Essays on the Carbon Sources of Carbon-Recycle Fuels (2)
— Points to Note Toward the Realization of a Decarbonized Economy in 2050—

May 2021

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1. Key points of this paper

- There are high expectations of the role that carbon- recycle fuels (CR fuels: synthetic methane and synthetic liquid fuels, algae cultivation biofuels, etc.) can play toward the realization of a decarbonized economy. Candidate carbon sources for carbon-recycle fuels include fossil fuels, biomass, and CO_2 in the atmosphere, but CO_2 reduction effect is the same regardless of which carbon source is chosen.
- On the other hand, the viewpoint of the total volume of CO_2 that is emitted from the carbon recycling system is also important in a decarbonized economy. When biomass or CO_2 in the atmosphere is utilized, the carbon recycling system as a whole can be regarded as generating net zero CO_2 emissions.[1] Conversely, when fossil fuel-derived CO_2 is reused, positive CO_2 emissions are generated in principle from the viewpoint of the whole system, including the power plants and industrial plants that burn fossil fuels.
- There are now ongoing discussions about carbon pricing and the decarbonized economy of 2050 in Japan, and these could have an impact on the approach to carbon sources. For example, if carbon taxes were strengthened, taxes may be imposed on systems that reuse fossil fuel-derived CO_2. Furthermore, in the realization of net zero emissions in 2050, if fossil fuel-derived CO_2 were reused, there would be a need to offset the positive emissions. As shown in the estimates drawn up in this paper, the “costs” of carbon-recycle fuels using fossil fuel-derived CO_2 include not only the costs of CO_2 procurement, hydrogen production, and fuel production, but also the costs to the CO_2 itself (carbon taxes and offsetting costs, etc.). It is also important to take these costs into consideration.
- At a point where carbon constraints are relatively lax (such as 2030 or 2040), fossil fuel-derived CO_2 could possibly hold the key to the expansion of carbon-recycle fuels. On the other hand, we cannot deny the possibility that constraints to the reuse of fossil fuel-derived CO_2 may arise by 2050 due to the abovementioned factors, making it necessary to shift to other carbon sources depending on the situation. It is important to have a CO_2 procurement strategy that takes the time horizon into consideration.

[1] To simplify the discussion, this paper disregards a number of points. It focuses on CO_2 emissions that arise from the combustion of biomass fuels and fossil fuels, but does not take into consideration CO_2 emissions in the processes of collecting/mining, transportation, etc. of these fuels. It also does not take into consideration CO_2 emissions that arise from the collection and transportation of biomass and the production and transportation of fossil fuels, as well as from the construction of direct air capture (DAC) facilities. It assumes that the energy needed for DAC and the production of carbon-recycle fuels is covered by zero-emission energy.

2. Body text

CO_2 reduction effect from carbon-recycle fuels: Same across all carbon sources

In response to the “net zero” declaration for 2050 presented by Prime Minister Suga in October 2020, efforts have accelerated toward the realization of that goal. In December the same year, the government unveiled the “Green Growth Strategy Through Achieving Carbon Neutrality in 2050,” and the bill to revise the Act on Promotion of Global Warming Countermeasures, which was approved by the Cabinet in March 2021, clearly set out the realization of a decarbonized economy by 2050.

Carbon recycling is a technology that is anticipated to contribute to the realization of decarbonization. Carbon recycling regards CO_2 as a resource and involves the reuse of CO_2 captured from power plants, industrial plants, and the atmosphere as fuel or raw material. In the reuse of CO_2 as fuel, the Green Growth Strategy points clearly to biomass fuel production through algae cultivation. Furthermore, the government’s Roadmap for Carbon Recycling Technologies, as well as councils, etc. contain descriptions of methane synthesis and liquid fuel synthesis (methanol, ethanol, diesel, etc.).

If these carbon-recycle fuels are used as substitutions for fossil fuels, it will be possible to avoid generating the volume of CO_2 emissions from the fossil fuels that were replaced. Examples of the carbon sources of carbon-recycle fuels include fossil fuels, biomass, and CO_2 in the atmosphere, and CO_2 reduction effect (CO_2 emission avoidance effect) is the same for all the carbon sources. Shibata (2020) has provided a detailed explanation, but we shall consider a few simple examples here.

> **[Example 1] Reusing CO_2 derived from fossil fuels**: Consider two companies, Company A and Company B, which are consuming natural gas. If Company A directly emits a tons of CO_2 per year, while Company B directly emits b tons of CO_2 per year, the total volume of emissions from the two companies would be a+b tons. Here, if Company A captures r tons of CO_2 ($r \leqq a$ and $r \leqq b$) and produces synthetic methane, after which Company B’s natural gas consumption is partially substituted, then the volume of emissions from the two companies would be a+b-r tons.[2] Comparing the emissions before and after the implementation of carbon recycling, CO_2 reduction effect would be (a+b)-(a+b-r)=r tons.
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> **[Example 2] Reusing CO_2 derived from biomass**: Assume that Company A is burning biomass (carbon content is equivalent to a tons of CO_2), and Company B is burning natural gas (carbon content equivalent to b tons of CO_2). In the case where carbon recycling is not carried out, the total direct emissions from the two companies would be 0+b=b tons. Here, if r tons of CO_2 derived from biomass ($r \leqq a$ and $r \leqq b$) is captured from Company A for the production of synthetic methane, while the natural gas consumption of Company B is partially substituted, the total volume of emissions from the two companies would be 0+b-r=b-r tons. The CO_2 reduction effect from carbon-recycle fuels would be b-(b-r)=r tons.
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> **[Example 3] Using CO_2 derived from the atmosphere**: Here, consider only the case of Company B. Assume that natural gas containing b tons of carbon is consumed prior to the implementation of carbon recycling. If r tons of carbon are captured from the atmosphere in-house, and substituted for natural gas in the form of synthetic methane, then carbon emission volume would be b-r. In this case, CO_2 reduction effect would be b-(b-r)=r.

[2] For simplification purposes, the elements of CO_2 capture efficiency are disregarded. The same applies to Example 2 and Figure 1 mentioned later.

While these are simple estimates, a comparison of emission volumes with and without carbon recycling shows that CO_2 reduction effect is not dependent on the carbon source (CO_2 reduction effect is *r* tons in all the examples).

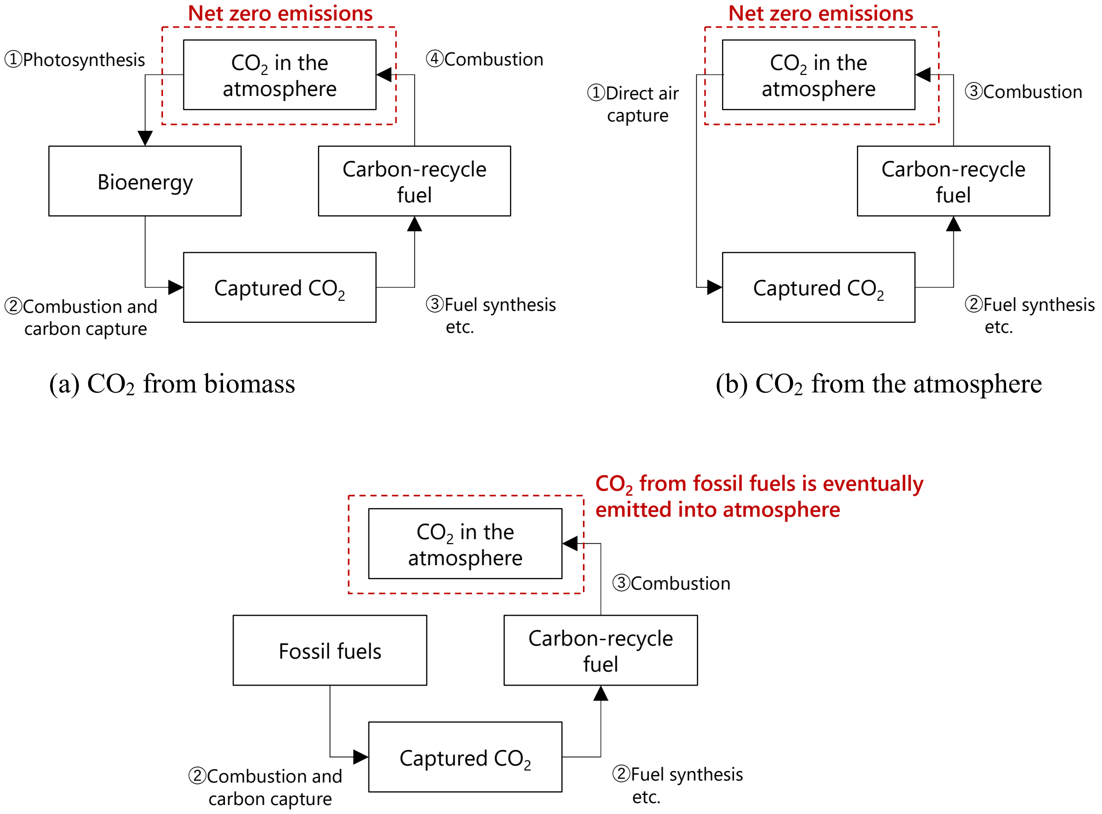
Carbon sources have an impact on the total volume of CO_2 emissions for the overall carbon recycling system

On the other hand, the total volume of CO_2 emissions for the overall carbon recycling system varies depending on the choice of carbon source. Here, the "overall carbon recycling system" refers to the total volume of direct emissions for both carbon providers (power plants, industrial plants, etc.) and users of carbon-recycle fuels. Looking at the three examples above, carbon emissions in the case where carbon recycling is carried out in Example 1 is $a+b-r$, and in Example 2 and 3 is $b-r$. Example 1 has the highest total volume of CO_2 emissions. While CO_2 reduction effect is the same for all the carbon sources, we can see that the total volume of emissions is different.

The impact that the choice of carbon source has on total volume of CO_2 emissions is also considered to form the viewpoint of the carbon flow. **Figure 1** shows the carbon flow for the carbon recycling system. The carbon source is biomass in **Figure 1a**, CO_2 from the atmosphere in **Figure 1b**, and fossil fuel in **Figure 1c**. In the cases where biomass or CO_2 from the atmosphere are used, as carbon that had originally been present in the air circulates, the combustion of carbon-recycle fuels is not regarded as a contributing factor to the increase in CO_2 in the atmosphere (**Figure 1a-b**). In contrast, when the carbon source is fossil fuel, CO_2 is ultimately discharged into the atmosphere even if it is reused. Hence, CO_2 emissions are positive for the whole of the carbon recycling system (**Figure 1c**).

There are now ongoing discussions about carbon pricing and the decarbonized economy of 2050 in Japan. If the total volume of CO_2 emissions for the overall carbon recycling system were taken into consideration, the choice of carbon source may be considerably significant. For example, if carbon taxes, which is one of the methods of carbon pricing, were introduced, a recycling system that uses fossil fuel-derived CO_2 would be subjected to taxes for positive emissions. Furthermore, in the realization of net zero emissions in 2050, if fossil fuel-derived CO_2 were reused, there would be a need to offset the positive emissions. Specific offsetting measures including afforestation, DACCS, BECCS, etc.,[3] and it would mean that the respective costs for these measures would be incurred (in the case of offsetting, it may be possible to be exempted from penalties such as carbon taxes, but offsetting costs are incurred instead). In the case where fossil fuel-derived CO_2 is reused, there is a need to consider not only the costs of hydrogen production, CO_2 separation and capture, and fuel synthesis in the boundary of the costs for the production of carbon-recycle fuels, but also the costs to the CO_2 itself that is derived from fossil fuels (that is, carbon taxes, offsetting costs, etc.). While taking these costs into account, it is important to take a perspective that considers which of these carbon source options—fossil fuel derivative, biomass derivative, or present in the atmosphere—is the most economically efficient.

[3] DACCS＝Direct Air Capture with CCS; BECCS＝Bioenergy with CCS.



(a) CO_2 from biomass

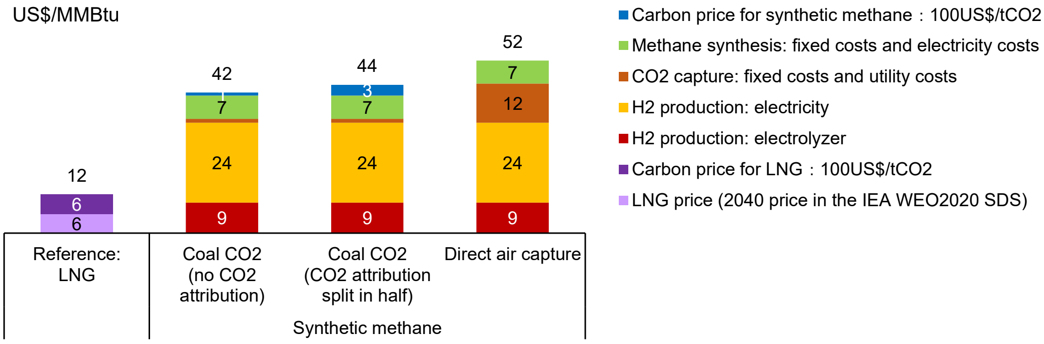
(b) CO_2 from the atmosphere

(c) CO_2 from fossil fuels

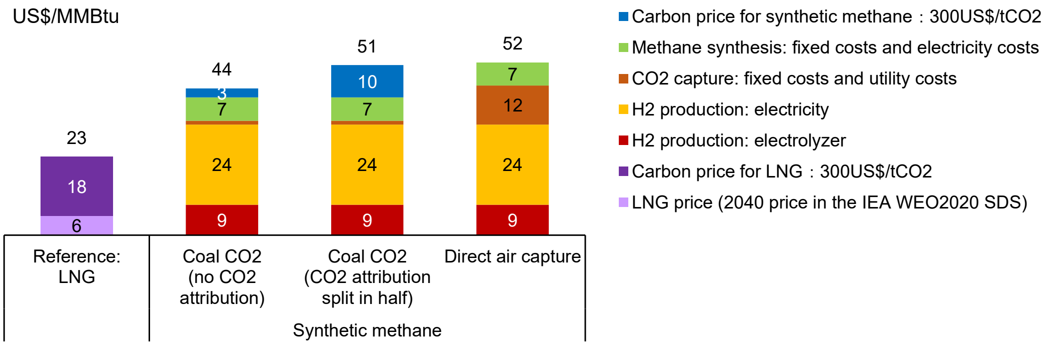
Figure 1 Carbon flow for carbon recycling fuel systems

While the question of who shoulders these carbon tax payments and offsetting costs (the carbon providers, the carbon users, or both parties?) is a contentious point,[4] this is actually a problem of the attribution of CO_2, which will be discussed in the third essay. Here, based on assumptions about attribution, we drew up estimates on the extent of impact that the costs to CO_2 itself could potentially have, using synthetic methane as the subject (**Figure 2**). The subject of the estimates is assumed to be systems in Japan that carry out water electrolysis and CO_2 capture, and methane synthesis (assumption of Sabatier reaction). The case in which CO_2 is captured from emissions gases after coal combustion, and the case of DAC, are taken into consideration. As for the case where coal-derived CO_2 is utilized, further estimates were drawn up for the case where CO_2 is not attributed to the synthetic methane side ("no CO_2 attribution" in the figure) and the case where CO_2 attribution is split in half ("CO_2 attribution split in half" in the figure). Estimates were based on three situations, with carbon tax (or offsetting costs) at US\$100/tCO_2, US\$300/tCO_2, and US\$500/tCO_2. For the detailed assumptions used for the estimates, refer to the appendix at the end of this paper. Carbon tax is also imposed in the case of "no CO_2 attribution" for synthetic methane in the figure. Refer to the appendix for the considerations on this point.

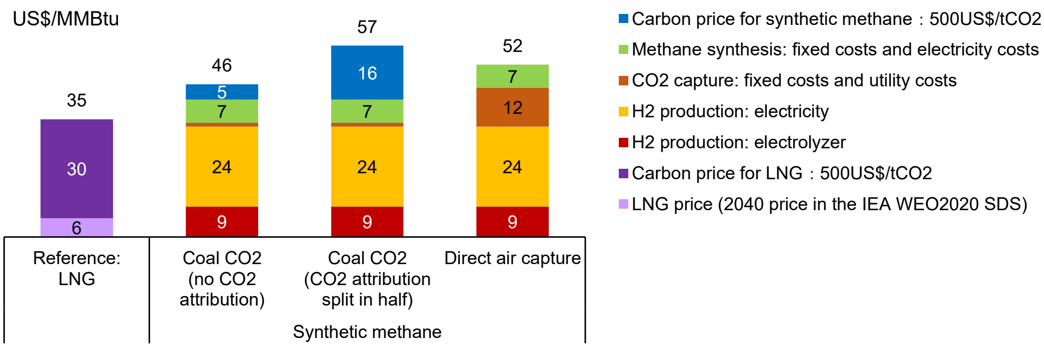
[4]With regard to the implementing entities of offsetting measures, there are various possibilities, including the implementation of offsetting measures independently by carbon providers or users of carbon-recycle fuels, or the implementation of negative emission projects by third parties in addition to the procurement of carbon offsetting credits for a part of the project. There is also a need to deepen future discussions on this point.



(a) When carbon tax is US$100/t$CO_2$



(b) When carbon tax is US$300/t$CO_2$



(c) When carbon tax is US$500/t$CO_2$

Figure 2 Production cost for synthetic methane, taking carbon tax into consideration

The following two main points are implied by **Figure 2**.

- In the case where carbon tax is US$100/t$CO_2$, it does not have a significant impact on the production costs of synthetic methane. Even in the case where CO_2 attribution is split equally in half, using coal-derived CO_2 is cheaper than using DAC. However, if the carbon tax is about US$100/ t$CO_2$, adding the carbon tax rate to LNG price is sufficiently cheap, and there is a need to pay attention to whether it is sensible to carry out CO_2 capture + hydrogen production + synthetic methane production domestically to begin with.

- In the case where environmental policies are tightened (US\$300/tCO_2 and US\$500/tCO_2), greater penalties are imposed for the use of coal (cost competitiveness falls for synthetic methane that uses coal-derived CO_2). The cost comes close to that of using DAC even when there is no CO_2 attribution, and cost significantly exceeds that of using DAC when CO_2 attribution is split in half. The reuse of coal-derived CO2 may not be economically rational.

According to data compiled by the IPCC in its Special Report on Global Warming of 1.5ºC, the global coal price that is necessary for achieving the 1.5ºC goal may rise to about US\$700/tCO_2.[5] To realize Japan's goal of a decarbonized economy by 2050, policies may be tightened to that level or above that level. Hypothetically, if that extent of climate change countermeasures is necessary, it would become difficult to reuse fossil fuel-derived CO_2 from the viewpoint of cost. Synthetic methane is used here as an example, but the cost is likely to be similar to that for using fossil fuel-derived CO_2 even for other carbon-recycle fuels such as synthetic petroleum and biomass fuels from algae cultivation. It will be important for business operators that are interested in carbon-recycle fuels to choose their carbon source based on this point.

As in the case of "no CO_2 attribution," when carbon-recycle fuel users are exempted from penalties, the penalties will be shouldered by the carbon providers. There is also a need for the carbon providers (thermal power plants, etc.) to consider whether or not to continue using fossil fuels as their fuel source even up to the point of taking on those penalties (shouldering a heavy carbon tax) (in short, whether to continue existing as a carbon source until 2050). In the case where they are unable to continue surviving as a carbon source (without fossil fuel consumption and the accompanying CO_2 emissions), the reuse of fossil fuel-derived CO_2 itself would become impossible. When environmental policies are tightened, splitting CO_2 attribution in half would make it less appealing, in terms of cost, to the users of carbon-recycle fuels (**Figure 2**). On the other hand, attributing CO_2 emissions to the carbon provider makes it less appealing to the providers. This creates a dilemma.

The need to select carbon sources taking into consideration the time horizon

This paper pointed out that carbon sources have an impact on the total volume of CO_2 emissions of the carbon recycling system. Here, those who have been reading in sequence from the first essay may have been confused by the difference from Figure 1 in the first essay. While an estimate was drawn up for the volume of emissions for the overall system in the first essay, it was pointed out that the volume of emissions remains the same regardless of the carbon source. This is because of the differences in the system boundaries and preconditions. In the first essay, the estimate is based on the assumption of a situation in which a fossil fuel user is present in the system, and it is shown that in such a case, emission volume remains unchanged for the system regardless of the carbon source used (in the case where fossil fuel-derived CO_2 is not reused, it is directly discharged into the atmosphere;[6] even if it were reused as carbon-recycle fuel, the same volume of CO_2 is ultimately released into the atmosphere). In contrast, this paper focuses only on the emissions from the parties involved in the production of carbon-recycle fuels (carbon providers and carbon-recycle fuel users).

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[5] Figure 2.26 in the Special Report on Global Warming of 1.5ºC shows the estimated carbon prices for multiple models and scenarios. Here, we referred to the median values of the analysis results for 1.5°C Low Overshooting. However, as shown in the same Figure, there is a significant range of carbon price estimates depending on the model. Hence, it is necessary to note that there is a high level of uncertainty.

[6] For example, if biomass-derived CO_2 is reused, fossil fuel-derived CO_2 will become the emission of a third party (no longer be emitted by the carbon provider or carbon-recycle fuel user). However, in the first essay, that CO_2 is also included in the system in the discussion.

The key is not to debate whether the approach in the first essay or this paper is correct. Rather, a choice should be made corresponding to the actual situation and time horizon. In the period of 2030–2040, many business operators will have no choice but to use fossil fuels in activities such as iron and steel manufacturing and cement production. In such situations, as discussed in the first essay, regardless of whether fossil fuel-derived CO_2 were reused or CO_2 derived from biomass or the atmosphere were reused, the volume of emissions in the overall system (such as in the economy as a whole) remains unchanged. Hence, it probably does not matter which carbon source is used.

In contrast, the preconditions change in the case where business operators using fossil fuels can take countermeasures other than carbon recycling in the move toward 2050. In short, in addition to the following options: (i) carry out carbon recycling; (ii) release directly into the atmosphere if they do not carry out carbon recycling, they also have the option of (iii) decarbonize through methods such as shift to electricity and hydrogen in final demand, and CCS. In the preconditions for the first essay, when CO_2 derived from biomass or the atmosphere is used, fossil fuel-derived CO_2 is discharged into the atmosphere. If (iii) can be implemented in such situations, then it would be possible to realize decarbonization for the overall system by combining carbon recycling through CO_2 derived from biomass/the atmosphere with (iii). On the other hand, if option (i) is selected even though option (iii) is available, net emissions would be positive. Therefore, the emission volume for the overall system changes depending on the carbon source.

Based on the above, during the transitionary period such as 2030 or 2040, we can say that promoting decarbonization through the active use of CO_2, including industrial CO_2, emitted from business operators who have no choice but to use fossil fuels, is an important option (it is assumed that carbon pricing, etc. is relatively lax in the short and medium term, and cost penalties are low even if fossil fuel-derived CO_2 is used). Against this, there is a need to choose the carbon source based on perspectives such as environmental policy, CO_2 offsetting cost and quantitative potential, and shift to electricity and hydrogen/CCS, in order to realize the goal of decarbonization by 2050. It may be necessary for both the carbon providers and the users to adopt a strategy that takes the time horizon into consideration, such as changing the carbon source in line with how stringent the environmental policy is. For example, for carbon users, it would be beneficial to make pre-assumptions on the alternative carbon source and CO_2 procurement method (CO_2 pipelines and liquefied CO_2 tankers), and based on that, choose the location for the carbon-recycle fuel manufacturing plant and develop the infrastructure. For the providers of fossil fuel-derived CO_2, it may be necessary to refine the response policy in advance in situations where environmental policy is tightened, or where an alternative CO_2 source emerges.

Issues in recapturing CO_2 from carbon-recycle fuels

Even if fossil fuel-derived CO_2 were used, if CO_2 from carbon-recycle fuels were recaptured, it would be possible to prevent discharge into the atmosphere. The last aspect that this paper shall examine is this recapturing of CO_2. While it is possible to prevent the discharge of CO_2 into the atmosphere through recapturing, there is a need to address the following two points.

The first issue comes from the viewpoint of CO_2 capture efficiency. Although this has been disregarded in the discussion up till this point, CO_2 capture efficiency from combustion gas and other sources is currently at a level of about 90%. For this reason, a portion of the fossil fuel-derived CO_2 becomes discharged into the atmosphere when capturing CO_2 from fossil fuels or recapturing CO_2 from carbon-recycle fuels (shown by the red dotted line in **Figure 3**). Even if carbon were recaptured and circulated, a portion of it continues to be discharged, making it necessary to offset that portion.

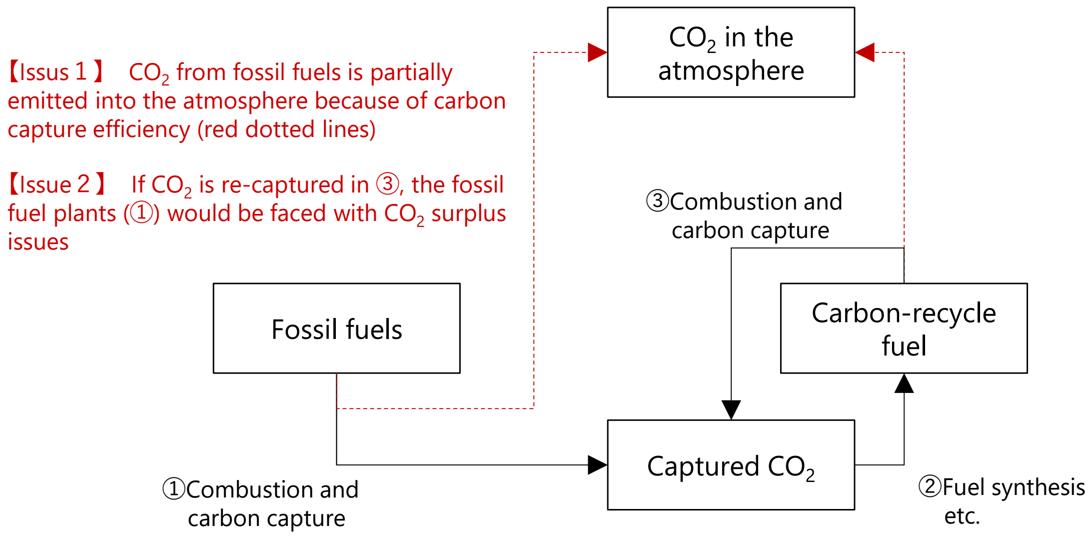

Figure 3 Carbon flow and systemic issues in the case of recapturing CO_2 from carbon-recycle fuels derived from fossil fuels

A more important issue is the decrease in the number of the accommodating parties for fossil fuel-derived CO_2 (flow (1) in **Figure 3**). For example, consider a system in which carbon-recycle fuel is manufactured from CO_2 captured at fossil fuel-based thermal power plants, and after combustion at an industrial plant or other facility, CO_2 is captured at the industrial plant and carbon-recycle fuel is produced for the same plant. Since CO_2 capture efficiency is not 100%, it will be necessary to replenish the carbon when fuel production is carried out the second time. However, it is sufficient to supply a smaller volume of CO_2 than that supplied from the power plant the first time. As a result, there will be surplus CO_2 at the power plant, making it necessary to put in place new measures (such as looking for other off-takers or carrying out CO_2 storage or fuel conversion). In cases where effective measures cannot be found, it may become difficult for the power plant to continue operating due to environmental constraints. From the perspective of the operator that owns the power plant, it may be impossible to say that this system is sustainable. Hence, we can see such challenges to the original carbon source in the case of recapture, as explained above.

Conclusion

This paper examined the potential of carbon-recycle fuels from the perspective of carbon sources. The key points are summarized in the following three items.

- Regardless of the carbon source that is chosen, CO_2 reduction effect (emission avoidance effect) is the same.
- On the other hand, total volume of CO_2 emissions for the carbon recycling system as a whole is impacted by the carbon source.
- The recapturing of CO_2 from carbon-recycle fuels gives rise to sustainability issues.

In aiming to achieve net zero emissions by 2050 for economy as a whole, the second point holds great importance. There are high expectations toward the reuse of fossil fuel-derived CO_2 in Japan, but such reuse may give rise to economic penalties (such as carbon taxes and offsetting costs). It is important to establish carbon procurement strategies based on a consideration of such penalties. If there are no means of offsetting the emissions, it would be difficult to introduce carbon-recycle fuels derived from fossil fuels in the move toward net zero emissions, and it may become necessary to use CO_2 from biomass or the atmosphere in the years leading up to 2050.

Of course, during the transitionary period, such as in 2030 or 2040, there are likely to be many operators (such as in the industrial sector) that have no other option but to use fossil fuels. The key to expanding the use of carbon-recycle fuels lies in the effective use of the carbon sources. As there is a need to physically procure CO_2 in carbon recycling, it is important to anticipate the situation from the transitionary period to 2050, select the carbon source and the location for carbon-recycle fuel production activities, and develop CO_2 procurement infrastructure.

Appendix: Assumptions for the estimates in Figure 2

The estimates in Figure 2 were drawn up based on the following assumptions, and established based on dissertations and reports from international and academic organizations.

- LNG prices in Figure 2 take reference from 2040 yearly value (US$5.7/MMBtu) for the Sustainable Development Scenario in the International Energy Agency's (IEA) World Energy Outlook 2020.
- Discount rate: 5%.
- Carbon content in fossil fuels (low calorific value standard) – Natural gas: 0.0560tCO_2/GJ, Coal: 0.0946tCO_2/GJ.
- Water electrolysis – Cost of equipment: US$450/kW, Conversion efficiency: 74% (low calorific value standard), Facility utilization factor: 30%, Facility lifespan: 15 years, Annual operational and maintenance costs: 1.5% of equipment cost, Cost of power supply: US$50/MWh (Approx. 5 yen/kWh), Cost of industrial water: US$0.6/$m^3$. Power supply is assumed to be zero emission electricity, including direct air capture and methane synthesis described below.
- CO_2 capture from gas after coal combustion (chemical absorption) – Cost of equipment: US$292/(t$CO_2$/year), Facility lifespan: 40 years, Annual operational and maintenance costs: 5% of equipment cost, Capture efficiency: 90%, Heat consumption: 1.5GJ/tCO_2, Heat supply price: US$61/t (refer to the value for steaming coal from the aforementioned IEA outlook), Coal calorific value (low calorific value standard): 26GJ/t.
- Direct air capture (High-temperature, aqueous solution system) – Cost of equipment: 815Euro/(tCO_2/year), Facility lifespan: 30 years, Annual operational and maintenance costs: 5% of equipment cost, Power consumption: 1.535MWh/tCO_2, Price of power supply: US$50/MWh. Exchange rate is assumed to be 1 Euro = US$1.19.
- Methane synthesis (Sabatier) – Cost of equipment: US$5,000/($Nm^3$-$CH_4$/hour), Facility utilization factor: 30%, Facility lifespan: 30 years, Annual operational and maintenance costs: 5% of equipment cost, Auxiliary power: 0.32kWh/Nm^3-CH_4.

In Figure 2, the amount equivalent to the carbon tax levied on synthetic methane was estimated for the case where CO_2 derived from coal is reused. The estimates were drawn up based on the following approach. When α tons of CO_2 is captured for use in methane synthesis, assuming that CO_2 capture efficiency is η, α/η of CO_2 is generated in the carbon source (Figure 4). Based on this breakdown, we can classify the CO_2 as (a) CO_2 accompanying heat consumption in a CO_2 capture facility, and (b) CO_2 derived from businesses such as power plants and industrial plants. When CO_2 is not attributed to the synthetic methane side, (a) that is not derived from businesses such as power plants and industrial plants was considered to be CO_2 emissions from the synthetic methane side. In the case where CO_2 attribution is split in half between the synthetic methane side and the carbon supplier, half of the sum of (a) and (b) ($\alpha/2\eta$) was considered to be the CO_2 emissions of synthetic methane.

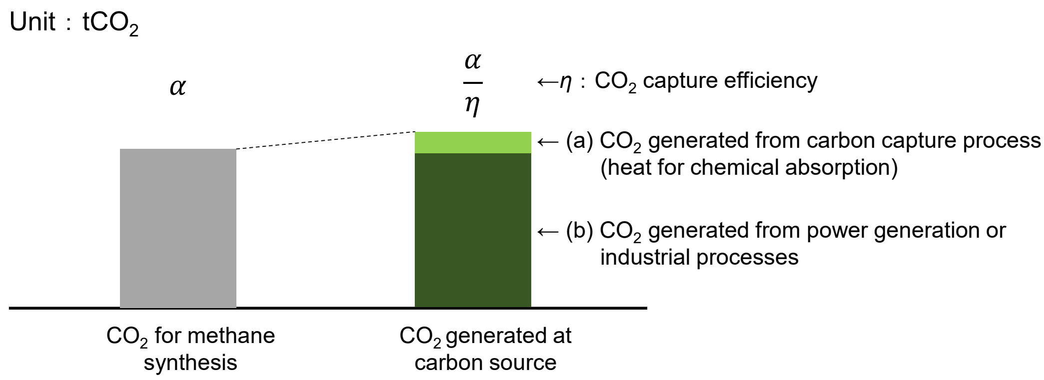

Figure 4 Illustration of the breakdown of CO_2 generated in carbon sources

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