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LCA study on the international cooperation of carbon circulation by Cryo-DAC and CN-methane

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1. Introduction

1.1 Research aims

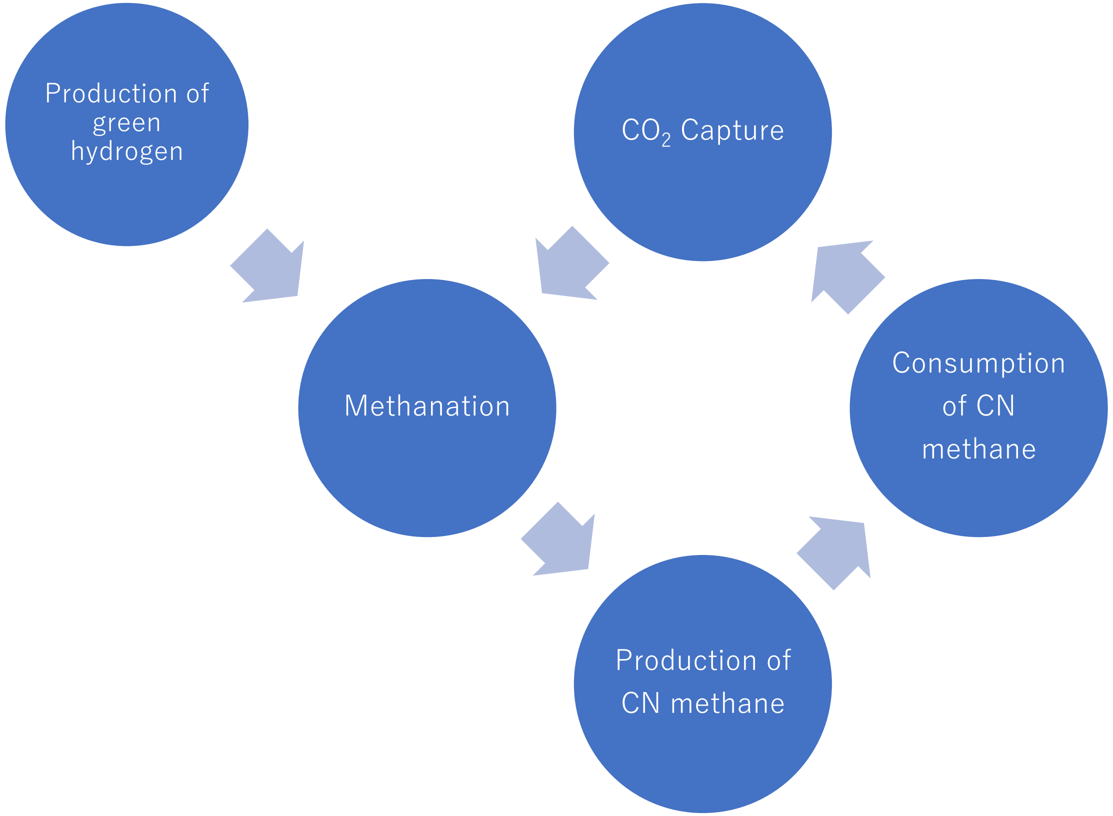
- Develop technology that separates and captures CO_2 for net zero emissions

- Cryo-DAC® system using LNG's unused cold energy

- Construct a carbon circulation system through international corporation between resource-rich countries and Japan
  - CO_2, generated when imported LNG is combusted, is directly captured from the atmosphere by the Cryo-DAC system. Other capturing sources are also considered.
  - The captured CO_2, which is rich in renewable energy, is exported overseas.
  - Carbon neutral (CN) methane is synthesized from green hydrogen produced from renewable energy, and is exported to Japan as liquefied CN methane (LCNM).

Evaluation of LCA of CO_2 emissions, energy input, and economic cost for LCNM

Figure 1 Carbon circulation through the production of carbon neutral methane



Production of green hydrogen

CO_2 Capture

Methanation

Consumption of CN methane

Production of CN methane

1.2 Overview of Cryo-DAC system

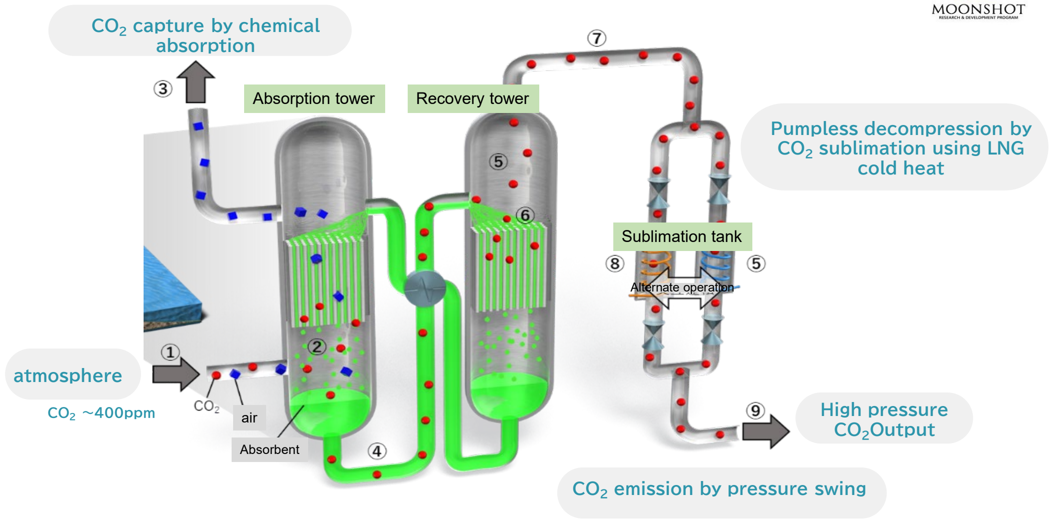
Table 1 Features of the preceding DAC development

	Carbon Engineering (Canada)	Climeworks (Switzerland)	Global Thermostat (USA)
CO2 capture method	High temperature type(900°C) Liquid solvent	Low temperature type(<100°C) Solid adsorption	Low temperature type(85～100°C) Solid adsorption
Capacity ($t\text{-}CO_2$/year)	365	900	4,000
CO_2 capture cost (US dollar/$t\text{-}CO_2$)	Current cost: 94～232	Current cost: 600 2025 Targeting Cost: 100	Current cost: 150 Achievable cost in the future: 50
CO_2 capture intensity (kWh/$t\text{-}CO_2$)	366	450	160

- CO_2 absorption by liquid solvent or solid adsorption
- A lot of energy input for CO_2 separation
- CO_2 capture cost is also $ 232–600/$t\text{-}CO_2$

Figure 2

Direct capture of atmospheric CO_2 by Cryo-DAC



- Technology to directly capture CO_2 from the atmosphere using LNG's unused cold energy.
- Sublimates CO_2 with cold energy, converts it to dry ice, and reduces the pressure.
- By depressurizing the absorption tower, CO_2 is released and recovered from the absorption liquid.
- No need for external energy input.
- Currently developing a system with the capacity to capture 200,000 tons-CO_2 per year with the aim of reducing costs.
- Cost comparable to DAC of Carbon Engineering

2. Analytical Framework

2.1 International cooperation of carbon circulation system by recovered CO_2 and methanation

Four Stages of circulation

First stage (A): green hydrogen production process using renewable energy in a resource-rich country.

Second stage (B): producing CN methane from green hydrogen and CO_2 transported from Japan.
The produced CN methane is liquefied and exported to Japan using an LNG carrier.

Third stage (C): Imported methane from a resource-rich country is consumed in Japan.

Fourth stage (D): Capturing CO_2 in Japan by Cryo-DAC from the atmosphere and carbon capture from fixed emission sources such as LNG thermal power plants.
The captured CO_2 is liquefied, transported to the resource-rich country, and used as raw material in stage (B) of methanation.

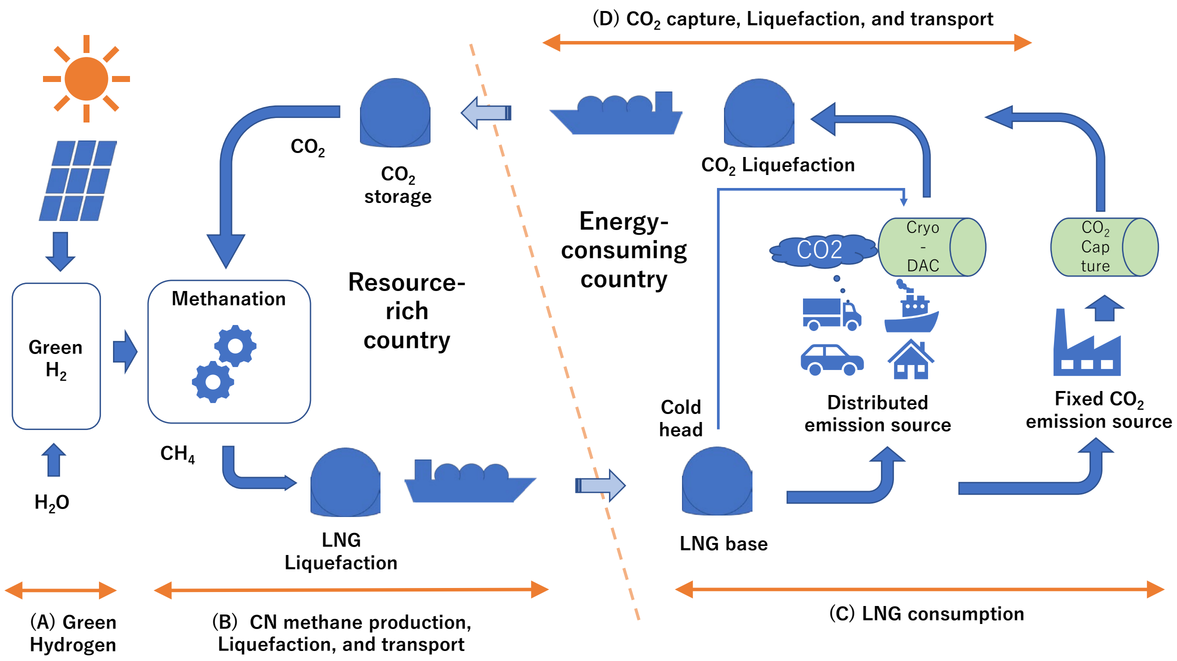


Fig. 3 International cooperation of carbon circulation by DAC-captured CO_2 and CN methane

At present, about 30% of domestic LNG is consumed as city gas, and the remaining 70% is used as fuel for thermal power generation in Japan.

Figure 4 System boundary for LCA evaluation of carbon circulation system by Cryo-DAC system and methanation

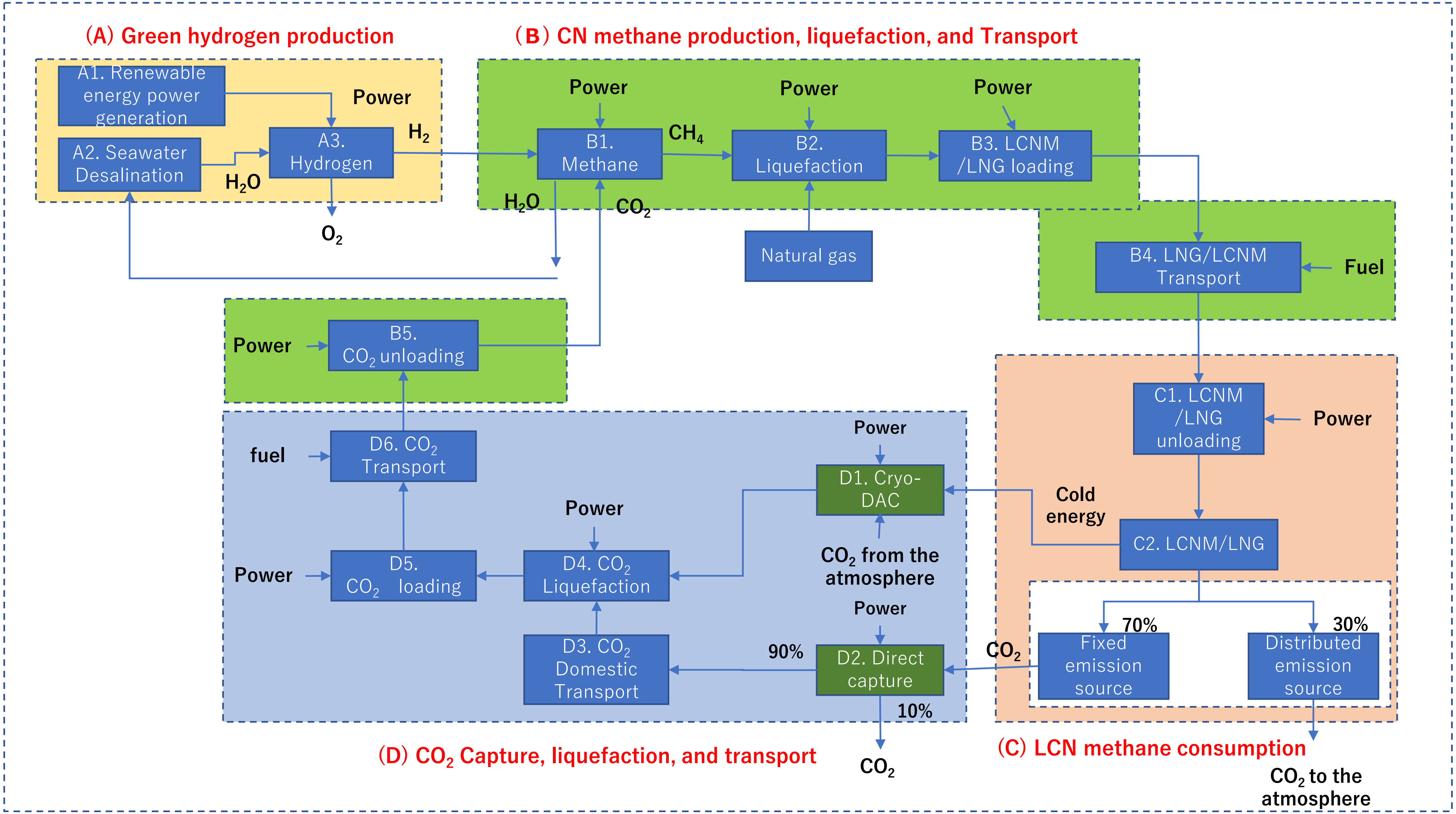


Table 2 shows the amount of resource input and production required at each stage when 1 ton of LNG is consumed in Japan.

Stage (A): From 4.834t of water, 0.537t of hydrogen and 4.297t of oxygen are produced by water electrolysis.

Stage (B): 1.074t of CN methane is manufactured from 0.537t of hydrogen and 2.954t of CO_2 transported from Japan.
2.417 tons of water is also produced as a by-product, which will be used in Stage (A).

The production of 1.074 tons of methane in Stage (B) takes into account the amount that is gasified in the process of international transport to Japan and consumed as transport fuel (see Jiří Pospíšil et. Al. (2019)).

Stage (C): Import 1t of LCNM to be consumed domestically. Currently, about 30% of LNG is used as city gas, and the remaining 70% is mainly used for combustion as fuel for thermal power plants.

Stage (D): CO_2 capture by Cryo-DAC with the unused cold energy of LCNM. At maximum, 0.800t of CO_2 can be captured using the latent heat of the cold energy of LNG1t.
Assuming that the efficiency percentage of CO_2 capture from fixed emission sources is 90%, the amount of CO_2 captured is 1.733t.
Their sum is 0.422 tons short for stable carbon circulation, in which 2.954 tons of CO_2 is required in Stage (B) .

Table 2 International carbon circulation system for CO_2 capture and methanation

Circulation stage	Country	Chemical reaction formula	Resource input	Output
(A) Green hydrogen production	Resource-rich country	$2H_2O \rightarrow 2H_2 +O2$	H_2O=4.834t	H_2=0.537t, O_2=4.297t
(B) CN methane production, liquefaction, and transport	Resource-rich country	$4H_2+CO_2 \rightarrow CH_4+2H_2O$	H_2=0.537t, CO_2=2.954t	CH_4=1.074t, H_2O=2.417t
(C) LCN methane consumption	Energy consuming country (Japan)	$CH_4+2O_2 \rightarrow CO_2+2H_2O$	LCNM=1.0t	-
(D) CO2 capture, liquefaction, and transport	Energy consuming country (Japan)	-	-	CO_2=-0.800t (by Cryo-DAC), CO_2=-1.733t (by direct capturing CO_2 from LNG-fired power generation) CO_2=-0.422t (shortfall)(Note 1)

(Note 1) The shortfall will be compensated by CO_2 captured by separation and recovery from coal-fired power generation or Cry-DAC from the atmosphere with excess cold energy of liquefied hydrogen.

・ To replace 100% of the LNG, it is necessary to supplement the 0.422t shortage of CO_2 by:
1) Separating and capturing the CO_2 from the combustion exhaust gas from fixed emission sources such as coal-fired power plants.
2) Supplementing with CO_2 captured from the atmosphere by Cryo-DAC using the excess cold energy of liquefied hydrogen.

2.2 Unit cost, energy intensity, and CO_2 emission intensity

- Unit costs, energy intensity, and CO_2 emission intensity have been set for each process in the carbon circulation system.
- The values were quoted from sources such as related documents and materials, and if necessary, estimated from the obtained information to suit the system assumed here.
- Although the evaluation time period differs depending on the reference literature, we attempted to take the value at the future time (2030–2050) as much as possible.

Unit cost

- Hydrogen production cost of 31.89 yen/Nm3 by water electrolysis was estimated in case of renewable energy power generation and seawater desalination. The high cost of hydrogen production is due to the high cost of the water electrolyzing equipment.
- Institute of Applied Energy (2020.3) reported that the hydrogen cost of reforming production with CCS is 8.87 yen/Nm3-H2, and the hydrogen production cost by water electrolysis with renewable energy is 40.0 yen/Nm3.

- For methane synthesis, the estimated value for 2050 was quoted as the unit cost from the report on the economic evaluation of synthetic methane by Methanation of the Institute of Applied Energy (2018).

- The LCN methane unit price for domestic consumption is the accumulation of costs for each stage so far.

- For Cryo-DAC, the cost was calculated by the Levelized Cost of Product method from the CAPEX and OPEX of 200 thousand CO_2-capturing systems using the Aspen Process Economic Analyzer.

- For CO_2 separation and capture, the cost of CO2-capturing (about 3,200 yen/t-CO_2) was quoted from the Economic Evaluation of Carbon Neutral Methane of the Institute of Applied Energy (2020).

3. Simulation Results

3.1 Simulation Conditions

Table 3 Conditions of each simulation

Common assumption	• Consider carbon circulation based on domestic consumption of LNG 1t (city gas 30%, LNG thermal power generation 70%) • Production of 1.074t-LNG is required in consideration of international transportation of LNG or LCNM. • Capture CO_2 from exhaust gas from LNG thermal power plants with a 90% efficiency rate. • CO_2 is captured from the atmosphere by Cryo-DAC using LNG cold energy.
Case 0	[LNG substitution rate by LCNM: 0.0%, as the reference case] • No CO_2 capture, no production of LCNM, and using only LNG.
Case 1	[LNG substitution rate by LCNM: 27.8%] • Capture 0.8 t-CO_2 by Cryo-DAC, produce 0.291 t-LCNM, and partly replace the LNG of 1.074t.
Case 2	[LNG substitution rate by LCNM: 85.9%] • Capture 1.733 t-CO_2 from fixed emission sources and 0.8 t-CO_2 from the atmosphere by Cryo-DAC. Produce 0.924 t-LCNM from a total of 2.533 t-CO_2, and partly replace the LNG of 1.074t.
Case 3a	[LNG substitution rate by LCNM: 100%] • In order to replace LNG by 100%, 0.422t-CO_2 is directly separated and recovered from other CO_2 fixed emission sources, such as coal-fired power, in addition to the CO_2 captured in Case 2. 1.074t of LCNM is produced as a whole.
Case3b	[LNG substitution rate by LCNM: 100%] • In order to replace the LNG by 100%, 0.422t-CO_2 is captured by Cryo-DAC with the cold head from the liquefied hydrogen, in addition to the CO_2 captured in Case 2. 1.074t of LCNM is produced as a whole.

・Regarding the carbon circulation system in Table 2, we calculated five simulations with different conditions in Table 3. The domestic consumption of 1 ton of LNG will be replaced by the LNCM produced by the carbon circulation system.

Case 0 is a reference case that does not capture CO_2.

In Case 1, an LCNM of 0.291t is produced using 0.8t-CO_2 recovered using only Cryo-DAC as a raw material and a part of LNG (27.8%) is replaced.

In Case2, an LCNM of 0.924t is produced from 0.8t-CO_2 with Cryo-DAC and 1.733t-CO_2 is directly separated and recovered from fixed emission sources, totaling 2.533t-CO_2. A part of LNG (85.9%) is replaced.

In Case 3a, 0.422t-CO_2 is supplemented with CO_2 that is directly captured from other CO_2 fixed emission sources, such as coal-fired power, and 1.074t of LCNM is produced (100%).

In Case 3b, 0.422t-CO_2 is supplemented with CO_2 recovered using Cryo-DAC due to excess cold energy such as liquefied hydrogen, and 1.074t of LCNM is produced (100%).

3.2 LCCO$_2$ emissions

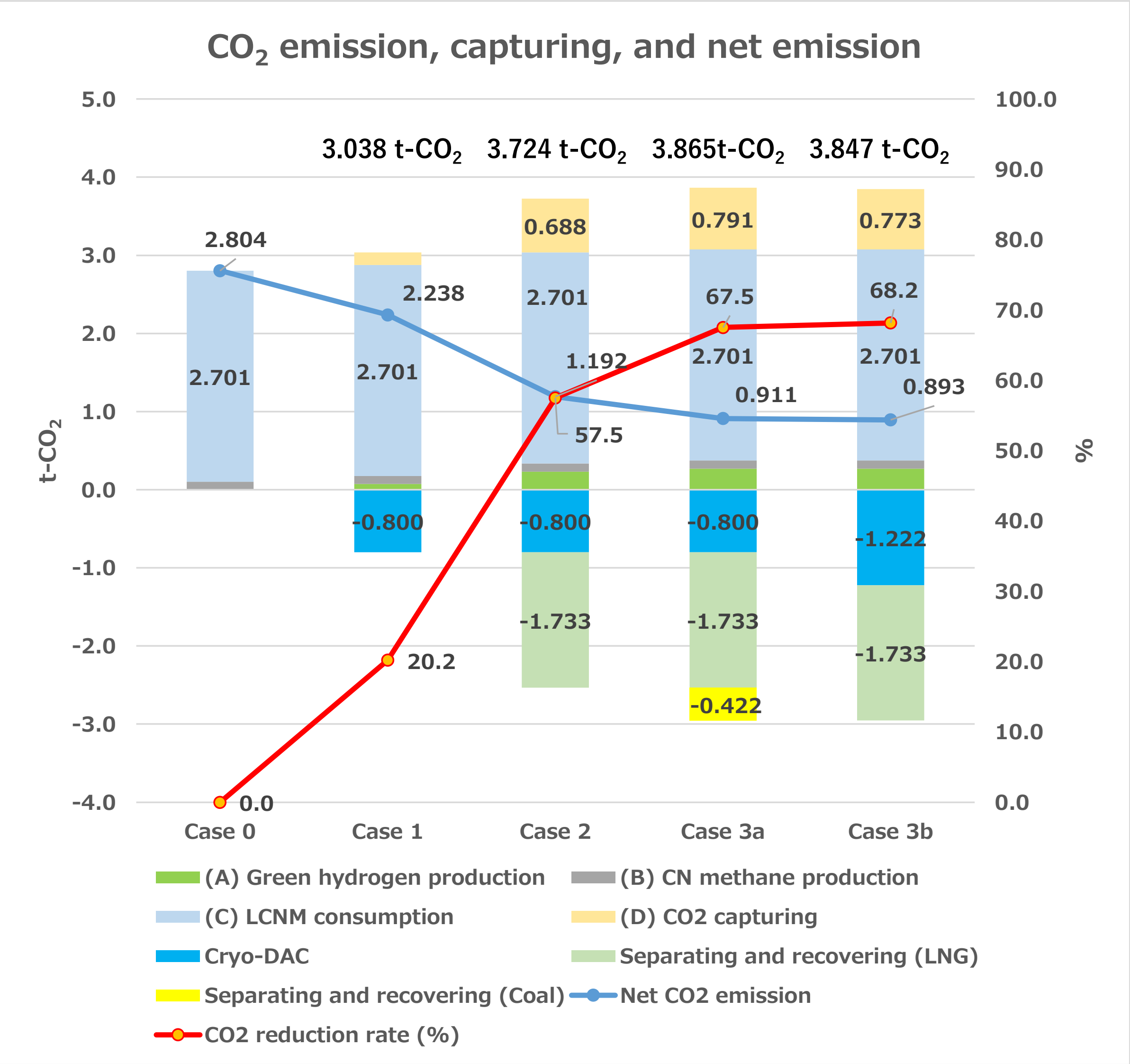
- In Case 1, which captures CO$_2$ using only Cryo-DAC, the replacement rate of LNG by LCNM is as low as 27.8%.
- In Case 2, CO$_2$ capturing increases to 85.9%, and CO$_2$ emissions also increase.
- Case 3a needs a higher energy input for additional CO$_2$ capture to attain a 100% replacement rate than Case 3b, so CO$_2$ emissions are higher.

-In all cases, CO$_2$ emissions at the "domestic consumption" stage, which includes CO$_2$ emissions during LNG or LCNM consumption, account for the majority.

- Net CO$_2$ emissions are 2.238 t-CO$_2$, 1.192 t-CO$_2$, 0.911 t-CO$_2$, and 0.893 t-CO$_2$ from Case 1 to Case 3b, respectively.
- In Case 0, CO$_2$ emissions are 2.804 t-CO$_2$.
- In contrast, Cases 1, 2, 3a, and 3b CO$_2$ emissions were reduced to 20.2%, 57.5%, 67.5%, and 68.2%, respectively.
- As for the reducing rate, Case 3b, which used Cryo-DAC for the full replacement of LNG, has the highest CO$_2$ emission reduction rate at 68.2%.

- Even in Cases 3a and 3b when LNG was fully replaced in the circulation system, the net CO$_2$ emissions were positive.
- To increase the CO$_2$ reduction rate, it is important to reduce CO$_2$ emissions at the CO$_2$ capturing stage.

Figure 5



3.3 Power consumption

・Case 1, with its low CO_2 capture, had the lowest power input at 8.45 MWh, Case 2 had 24.78 MWh, Case 3a had 28.75 MWh, and Case 3b had 28.80 MWh, which is the largest.

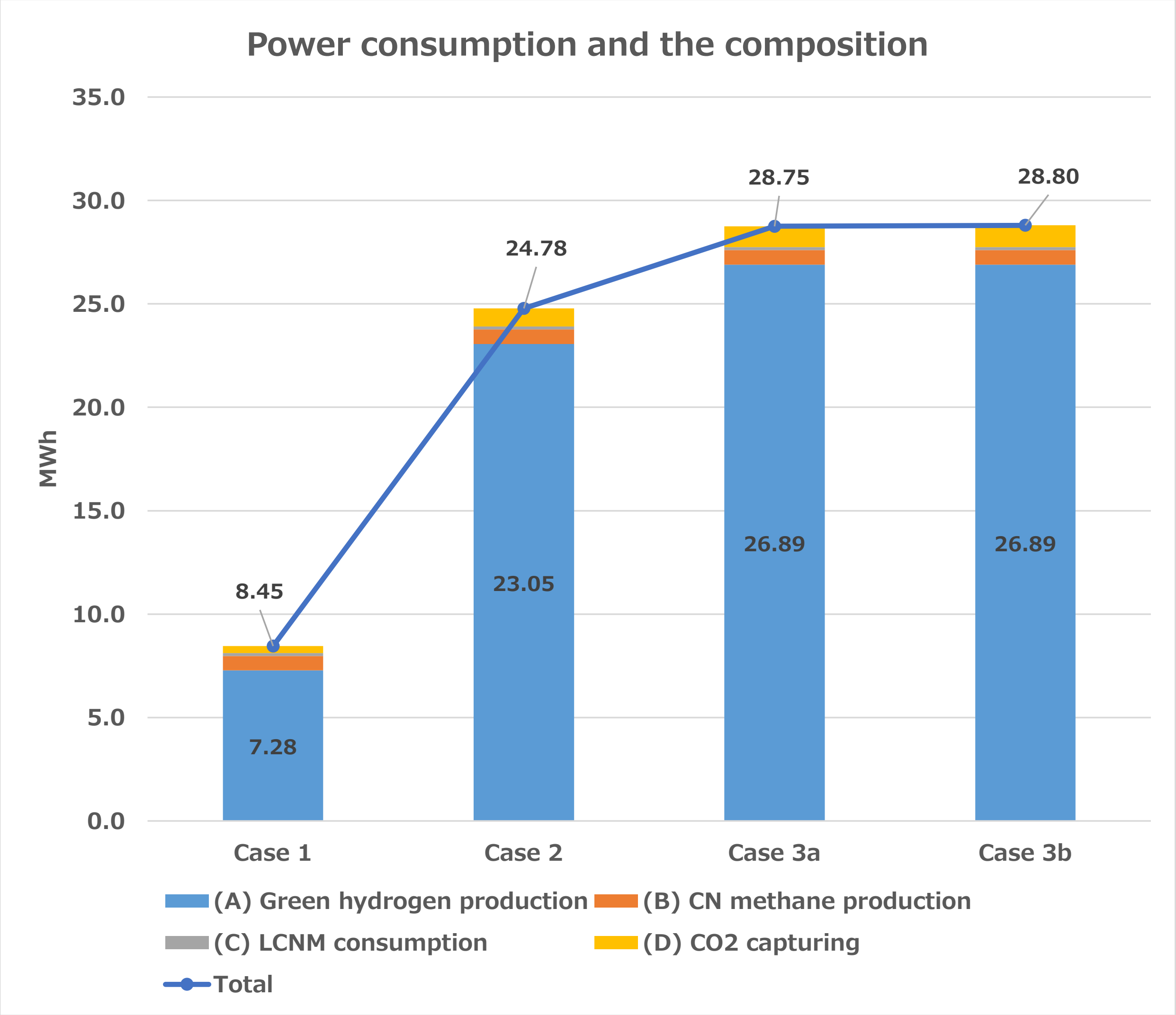
・The share of power consumption in Stage (A), which produces green hydrogen, is the highest, accounting for 86.16% to 93.39%.

・Next, the share of Stage (D) in CO_2 capturing is 3.65% to 3.97%, and that of Stage (B) in CN methane production is 2.47% to 8.17%.

-Hydrogen production requires a large amount of power input generated by renewable energy in our carbon circulation system. Therefore, Stage (A) should be installed in a country where such conditions can be met.

-In terms of cost reduction, it will be important for the hydrogen production process to be able to procure a large amount of electricity at a low cost.

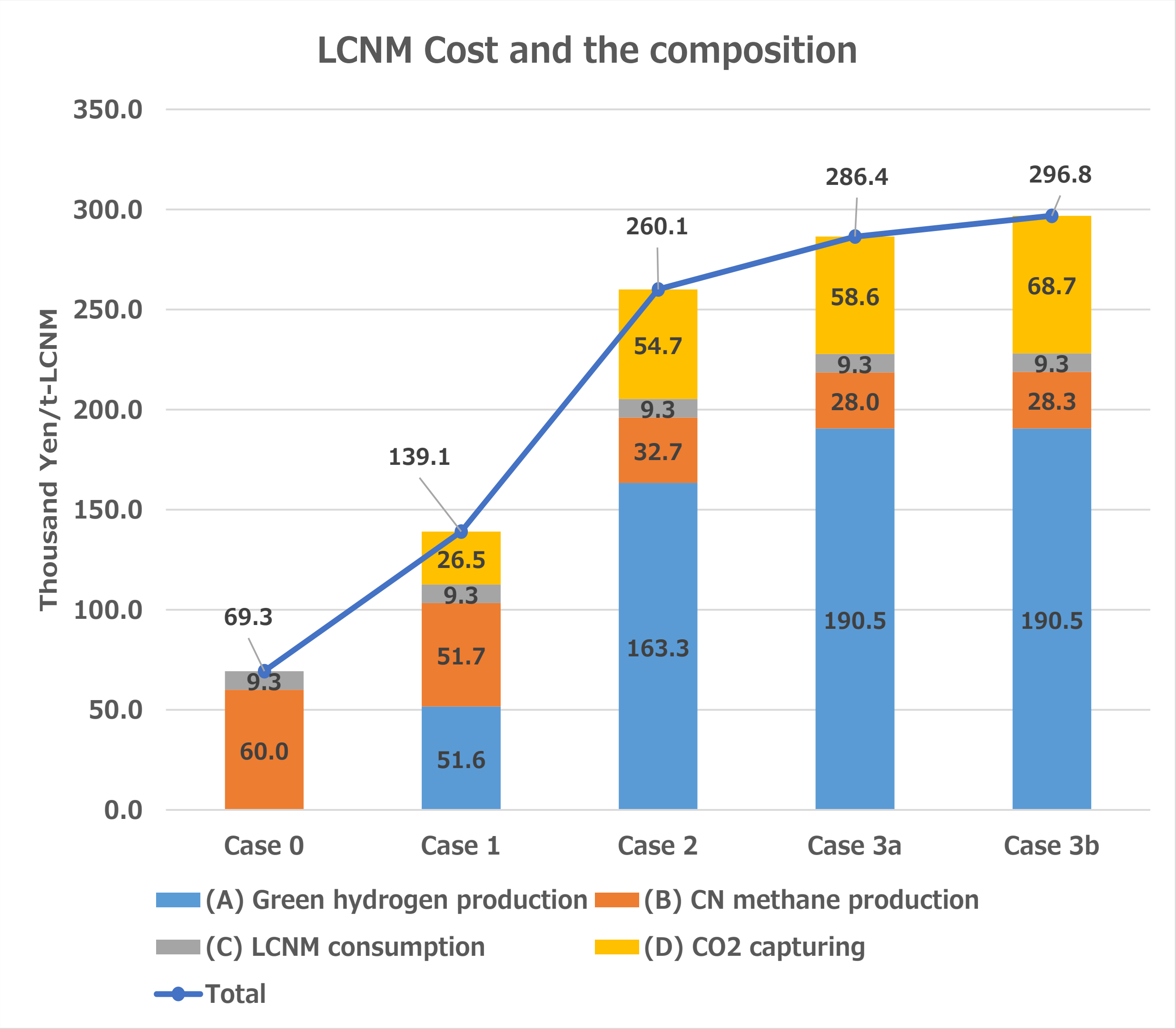
Figure 6



3.4 Cost analysis

- The LCNM/LNG average costs for Cases 1 to 3b are 139 thousand yen/t, 260 thousand yen/t, 286 thousand yen/t, and 297 thousand yen/t, respectively. Compared to the LNG cost of 69 thousand yen/t, such values are 2.0 to 4.3 times more expensive.
- In Case 1, which only performed the Cryo-DAC capture, the average cost is about double because the LNG substitution rate is as low as 27.8%. However, that in Case 3b rose to about 4 times.
- Case 3b, which has the best CO_2 reducing rate, showed the highest cost because it uses more Cryo-DAC, which is more expensive than direct capture from fixed CO_2 emission sources.
- Looking at the cost composition of Cases 3a and 3b, which replace LNG by 100%, the cost composition ratio in the green hydrogen production process is the highest, with 64–67%, followed by the CO_2 capture process accounting for 20–23%. Therefore, reducing hydrogen production and CO_2 capture costs is a major issue.

Figure 7

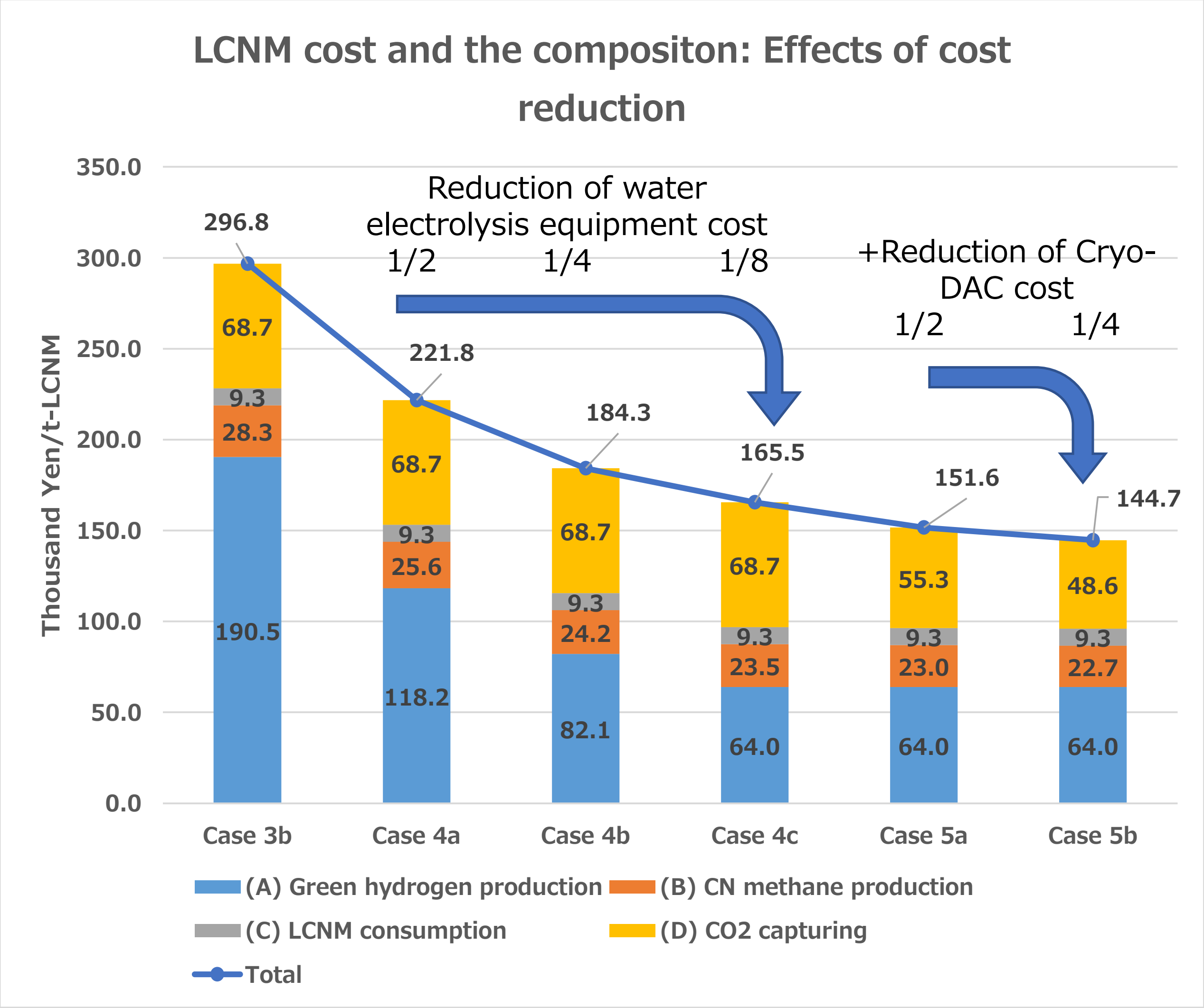


3.5 Impact of hydrogen production cost and CO_2 capture cost reduction

Table 4 Conditions of each simulation

Case 4a	[100% LNG replacement with CN methane] Halving the cost of water electrolysis equipment for green hydrogen production based on Case 3b
Case 4b	[100% LNG replacement with CN methane] Reducing the cost of water electrolysis equipment for green hydrogen production to 1/4 based on Case 3b
Case 4c	[100% LNG replacement with CN methane] Reducing the cost of water electrolysis equipment for green hydrogen production to 1/8 based on Case 3b
Case 5a	[100% LNG replacement with CN methane] Reducing the cost of water electrolysis equipment for green hydrogen production to 1/8 and halving Cryo-DAC costs, based on Case 3b
Case 5b	[100% LNG replacement with CN methane] Reducing the cost of water electrolysis equipment for green hydrogen production to 1/8 and reducing Cryo-DAC costs to 1/4, based on Case 3b

Figure 8



- Compared to Case 3b's cost, 297 thousand yen/t, the cost reduction for water electrolysis equipment brings the LCNM cost to 165 thousand yen/t in Case 4c, which is almost half the cost of the reference, Case 3b.

- Furthermore, if Cryo-DAC cost is halved (Case 5a), it will be reduced to 152 thousand yen/t. If it is reduced to 1/4, it will be brought down to 145 thousand yen/t.

-From this, it can be seen that in order to reduce the production cost of LCNM in the carbon circulation system, it is important to reduce the green hydrogen production cost. The cost reduction of the CO_2 capture process also becomes an issue.

3.6 Comparison with domestic carbon circulation system

Table 4 Conditions of each simulation

Case 6a	[100% replacement of LNG with CN methane] Circulating carbon only in Japan under the same conditions as Case 5b
Case 6b	[100% replacement of LNG with CN methane] Circulating carbon only in Japan under the same conditions as Case 5b. The price of domestic electricity is assumed to be halved.

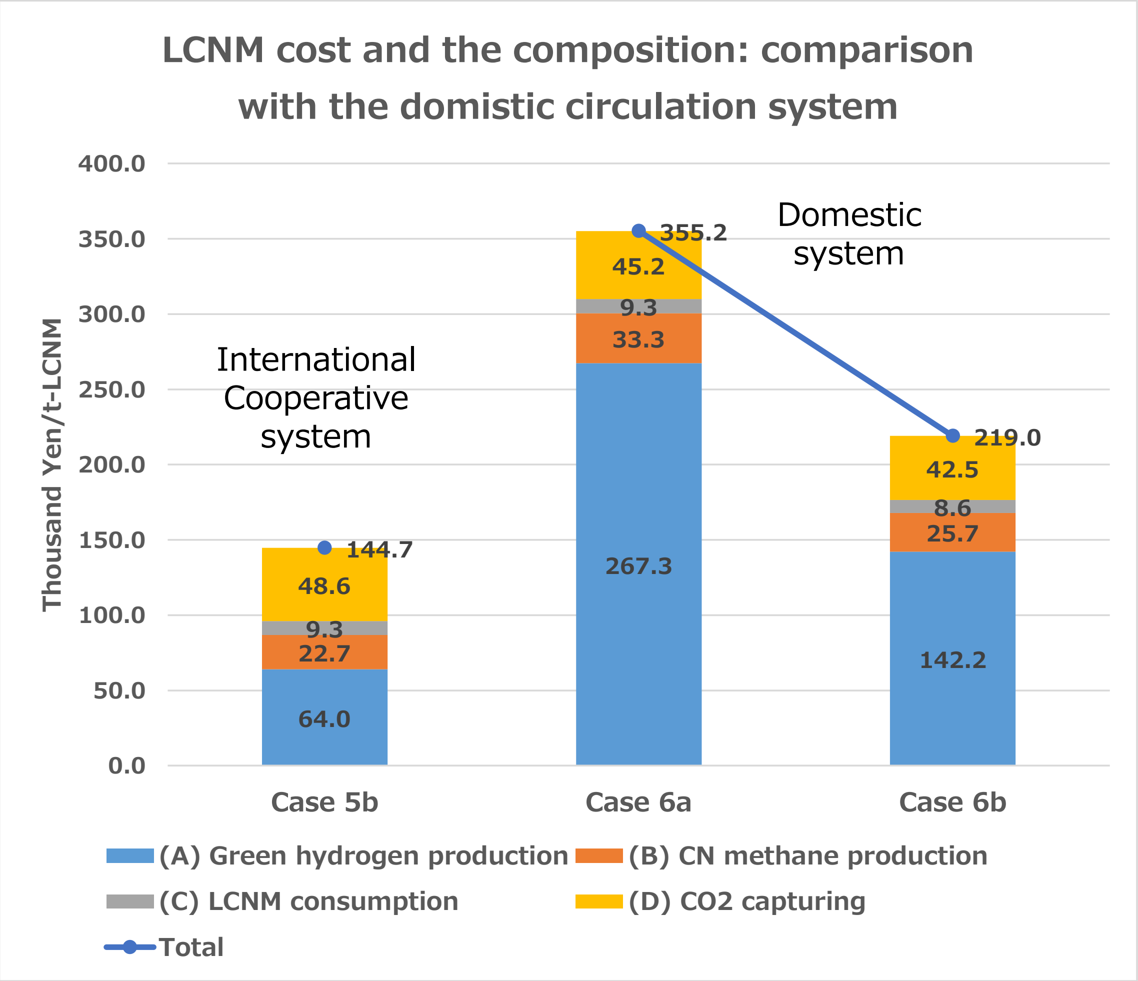
- In Case 6a, the domestic electricity price, assumed to be 10 yen, is higher than that of the resource-rich country, so the production cost of LCNM is 355 thousand yen/t, which is 2.5 times the cost of Case 5b.

- If the electricity price is halved, the cost of LCNM will be 219 thousand yen/t in Case 6b, which is 1.5 times that of Case 5b.

- As long as the cost of renewable energy generation is high, it is highly possible that an international cooperation system that produces hydrogen and synthesizes methane in the Middle East, where the cost of renewable energy is low, can be cheaper than producing everything in Japan.

- In order to realize the carbon cycle domestically, reducing the cost of hydrogen production, especially that of renewable energy power generation, and the cost of CO_2 capturing are important issues.

Figure 9



4. Concluding Remarks

Research findings

- Since each process of the carbon cycle has CO_2 emissions due to energy input, even if it is a sustainable carbon circulation system that replaces LNG completely, the net CO_2 emissions would not be zero. However, net emissions were 23.2% of total emissions in Case 3b. This reduced the CO_2 emissions (Case 0) of the original LNG by 68.2%.

- The total electricity input per one-ton of domestic consumption of LCNM is 28.8MWh, of which 93.39% is used for green hydrogen production in a resource-rich country (Case 3b).

- The LCNM production cost in the full carbon circulation system is 297 thousand yen/t (Case 3b), which is about 4.3 times higher than the reference case of LNG. This is due to the high cost in hydrogen production and CO_2 capturing.

- Cost reduction of water electrolysis equipment will reduce the LCNM cost to 165 thousand yen/t (Case 4c) (if reduced to 1/8). Furthermore, due to the reduction in Cryo-DAC cost (1/4), it will be 145 thousand yen/t (Case 5b), which is about twice the LNG cost in the reference case.

- If all carbon circulation systems are operated domestically, the LCNM price will rise to 355 thousand yen/t (Case 6a), which is nearly 2.5 times the 145 thousand yen/t of the corresponding international cooperation case (Case 5b). If the electricity price is halved, it will drop about 1.5 times to 219 thousand yen/t.

Implications of the research

- By substituting LNG with LCNM, about 70% of CO_2 emitted from LNG consumption will be reduced. In addition, when trying to capture CO_2 completely, it is necessary to capture more CO_2 than that required in methane synthesis.

- Operating all carbon circulation systems domestically is disadvantageous in terms of cost, and international cooperation with resource-rich countries with inexpensive and abundant renewable energy can reduce costs. This also matches the policy goals of resource-rich countries aiming for industrialization from resource extraction.

- In order to reduce high LCNM production costs, reducing the equipment cost of water electrolysis and Cryo-DAC is an issue. If these costs are sufficiently reduced, fossil fuels would be replaced by CN methane.

Remaining issues

- The values of energy intensity, CO_2 emission intensity, and unit cost of each process obtained from several research do not necessarily depend on similar condition, which constrains the results of our analysis.
- Our Cryo-DAC system is also under development to improve CO_2 capturing capacity and cost reduction. It is necessary to reflect these improvements in simulations in the future.

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