotion of recycling of waste plastics, is scheduled to be enforced in April 2022 [9].

Welsby et al. [10] indicated that petroleum and fossil methane gas reserves and coal reserves of 60% and 90%, respectively, in 2050 will achieve the 1.5 °C target. They also argue that petroleum and fossil methane gas production needs to be reduced by 3% annually by 2050 to achieve the 1.5 °C target [10]. Many countries, such as Japan, have not clearly announced specific measures to reduce fossil fuel consumption to achieve the 1.5 °C target. However, they recognized the extreme fossil fuel reductions established by Welsby et al. [10] for achieving the 1.5 °C target. This indicates that the current socioeconomic system must be transformed.

Conversely, fossil-fuel-based industry relates to broad industries such as fuels, plastic products, fertilizers, and pharmaceuticals, and has a complicated supply chain structure. By-products, such as carbon dioxide gas and sulfur produced by petroleum refining, are also used as raw materials in other industries. For example, dry ice, which is used for maintaining low temperature when transporting refrigerated products and pharmaceuticals such as COVID-19 vaccines, is produced using carbon dioxide gas. Gaseous carbon dioxide is a by-product of petroleum refining. Quickly reducing fossil fuel consumption may affect society and the economy. Hence, rapidly proceeding with efforts to achieve the 1.5 °C target is important.

This study aims to clarify how a reduction in petroleum consumption in Japan would affect the domestic supply chain. First, the processes related to petroleum refining are organized as a material flow. Next, based on the reduction rate of Welsby et al. [10], the outlook of domestic petroleum treatment, petroleum products, and by-products required to achieve the 1.5 °C target is estimated. Then, we discuss whether there is an output gap by comparing these results with demand. This study shows the impact and challenges of reducing petroleum consumption on the Japanese petroleum supply chain. The study also intends to provide an impetus for government policymakers to consider ways to achieve the 1.5 °C target from economic and social perspectives and to examine and mitigate the obstacles to achieving the target.

Various studies discuss the social system that contributes toward achieving the Paris Agreement and the 1.5 °C target. For example, in studies focusing on energy system transformation, Liu et al. [11] indicated that CO_2 emissions by sectors such as industry, electricity, and transportation in China in 2050 increased by 81% compared to 2015 levels. They argued that to reduce CO_2 emissions, an annual acceleration rate of 2.1% is necessary to retain the temperature rise below 2 °C. Davis et al. [12] indicated that a renewable energy-based energy mix from fossil fuels can reduce greenhouse gas emissions in 2050 from 2005 levels to 90% in the case of electricity production in Alberta, Canada. Tina and Nicolosi [13] analyzed the impact of climate change on the current and future Italian electricity system. Mekonnen et al. [14] analyzed the impact of climate-change-related droughts on hydropower. Rosa and Castro [15] simulated the energy mix in Australia's electricity system for 2030. They indicated that while wind and solar energy contribute significantly to the national electricity market, more than 50% of the electricity system continues to depend on fossil fuels.

Considering studies focusing on the viewpoint of transportation, Arioli et al. [16] analyzed the path to meeting the 1.5 °C target for emerging economies and showed that achieving this requires dramatic changes in travel patterns, technology, and fuels, as well as significant enhancements to current policy approaches. Bhat and Garcia [17] examined the EU's intra-carbon emissions associated with diesel and gasoline consumption to meet road transport requirements. They argued that without significant reductions in diesel and gasoline carbon emissions, climate change targets would not be achieved. In addition, many analyses of the effects of climate change measures through the promotion of electrification of vehicles and other measures such as decarbonization in automobiles have been conducted [18–20]. Al-Enazi et al. [21] conducted a review to examine the feasibility and environmental aspects of alternative fuels to heavy fuel oil in maritime transportation.

Considering studies focusing on the viewpoint of impacts of climate change in cities and countries, Nishiura et al. [22] estimated the economic impact of achieving the 1.5 °C target in Asian countries and mitigating the economic impact of reducing greenhouse gas emissions. Alabsi et al. [23] proposed a sustainability index to evaluate climate change impacts and the effectiveness of adaptation in traditional West Asian cities. Liu et al. [24] analyzed the impact of urban sprawl on carbon emissions per capita in China. Pai et al. [25] indicated that the energy source shifts from fossil fuels to renewables to restrict temperature rise below 2 °C reduces employment in the fossil fuel industries while creating more employment in the renewables industry. Riedl [26] analyzed corporate cash flows using petroleum majors as an example. The author criticized the fact that investors still measure corporate value by operating profit margin and petroleum price against the importance of responding to climate policies for achieving the 1.5 °C target.

Considering studies that focus on national policy and innovation perspectives, Takeishi [27] indicated that reducing fossil fuel consumption would provide global policy coherence in determining future energy supply and demand scenarios. Akimoto [28] analyzed the current state of energy and CO_2 emissions. The author discussed the need for innovation to reduce CO_2 emissions. Conversely, Hansen [29] argued that countries where fossil fuels are dominated by state-owned enterprises might face political obstacles regarding climate movement because reduced fossil fuel consumption might result in financial losses.

Studies focusing on climate justice and fairness by Chapman et al. [30] have indicated that the conversion from fossil fuels to renewable-energy-based electricity improves social fairness in middle-income countries, but renewable energy shares are rising in high-income countries. They also indicated that low-income countries rely on fossil fuels for electricity, and the conversion rate to renewable energy is slow. Cronin et al. [31] indicated that while achieving the 1.5 °C target is essential from the perspectives of climate justice and fairness, economic disparities between the Global North and South might be encouraged. They argued that an interdisciplinary research agenda is necessary to conduct research that assists in establishing countries' contribution.

These studies have discussed the potential and challenges of converting fossil fuels to renewable energy sources. While many studies have discussed the importance of reducing production and consumption of petroleum in achieving the 1.5 °C target, there are few studies that have examined the potential economic and social impacts of achieving that target. This study considers the social and economic impact of achieving the 1.5 °C target on the petroleum industry and supply chain from the perspective of petroleum products and by-products. This study aimed to minimize the future impact of petroleum products and by-products on supply and demand.

This section describes the structure of this study. In Section 2, this is followed by data collection to create a material flow diagram for understanding the integrated process from petroleum refining to the manufacture of plastic products and by-products in Japan. The methodology is also described to estimate the production of plastic products and by-products if the 1.5 °C target is achieved, with 2030 and 2050 as milestones. In Section 3, a material flow diagram is created to show the current status of petroleum refining and plastic product and by-product production in Japan. Next, based on the results of the material flow diagram, the volume of plastic product and by-product production up to 2050 is estimated and compared with the results of demand projections to show the extent to which an output gap may exist. Based on these results, the impact of meeting the 1.5 °C target on Japan's economy and society is projected, and measures to mitigate this impact are discussed. Section 4 summarizes the above results and presents our conclusions.

2. Materials and Methods

2.1. Target Products and System Boundary of Material Flow

A material flow, focusing on the processes related to petroleum refining shown in Figure 1, was created to understand the trend of petroleum consumption in Japan. The material flow was created in 2019, when the latest materials related to the supply chain were available. In the material flow, the following three processes were focused on: (1) naphtha as petroleum products; (2) plastic products; and (3) hydrogen, carbon dioxide, and sulfur as petroleum by-products.

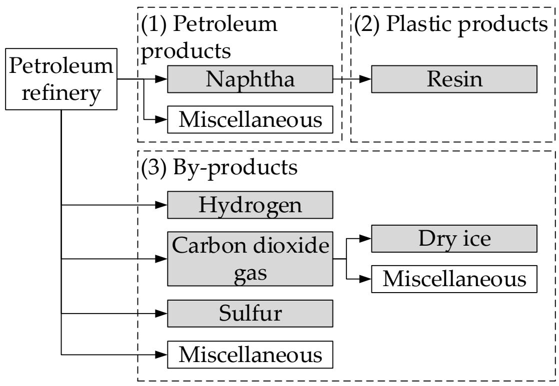

Figure 1. Processes related to petroleum refining.

In process (1) in Figure 1, petroleum products include naphtha, gasoline, jet fuel oil, kerosene, light oil, heavy oil, kerosene, asphalt, grease, paraffin, LPG, and LNG. Among these petroleum products, naphtha was selected because it is consumed as a product without being used as fuel, and it has the shortest life cycle until it becomes waste. In process (3) shown in Figure 1, hydrogen, carbon dioxide gas, and sulfur were selected because they were shipped. Hydrogen is a by-product of the catalytic reforming process. All the hydrogen generated by catalytic reforming is self-consumed to remove sulfur and nitrogen from petroleum products. However, because this alone is insufficient in terms of the amount of hydrogen produced, additional hydrogen is produced in hydrogen plants adjacent to petroleum refinery plants. Carbon dioxide gas is a by-product of petroleum refining. In this study, we focused on dry ice. One reason is that demand is rapidly increasing due to the transportation of the COVID-19 vaccine, while the shortage of raw materials is becoming more serious in Japan [32]. Sulfur is obtained through desulfurization during petroleum refining and used as a raw material for fertilizers and chemicals.

2.2. Data Collection

Data relating to the processing of petroleum products in process (1) shown in Figure 1 apply statistical data published by the Japan Agency for Natural Resources and Energy [33]. The data utilized were production, shipment, import, export, and stock. Data relating to the processing of plastic products process (2) shown in Figure 1 apply statistical data published by the Japan Plastic Waste Management Institute [34]. The utilized data were resin manufacture, plastic product manufacture and consumption, waste disposal, and recycling. Considering the data relating to by-product process (3) shown in Figure 1, there were no statistical data on hydrogen and carbon dioxide gas. Hydrogen production was applied to the survey results (14.02 billion Nm^3) of Mizuho Research & Technologies Ltd (Mizuho Research & Technologies Ltd, Tokyo, and Japan.) [35]. The annual domestic demand for dry ice is approximately 350.00 thousand ton, of which approximately 25.00 thousand ton is imported [36]. Hence, a difference of 325.00 thousand ton was set as the domestic dry ice production. The Japan Industrial and Medical Gases Association [37] states that 48.8% of domestic liquefied carbon dioxide production is derived from petroleum-refining plants. Therefore, this study assumed that the ratio of dry ice production from an oil refinery plant is equivalent to the production of liquefied carbon dioxide, which is estimated to be 157.30 thousand ton. Data relating to sulfur apply statistical data published by the Japan Ministry of Economy, Trade and Industry [38]. The data utilized concern sulfur production.

Data from the petroleum refinery to processes (1) to (3) are connected in a consistent manner to create a material flow.

2.3. Outlook of Material Flow by Meeting 1.5 °C Target

Based on the created material flow, outlook of petroleum treatment, plastic resin, and by-product production by 2050 was estimated by adopting the 3% annual petroleum production reduction rate required to achieve the 1.5 °C target [10]. These results were compared with the demand, and the social and economic impacts were discussed. Table 1 lists the material intensity coefficients of the plastic resin and the by-products. These coefficients were calculated by dividing petroleum treatment in 2019 [33] by plastic resin and by-product production in 2019 [34–38]. These coefficients were assumed to be constant until 2050.

Table 1. Material intensity coefficients of plastic resin and by-products.

Products (Unit)	Material Intensity Coefficients
Plastic resin (ton/kL)	0.59×10^{-1}
Hydrogen (Nm^3/kL)	79.19
Dry ice (ton/kL)	0.89×10^{-3}
Sulfur (ton/kL)	0.92×10^{-2}

In addition to the above target, plastic product process (2) shown in Figure 1 is discussed using the milestones in 2030, stipulated in the plastic resource recycling strategy formulated by the Japan Ministry of Environment (JMOE) [39] in 2018. These milestones set the following goals for the 3Rs (reduce, reuse, recycle) of plastics [39]:

✓ 25% reduction of disposable plastic by 2030,
✓ 60% reuse and recycling of waste plastic containers and packaging by 2030,
✓ 100% reuse and recycling of used plastics by 2035,
✓ Double the recycling of waste plastic by 2030, and
✓ Introducing 2000.00 thousand ton of biomass plastic by 2030.

3. Results and Discussion

In this section, a material flow diagram is created to understand the current status of petroleum refining and the manufacture of plastic products and by-products in Japan. This is followed by an investigation of the impact of the reduction in petroleum refining associated with the achieving of the 1.5 °C target on the demand for and supply of plastic products and by-products.

3.1. Material Flow of Petroleum-Related Processes

Figure 2 shows the material flow related to petroleum refining. Figure 3 shows the material flow from manufacturing to disposal and recycling of plastic products. The material flows shown in Figures 2 and 3 are linked. The total amount of petroleum received in 2019 was approximately 188,671.00 thousand kl. Approximately 177,048.00 thousand kl was used to manufacture petroleum products. As shown in process (1) in Figure 2, approximately 18,087.00 thousand kl of naphtha was manufactured. As shown in process (2) in Figure 3, approximately 10,500.00 thousand ton of plastic resin was manufactured, and approximately 10,110.00 thousand ton of plastic products was manufactured with imported and recycled resins. Approximately 7830.00 thousand ton of plastic products, which is approximately 83% of the consumption, was disposed of, and approximately 8510.00 thousand ton was waste plastic, including industrial loss. Approximately 1860.00 thousand ton of waste plastic, which is approximately 22% of waste plastic, was mechanically recycled, and approximately 910.00 thousand ton was returned to domestic plastic production as recycled resin. As shown in process (2) in Figure 3, approximately 1629.00 thousand ton of sulfur and approximately 157.00 thousand ton of dry ice were produced and 14.02 billion Nm^3 of hydrogen was produced, all of which was self-consumed.

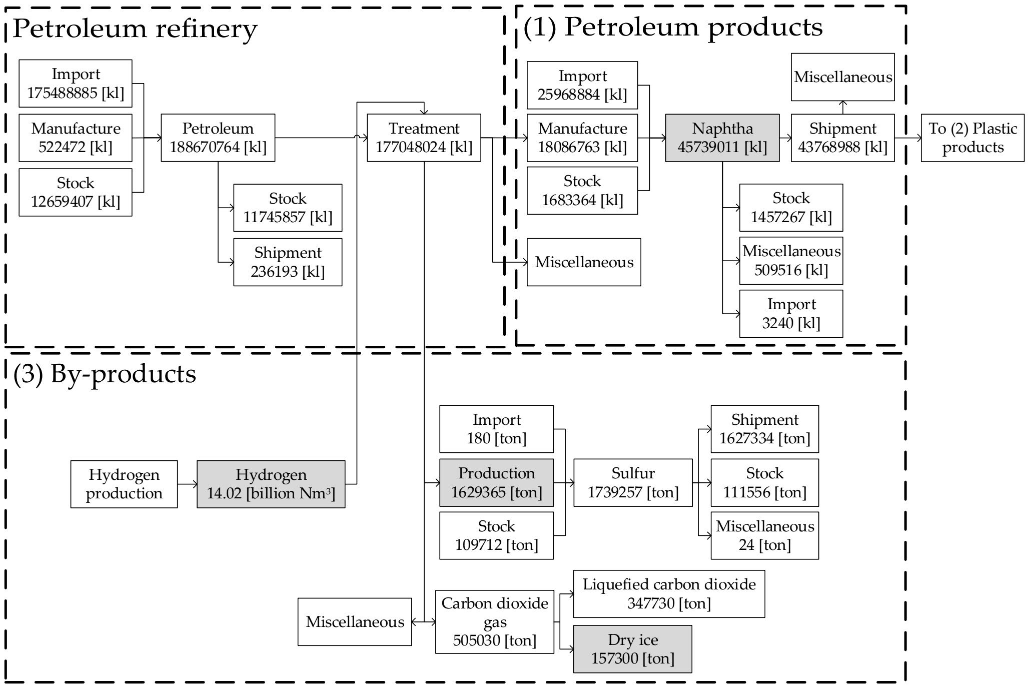

Figure 2. Material flow relating to petroleum refining.

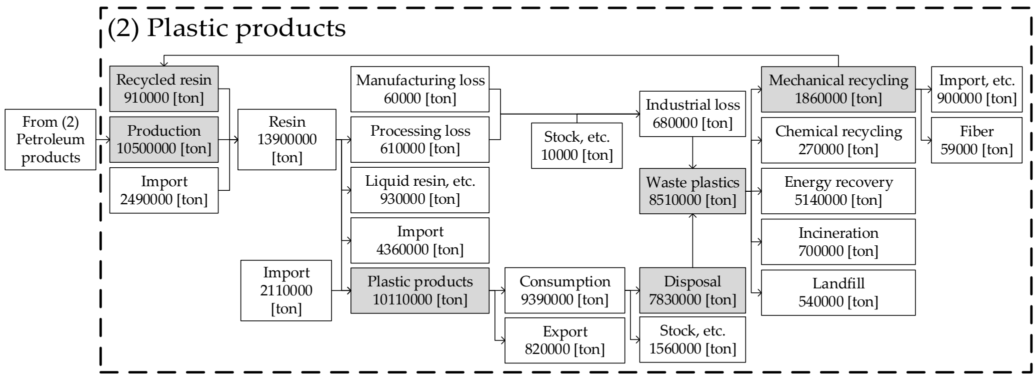

Figure 3. Material flow relating from manufacturing to disposal and recycling of plastic products.

3.2. *Outlook of Naphtha, Plastic Products, and By-Products*

Table 2 shows the estimation of the outlook for petroleum treatment, plastic resin, and by-product production from 2019 to 2050. Based on Welsby et al. [10], petroleum treatment needs to be reduced by approximately 61% from 2019 to 2050 for achieving the 1.5 °C target. Accordingly, the production of plastic resin and by-products is also expected to decrease, as shown in Table 2. In the following sections, the social and economic impacts of the reduced production of plastic resins and by-products are discussed.

Table 2. Outlook of petroleum treatment, naphtha, plastic products, and by-products.

	2019	2020	2030	2040	2050
Petroleum treatment (thousand kL)	177,048.00	171,737.00	126,643.00	93,389.00	68,868.00
Plastic resin production (thousand ton)	10,500.00	10,185.00	7511.00	5539.00	4084.00
Hydrogen production (billion Nm^3)	14.02	13.60	10.03	7.40	5.45
Hydrogen production * (billion Nm^3)	21.40	20.76	15.31	11.29	8.32
Dry ice production (thousand ton)	157.00	153.00	113.00	83.00	61.00
Sulfur production (thousand ton)	1629.00	1580.00	1165.00	859.00	634.00

* Maximum hydrogen production when the hydrogen production plant is operated.

3.2.1. Plastic Products

The plastic resin production was approximately 10,500.00 thousand ton in 2019. According to the Japan Plastic Industry Federation [40], plastic resin production has remained at the same level since 2009. This means that the domestic demand for plastic products remains high, and consumption has not been reduced. In future, the production volume should be reduced by reducing the use of disposable plastics. The global plastics market is growing steadily, with an annual growth rate of 3.4% for the projected period 2021–2028 [41]. High-performance materials such as conductive plastics are used in various high-tech products, and the demand might remain at a certain level in the future from the perspective of product weight reduction and energy saving of electronic equipment.

Figure 4 shows the outlook of the supply and demand volume of plastic resin production. The figures in Table 2 were used for the supply transition. Trends in demand were estimated assuming that the annual growth rate (3.4%) indicated above would continue until 2050. Plastic resin production is expected to reduce to approximately 7511.00 thousand ton by 2030 and approximately 4084.00 thousand ton by 2050. Conversely, the plastic resin production from petroleum refineries in 2019 was approximately 10,110.00 thousand ton from Figure 3. If the demand volume is changed at the aforementioned annual growth rate, approximately 15,168.00 thousand ton of resin production from petroleum refineries is expected to be required by 2030. In 2050, 29,602.00 thousand ton is expected to be needed. This result indicates that a large output gap might occur in the plastic resin. Japan currently relies on imports for more than half of its demand for naphtha. Covering all shortfalls of naphtha and plastic resins by imports is difficult under the international commitment to fossil fuel reduction.

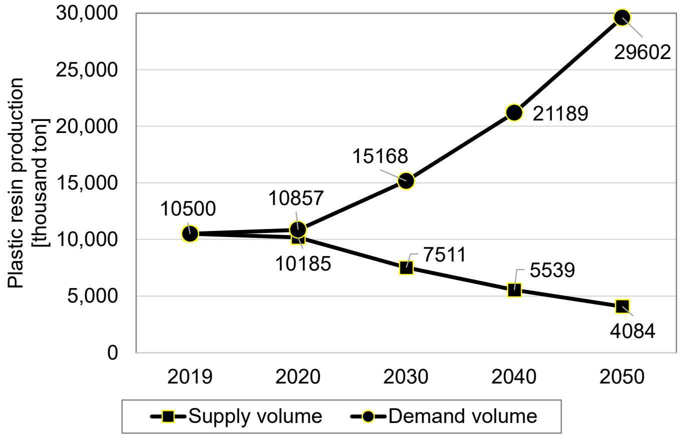

Figure 4. Outlook of supply and demand volume of plastic resin production.

3.2.2. Hydrogen

The domestic hydrogen production was approximately 14.02 billion Nm^3 in 2019, and this was fully self-consumed. If the hydrogen plant adjacent to the petroleum refinery was fully operational, hydrogen production would increase to approximately 16.16 billion Nm^3 and approximately 2.14 billion Nm^3 of the produced hydrogen might be supplied externally [35]. Hydrogen is used as a raw material for nitrogen fertilizer through the Haber process, as an energy source. The global fertilizer market is expanding and the annual growth rate for 2025 is expected to be 2.0% [42]. With the reduction in petroleum treatment, the external supply of hydrogen is expected to reduce to 1.53 billion Nm^3 in 2030 and 0.83 billion Nm^3 in 2050. These production volumes are expected to be used for the production of nitrogen fertilizers and as energy sources.

3.2.3. Dry Ice

The global plastics market is growing steadily, with an annual growth rate of 3.81% for the projected period 2016–2026 [43]. The demand for dry ice is expected to increase further, with the expansion of the food delivery market and for transportation of pharmaceuticals such as the COVID-19 vaccine. Japan currently has an output gap for dry ice, and this gap is expected to widen if the national government does not take measures. Figure 5 shows outlook of supply and demand volume of dry ice production. The figures in Table 2 were used for the supply transition. Trends in demand were estimated assuming that the annual growth rate (3.81%) indicated above would continue until 2050. Domestic dry ice production derived from petroleum by-products was approximately 157.00 thousand ton in 2019 and is expected to decrease to approximately 61.00 thousand ton in 2050. If the demand volume is changed at the aforementioned annual growth rate, approximately 237.00 thousand ton of resin production from petroleum refineries is expected to be required by 2030. In 2050, 501.00 thousand ton is expected to be needed.

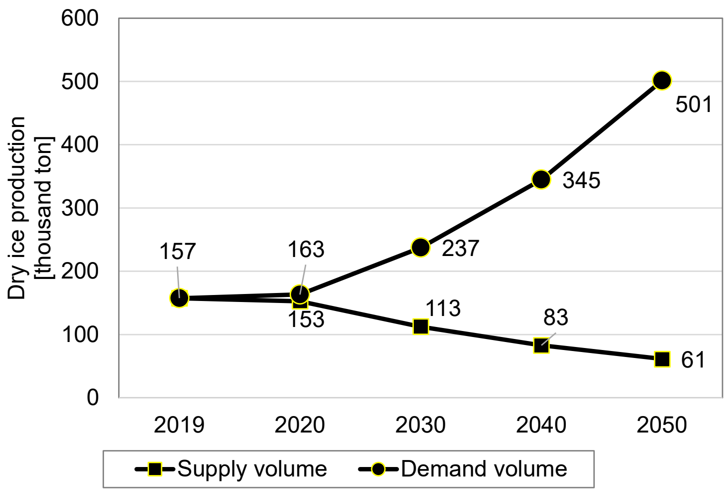

Figure 5. Outlook of supply and demand volume of plastic resin production.

3.2.4. Sulfur

Sulfur is also a raw material for fertilizers such as hydrogen, and its demand is expected to increase [42]. Figure 6 shows the outlook of the supply and demand volume of dry ice production. The figures in Table 2 were used for the supply transition. Trends in demand were estimated assuming that the annual growth rate (2.0%) indicated above would continue until 2050. Domestic sulfur production was approximately 1629.00 thousand ton in 2019 and is expected to decrease to approximately 634.00 thousand ton in 2050. If the demand volume is changed at the aforementioned annual growth rate, approximately 2026.00 thousand ton of resin production from petroleum refineries is expected to be required by 2030. In 2050, 3010.00 thousand ton is expected to be needed. Domestic sulfur production is derived entirely from desulfurization during petroleum refining [44]. Therefore, a decrease in sulfur production as a petroleum by-product directly leads to a decrease in domestic sulfur production.

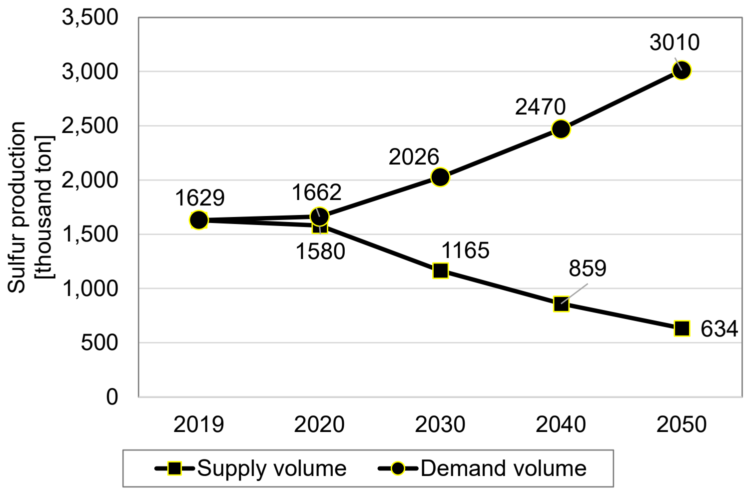

Figure 6. Outlook of supply and demand volume of sulfur production.

3.3. Discussion

This study used annual global market growth rates for each product to estimate demand for plastics, dry ice, and sulfur. The annual growth rates for these products in the Japanese market might differ from those in the world market. In addition, the growth rates might not remain the same until 2050, and the estimates are rough. This is also similar for the estimation of the supply of each of these products. Nevertheless, the fact that estimates were able to show that the output gap for these products would be large enough to achieve the 1.5 °C target is a significant contribution.

Regarding plastic products, a very large discrepancy between the supply and demand of plastic resins became evident as the 1.5 °C target was achieved. In accordance with the Plastic Resource Circulation Act, the Japanese government is required to promote the recycling of plastic waste. Figure 3 indicates that the recycling rate of plastic waste in 2019 was 85%, and most plastic waste was already being used effectively [34]. However, energy recovery, which accounts for approximately 60%, is integrated into the recycling process. By converting waste plastics that have been energy recovered, incinerated, and landfilled to mechanical recycling, the achievement of the milestone in 2030 set by JMOE [39] doubles the recycling of waste plastic from 910.00 thousand ton in 2019 to 1800.00 thousand ton in 2030. However, the national government should discuss the increased labor and infrastructure costs for transporting, sorting, and cleaning waste plastics to achieve this [45].

In addition, the introduction of 2000.00 thousand ton of biomass plastic, which JMOE [39] set as a milestone for 2030, is extremely difficult considering that the production volume was only 45.00 thousand ton in 2018 [46]. Biomass plastics are 1.5 times more expensive than polyethylene made from fossil fuels, and the price difference is an obstacle to the spread of biomass plastics [47]. For biomass plastics to have the same competitiveness as fossil-fuel-based plastics, national government should take the initiative to ensure a stable biomass supply as raw materials, reduce costs through mass production, and tax fossil-fuel-based plastics.

Regarding hydrogen, the Japanese government has positioned hydrogen as an important energy source. They have been jointly developing technologies related to the construction of fuel cell vehicles and hydrogen energy infrastructures [4]. According to the New Energy and Industrial Technology Development Organization (NEDO) [48], if hydrogen power generation becomes a reality, domestic hydrogen demand in 2030 is expected to rise to 2.2 billion Nm^3. According to the results of this study, 1.53 billion Nm^3 is expected to be available in 2030, and hydrogen production associated with petroleum refining could be one way to ensure supply against demand. However, hydrogen production declines as the 1.5 °C target is achieved, so hydrogen production is not expected to be a permanent energy source.

Regarding dry ice, one measure to solve the output gap is to increase the import volume of dry ice. However, imports not only incur higher transportation costs than domestic production but also depend on the production situation of exporting countries such as South Korea [49]. If the exporting countries were making efforts to achieve the 1.5 °C target, the production volume of the dry ice that Japan imports would also be expected to reduce accordingly. Other measures include installing new equipment to produce dry ice from low-concentration carbon dioxide, and storage equipment to stabilize the supply. However, this also incurs the cost of expanding the facilities, and the current situation cannot achieve the current demand for dry ice. This result reveals that dry ice is one of the products that have a great social and economic impact due to the reduction in petroleum consumption. The national government should recognize that securing dry ice supply is an issue for reducing petroleum consumption.

Regarding sulfur, at present, approximately 1000.00 thousand ton of produced sulfur is exported, mainly to China, and domestic demand remains at approximately 500.00 thousand ton [50]. If the production volume is decreased to the 2050 level, adjusting the export volume might be one of the measures to achieve domestic demand. However, export restrictions are a powerful diplomatic option that may be subject to retaliation from the target country and require increased attention.

4. Conclusions

This study discussed how the reduction in petroleum consumption required to achieve the 1.5 °C target could affect the domestic supply and demand of petroleum products and by-products. The findings of this study are described below.

(1) Data pertaining to petroleum refining, petroleum product manufacturing, and plastic product manufacturing processes in 2019 were collected to create a material flow diagram that provides a consistent picture of the current state of domestic petroleum supply and demand. The material flow also covered the production of sulfur, a petroleum by-product, as well as dry ice, one of the uses of carbon dioxide gas.

(2) The domestic production of plastic resins in 2019 was approximately 10,500.00 thousand ton, and the production in 2030 will be approximately 7511.00 thousand ton, if the reduction in petroleum consumption that contributes to achieving the 1.5 °C target is achieved. The JMOE is planning to recycle waste plastics and produce biomass plastics in its plastic resource recycling strategy. However, this requires further separation of waste plastics and reduction of production costs through mass production of biomass plastics.

(3) Hydrogen is produced and consumed during the petroleum refining process, with hydrogen produced in an adjacent hydrogen plant. Hydrogen is produced in the amount of 14.02 billion Nm^3, but is consumed entirely on site. At maximum operation of this hydrogen plant, there is a potential external supply of 2.14 billion Nm^3, which would decrease to 1.53 billion Nm^3 in 2030 if petroleum consumption were to decrease at the rate targeted for the reduction.

(4) Domestic production of dry ice derived from petroleum by-products in 2019 was approximately 157.00 thousand ton, which would decline to approximately 61.00 thousand ton in 2030 if the above target is achieved. There are many import and technological challenges to cover the shortfall, and it is expected to be difficult to secure supply to achieve the expected increase in demand.

(5) Domestic sulfur production from petroleum by-products in 2019 was approximately 1629.00 thousand ton. This would decrease to approximately 1165.00 thousand ton in 2030 if the above target is achieved. Since domestic demand for sulfur has remained

at approximately 500.00 thousand ton, the majority of which is exported, the future domestic demand could be achieved by adjusting the volume of exports.

This study has a limitation in that only plastic products, hydrogen, dry ice as carbon dioxide, and sulfur are the focus, but it has shown that reducing petroleum consumption might affect the supply and demand of these products. Although this study was conducted in Japan, it is not a unique case, especially in countries where petroleum refining and the production of plastics, etc. are the mainstay of their industries. It is important for other countries to calmly assess the impact on their own industries and societies to achieve the 1.5 °C target, and then to consider the impact on their own economies and societies. Measures need to be taken to minimize the impact.

Japan has adjusted to produce petroleum products that meet domestic demand by selecting the type of petroleum to be imported, before decomposing and reforming it [50]. However, perfectly matching the production of all petroleum products with demand is difficult, and the supply of naphtha is covered by imports. This situation is the same for plastic products made from naphtha and dry ice. In the future, petroleum treatment might be reduced to achieve the goal of the 1.5 °C target, and the gap in demand might be widened. The Japanese government should support the minimization of the economic and social impacts by adjusting the import volume, securing the supply volume, and funding the development of products that replace conventional petroleum products and petroleum by-products, such as biomass plastics. The milestone of plastic resource circulation announced by the JMOE [39] that this study considered, which is just a target value, involves the expansion of laws and policies regarding reuse and recycling, and reliable implementation is required. The Plastics Resource Circulation Act [9], which is scheduled to come into effect in April 2022, is expected to experience effects that might be exhibited from the perspective of reducing the petroleum consumption and substituting petroleum products. In addition to such 3R measures, national government should recognize that achieving the 1.5 °C target requires significant transition in policies and industrial and social systems.

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