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A Feasibility Study on Hydrate-Based Technology for Transporting CO_2 from Industrial to Agricultural Areas

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Abstract: Climate change caused by global warming has become a serious issue in recent years. The main purpose of this study was to evaluate the effectiveness of the above system to quantitatively supply CO_2 or CO_2 hydrate from industrial to agricultural areas. In this analysis, several transportation methods, namely, truck, hydrate tank lorry, and pipeline, were considered. According to this analysis, the total CO_2 supply costs including transportation ranged from 15 to 25 yen/kg-CO_2 when the transportation distance was 50 km or less. The cost of the hydrate-based method increased with the transport distance in contrast to the liquefied CO_2 approach. However, the technology of supplying CO_2 hydrate had merit by using a local cooling technique for cooling specific parts of agricultural products.

Keywords: CO_2 hydrate; agro-industrial system; separation of CO_2; transformation; feasibility study

1. Introduction

The climate changes caused by global warming has become a serious issue in recent years [1]. Thus, the reduction of CO_2 emissions has become increasingly important. In this sense, solutions promoting industrial activity while reducing CO_2 emissions are required. One effective way of selecting environmentally favorable CO_2 sources for CO_2 utilization is of importance [2], and we proposed an agro-industrial system [3] as is shown in Figure 1. In this system, industrial and agricultural areas are connected. The former releases CO_2 and heat as a result of production processes, while the latter can make use of air-conditioning-derived heat and residual industrial heating for agricultural production. The main purpose of this study was to evaluate the effectiveness of the above system to quantitatively supply CO_2 or CO_2 hydrate from industrial to agricultural areas located within a distance of 50 km or less.

In this analysis, we focused on the utilization of hydrate transport technology in the agriculture field, especially facility horticulture. The supply of CO_2 by hydrate has the merit that it can simultaneously supply cold heat necessary for cultivation. These simultaneous supplies can keep the CO_2 concentration relatively high under suitable temperatures in greenhouses, so it is expected to increase the yield [4,5]. As an example of a city, more than 200 thousand tons of CO_2 are discharged from one factory in a year. On the other hand, the CO_2 necessary for photosynthesis is supplied by burning a boiler, and its supply amount is around 5–10 thousand tons a year in the agricultural field

[1,4]. If CO_2 is transported from industrial areas, it will be possible to reduce emissions of CO_2 by the combustion of boilers in agricultural areas.

We calculated the energy consumption and cost for separating CO_2 from an industrial exhaust gas stream via chemical absorption and transporting it to the agricultural area via boosting or hydration technologies. Several transportation methods, namely, truck, hydrate tank lorry, and pipeline, were considered. Finally, we compared the energy consumption and cost required for CO_2 separation and transportation by these methods and subsequently evaluated the effectiveness of the proposed system connecting agricultural and industrial areas.

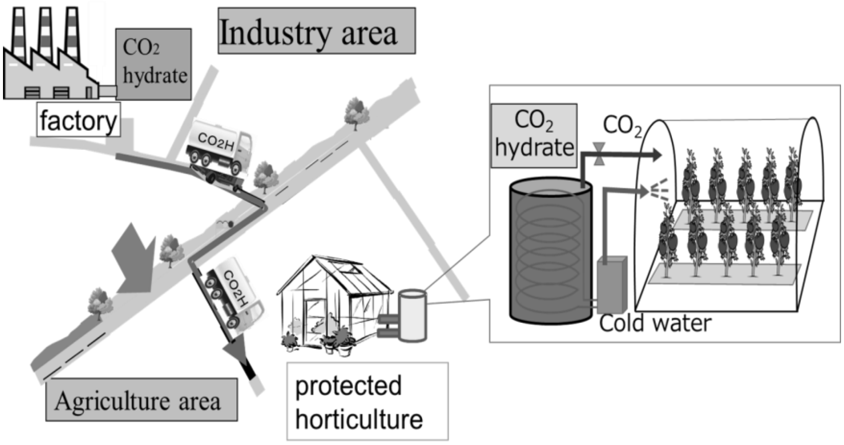

Figure 1. The agro-industrial system.

2. Outline of the CO_2 Supply System from Industrial Areas

2.1. Outline of Some CO_2 Supply Methods

We calculated the cost of the CO_2 supply system involving the separation of CO_2 from an industrial exhaust gas stream and the subsequent transportation of this CO_2 from industrial to agricultural areas. In this calculation, the cost of the CO_2 supply process was divided into transporting and collecting costs, and the collecting cost was further divided into separation and boosting costs. Table 1 shows some CO_2 supply methods considered herein.

Table 1. Some CO_2 supply methods.

Type	**Collecting**		**Transportation**
	Separating	**Boosting**	
(1)	Chemical absorption	Liquefaction	Truck
(2)	Chemical absorption	Hydration	Tank lorry
(3)	Chemical absorption	Compression	Pipe line

With regard to the pressurization and transportation of CO_2, three cases were considered:

(1) Truck type

CO_2 is separated from exhaust gas by chemical engineering, liquefied into the cylinder, and finally transported by truck.

(2) CO_2 hydrate type

CO_2 is separated from exhaust gas by chemical engineering, hydrated, and finally transported by tank lorry.

(3) Pipe line type

CO_2 is separated from exhaust gas by chemical engineering, compressed to 3.5 MPa, and finally transported by pipeline.

Figures 2–4 show the outline for each CO_2 separation and transportation process.

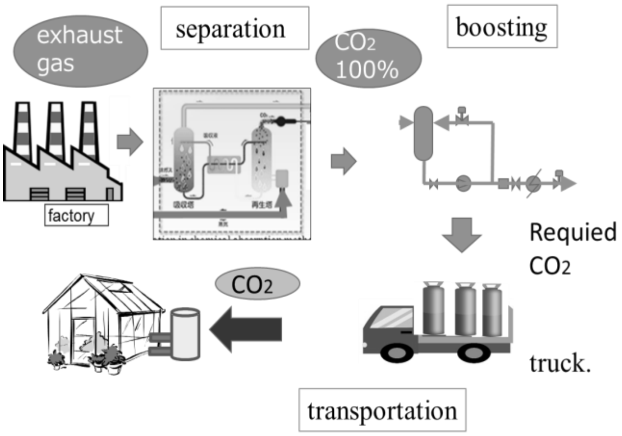

Figure 2. Transportation by truck type.

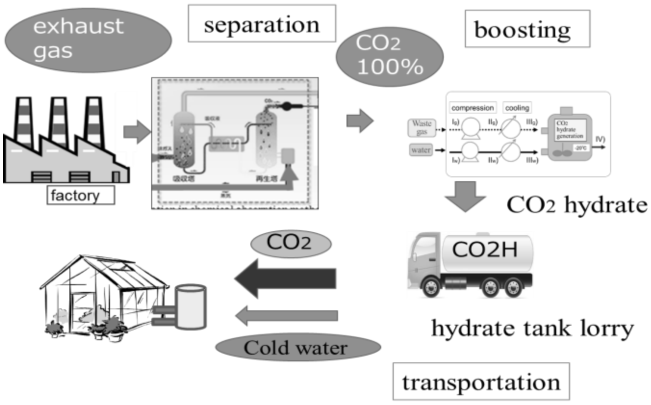

Figure 3. Transportation by pipeline type.

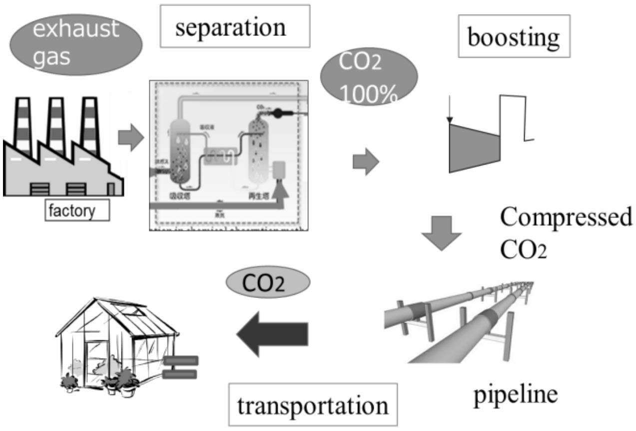

Figure 4. Transportation by pipeline type.

2.2. Basic Principle of Various Applied Separation and Recovery Devices

The CO_2 separation method and the various compression methods considered herein are presented next. Figure 5 describes the principle of a standard amine-based CO_2 absorption–desorption process [6]. The system was comprised of a simple absorber and desorber with a reboiler and a condenser, an amine/amine heat exchanger, pumps, and a cooler. The CO_2 from an exhaust gas stream is absorbed in the absorption column containing the amine solvent. Once absorbed, the CO_2-

rich amine solution is pumped from the absorption column through the amine heat exchanger where it is heated before entering the stripper for regeneration.

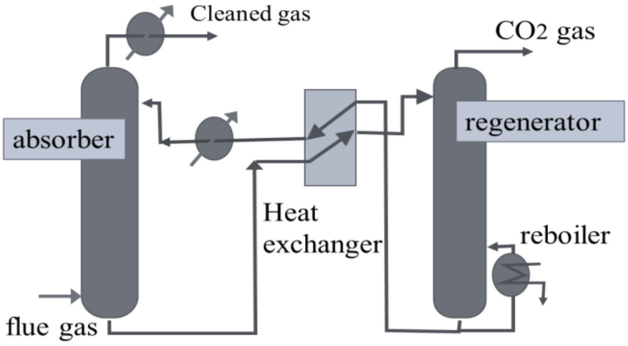

Figure 5. CO_2 absorption–desorption process.

Figure 6 shows the liquefying system of CO_2 [7], the CO_2 was subsequently liquefied with a high-pressure pump. This system allows for a flexible operation depending on the supply while eliminating manual handling of large amounts of gases in cylinders. A self-contained storage vessel consisting of a low-temperature-grade carbon steel coded vessel and insulation and control systems equipped with approved class valves, piping, and fittings was considered.

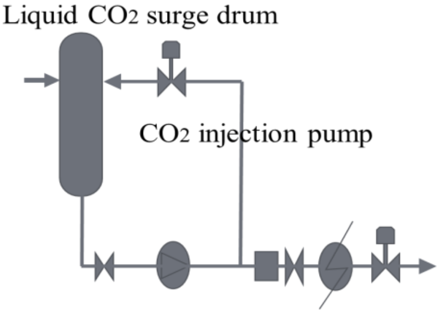

Figure 6. Liquefaction process of CO_2.

So far, CO_2 separation and capture from waste gas by means of CO_2 hydrate has been proposed [8–10]. Figure 7 shows the CO_2 hydrate production system [11]. This system was conducted in a stirring-vessel-type reactor at certain given conditions for hydrate formation. The pressure and temperature conditions for hydrate formation were set as operational variables for the energy consumption estimations. Herein, the base temperature and pressure were assumed to be 275 K and 2.0 MPa, respectively, and the hydrate formation rate depends on these conditions. The heat released during the formation of the hydrate was employed for pumping brine, while the cooling derived from the CO_2 release was employed to recover the brine temperature.

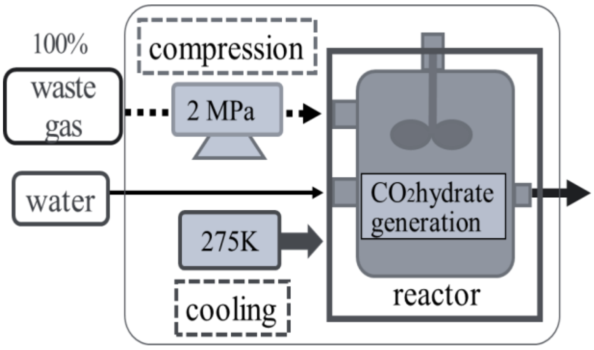

Figure 7. CO_2 hydrate production.

3. Calculating the Cost of the CO_2 Supply System

3.1. Calculating the Energy Consumption and Cost of the CO_2 Collection System

The main conditions employed for calculating the cost of the collecting system are shown in Table 2. Here, CO_2 collection efficiency and the collected rate of CO_2 were based on the value of the literature of the chemical absorption method [6].

Table 2. Conditions for calculating energy and cost.

Condition	Value	Unit
Coal-based power generation plant	1000	(kW)
CO_2 collection efficiency	90	(%)
Collected rate of CO_2	700	(t/h)
Amount of collected CO_2 per year	5000	(kt/y)
CO_2 density in the exhaust gas	20	(%)
Temperature of the exhaust gas	90	(°C)
Absorption tower inlet gas	3000	(km^3/h)
Annual operating time	8000	(h)
Electricity cost	12	(yen/kWh)
Years of depreciation	10	(years)
The number of employees	8	(-)
Thermal price	0.3	(yen/MJ)

3.1.1. Energy and Cost of Separating CO_2

Table 3 shows the cost and energy consumption of the main devices required for the operating chemical absorption method obtained from the literature [6]. With regard to the separation energy, we considered the power consumptions of main devices, such as the wash column, absorber, regenerator, reflux drum, heat exchange, booster fan, pomp, CO_2 pomp, and CO_2 compressor.

In the calculation of separation costs, capital (fixed) costs and operating (variable) costs were considered. Capital cost is the expense required to make the project commercially viable, and equipment costs and labor costs were considered in this analysis. The operating cost is the expenses related to the operation of equipment or equipment, in which we considered the electric power, the heat supplied, and the cooling water in this system. The total amount of electric power was calculated by considering the total power required for the separating equipment.

Table 3. Cost and energy consumption of the main devices in the chemical absorption method.

• **Main equipment**				
wash-column, absorber, regenerator, packing, reflux drum, heat exchange, booster fan, pomp, CO_2 pomp, CO_2 compressor				
• **Capital (fixed) cost**				
Equipment cost			1.2	(yen/kg-CO_2)
Labor cost			0.01	(yen/kg-CO_2)
• **Operating (variable) cost**				
Power	0.14	(kWh/kg-CO_2)	1.7	(yen/kg-CO_2)
Heat	2.5	(MJ/kg-CO_2)	0.8	(yen/kg-CO_2)
Etc.	52	(MJ/kg-CO_2)	0.4	(yen/kg-CO_2)

Equipment cost = (construction cost / depreciation period) / annual CO_2 collection amount; Construction cost = major equipment cost × 4.74 (Lang coefficient); Labor cost = (the number of employees × 4 Myen/ year) / annual CO_2 collection amount.

3.1.2. Boosting Energy and Cost of the Collected CO_2

(1) Liquefaction and compression

The boosting energy (i.e., the energy produced upon increasing the pressure of the exhausted gas) can be derived from Equation (1) under the assumption of an ideal gas adiabatically compressed [12].

$$E_{bst} = C_{v\_co2} \cdot T(\frac{p^{(\gamma-1/\gamma)'}}{p} - 1) \tag{1}$$

Here, Cv denotes the specific heat at a constant volume of CO_2, T is the absolute temperature before compression, p is the pressure before compression, p' is the pressure after compression, and γ is the fraction of specific heat of CO_2 in the exhausted gas.

The boosting cost of the liquefying facility requiring the pressurization of CO_2 is defined by Equation (2) obtained from the literature [7].

$$Y_{liq} = 160 \cdot \left(\frac{E_{liq}}{0.228}\right)^{0.7} \cdot 10^8 \tag{2}$$

(2) Hydration

With regard to the energy consumed in the hydrate method, the hydrating energy was obtained from the relationship between the hydrate formation energy and the temperature at various concentrations of exhaust gas (Figure 8), as previously reported in the literature [10]. As shown in Figure 8, the energy required for generating the hydrate greatly depended on the concentration of the exhaust gas. When directly generating the hydrate from the exhaust gas, the energy required was significantly large (1.6 kWh/kg-CO_2) owing to the low concentration of the exhaust gas (20%).

The formation of hydrates is a stochastic process and a subcooling is needed for hydrate formation in general. For this reason, a variety of studies on hydrate promoters has been performed to reduce the equilibrium pressure. In addition, CO_2 hydrate formation using supercooled aqueous nanodroplets [13] and using others such as ice at temperatures just below 273 K [14] or ice melting water [15] may also be a potential candidate for rapid CO_2 hydrate growth. Either way, it will be possible to reduce the energy consumed in the hydrate method.

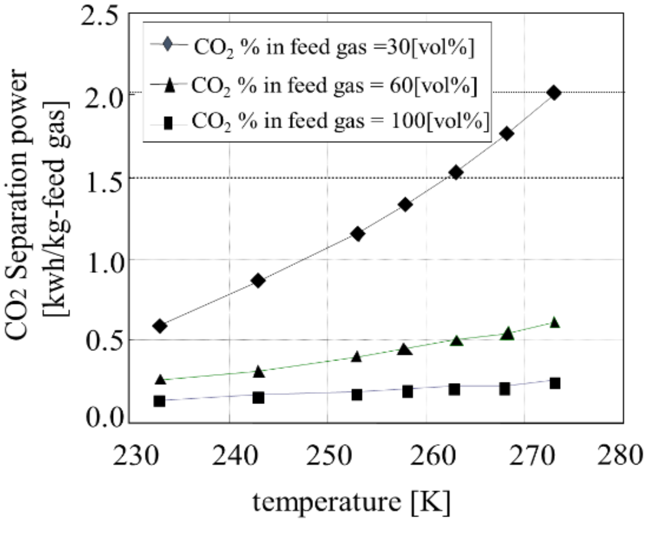

Figure 8. Relationship between hydrate formation energy and temperature at various concentrations of exhaust gas

With regard to the cost in the hydrate method, we considered the power consumptions of main devices, such as the reactor, agitator, cooling system, gas compressor, heat exchange, pomp, CO_2 pomp, and hydrate tube. The costs of the main equipment were determined from a literature value based on the material and pressure condition of the equipment [3]. Labor costs were determined according to the calculation by the chemical absorption method in Table 3.

3.2. Calculating the Cost for Transporting CO_2

3.2.1. Calculation of the Load Capacity

(1) Cylinder truck case

The CO_2 loading capacity of the cylinder truck was calculated at the conditions summarized in Table 4. The capacity was calculated from Equation (3), where the cylinder capacity for CO_2 was calculated according to Equation (4).

$$V_{\mathrm{CO2}} = V_{tr} \cdot \frac{V_{cyl}}{V_{cyl} + W_{cyl}} \tag{3}$$

$$V_{cyl} = \frac{V_{gas}}{V_{m\_CO2}} \cdot \frac{W_{m\_co2}}{1{,}000}. \tag{4}$$

Table 4. Calculation condition of CO_2 load capacity by gas bomb truck.

Condition	Value	Unit
Truck load capacity	10,000	(kg)
Gas filling capacity	7.00	(Nm^3)
Molar volume	0.0224	(Nm^3/mol)
CO_2molecular weight	44.0	(g/mol)
Cylinder capacity	13.75	(kg)
Weight of cylinder	52.00	(kg)

According to these equations, the CO_2 loading capacity per tank truck was calculated to be 3846 kg.

(2) Transportation of CO_2 hydrate case

The load capacity of the hydrate tank lorry was calculated with Equation (5). The container capacity was defined as the volume of the container multiplied by the density of the content. By using these equations, the loading capacity for transporting CO_2 hydrates was calculated. In this calculation, the same conditions (i.e., capacity, weight, and volume of the container) as the cylinder transportation case were used. The density of CO_2 hydrate was assumed to be 1.105 g/cm^3 [16]. The CO_2 loading capacity when a hydrate tank truck was used for transportation was calculated at the conditions summarized in Table 5. According to these conditions, the CO_2 loading capacity of CO_2 was calculated to be 2193 kg.

Table 5. Calculation condition of CO_2 hydrate load capacity.

Condition	Value	Unit
Tanker load capacity	10,000	(kg)
Container volume	47.0	(L)
Contents density	1.105	(kg/L)
Container weight	52.0	(kg)
Contents of container	43.09	(kg)

$$V_{tank} = V_{tr} \cdot \frac{V_{cyl}}{V_{cyl} + W_{cyl}} \tag{5}$$

$$V_{co2H} = V_{\mathrm{tank}} \cdot \frac{44}{44 + 103.5}. \tag{6}$$

Furthermore, we calculated the cooling heat of CO_2 hydrate. In this calculation, three types of heat were considered: latent heat generated upon CO_2 hydrate collapse into CO_2 gas and water, water generated when the CO_2 hydrate collapsed, and sensible heat increasing the temperature of the CO_2 hydrate increase from 5 (i.e., formulation temperature of CO_2 hydrate) to 25 °C (normal temperature). Subsequently, the amount of cooling heat supplied by CO_2 hydrate was calculated with Equation (7) at the conditions summarized in Table 6. According to Equation (7), the CO_2 loading capacity per tank truck was calculated to be 2,288 (MJ).

$$H_{co2H} = \frac{H_{gas\_co2H}}{0.044\cdot\left(\frac{44}{147.5}\right)} + C_{water}\cdot\left(\frac{103.5}{147.5}\right) + C_{gas\_co2}\cdot\frac{44}{147.5}\cdot 20. \tag{7}$$

Table 6. Calculation condition of cold load capacity.

Condition	Value	Unit
CO_2 hydrate load capacity	4,531	(kg-CO_2)
Heat of formation of hydrate	65.0	(kJ/mol-CO_2)
Specific heat of water	4.217	(kJ/kg·K)
Specific heat at CO_2	0.8518	(kJ/kg·K)
Cold supply	504.94	(kJ/kg·K)

3.2.2. Calculating the Transportation Cost

The transportation cost in the case of a cylinder truck or a CO_2 hydrate tank lorry was calculated with Equation (8) assuming that the cost per unit of transport volume was proportional to the transport distance.

$$Y_{trns} = \frac{\left(Y_{lo}/Y_{fc} + Y_{lab}\right)\cdot 2\cdot N_{tr} + Y_{mnt} + Y_{tr}/Y_{rp}}{D/2\cdot W}. \tag{8}$$

Here, it was assumed that the gas was filled in a container similar to a 47 L gas cylinder. The loading amount was defined as the maximum weight of CO_2 that a vehicle can transport with a 10 t cylinder. Additionally, in the case of CO_2 hydrate transportation, the amount of CO_2 loaded was calculated by considering the weight fraction of CO_2 in the CO_2 hydrate based on the number of CO_2 and H_2O molecules of this compound. We considered a light oil price of 108 yen/L, a fuel consumption of 3 L/km, a labor expense of 64 yen/km, a maintenance cost (e.g., insurance and tax) of 305,800 yen/number of truck/year, a truck price of 10,000,000 yen, a recovery period of 10 years, an annual mileage of 10,000 km/year, a cylinder capacity of 47 L, and a cylinder weight of 52 kg.

Furthermore, the CO_2 emissions associated with the transportation by vehicles were calculated as shown in Equation (9).

$$W_{em\_co2} = 2\cdot\frac{F_{lo}}{Y_{fc}}/W \tag{9}$$

3.3. Calculating the Cost in the Case of a Pipeline System

When using a pipeline system, the annual transport cost was assumed to be proportional to the transport distance and constant with respect to the transportation volume (i.e., the cost per unit of transport volume was inversely proportional to the annual volume transported). Therefore, the cost was calculated with Equation (10) using a reference value for the transportation cost corresponding to an annual CO_2 transport volume of 200,000 t [17].

$$Y_{p-trns} = 18{,}000/(w_{ann}). \tag{10}$$

4. Results and Discussion

4.1. Cost of the CO_2 Collecting System (Separation and Boosting Costs)

Tables 7 and 8 display the separation and boosting energies required for each method. The separation energy for the chemical absorption method was 0.39 kWh/kg-CO_2. The thermal energy cost required to separate CO_2 from the amine solution was high. With regard to the CO_2 separation system, a chemical absorption method involving an exhaust gas stream was considered. When using this system, we suggest that it is indispensable to reduce this thermal energy by using the exhaust heat. On the other hand, the CO_2 liquefying cost was considered to be 0.12 yen/kg-CO_2, according to previous reports. In the calculation of the hydrate method, the hydrate was generated from a pure CO_2 gas stream recovered by the chemical absorption method. The hydrate generation cost was relatively high value at this setting condition.

Table 7. Separation and boosting energies required for each method.

Collecting Method		Separation Energy (kWh/kg-CO_2)	Compression Energy		
			Liquefaction (kWh/kg-CO_2)	**Compression (kWh/kg-CO_2)**	**Hydrate (kWh/kg-CO_2)**
(1)	CA + LQ	0.13	0.12	---	---
(2)	CA + CO_2H	0.13	---	---	0.17
(3)	CA + CM	0.13	---	0.07	---

CA: chemical absorption (waste heat use); LQ: liquefaction; CM: compression; CO_2H: CO_2 hydrate.

Table 8. Collection cost for each method.

Collecting Method		Separation Cost (yen/kg-CO_2)	Compressed Cost (yen/kg-CO_2)	Collection Cost (yen/kg-CO_2)
(1)	CA+LQ	3.58	0.12	5.61
(2)	CA+CO_2H		0.17	6.02
(3)	CA+CM		0.07	4.76

CA: chemical absorption (waste heat use); LQ: liquefaction; CM: compression; CO_2H: CO_2 hydrate.

4.2. Cost of the CO_2 Transportation System

Table 9 shows the transportation results (i.e., the relation between the CO_2 loading capacity and the transportation cost). In particular, this table shows the amount of CO_2 emissions associated with the transportation process. The liquefied CO_2 loading capacity was large, and this method was therefore promising. Additionally, this CO_2 liquefaction system showed the lowest transportation costs among the methods studied herein. On the other hand, the transportation costs for compressed air (i.e., pipeline transportation) were large, although these values depended on the amount of CO_2 transported.

Table 9. Transportation results (CO_2 loading capacity and the transportation cost).

Transporting Method	CO_2 Load Capacity (kg/one truck)	Transportation Cost (yen/kg-CO_2/km)	Amount of CO_2 Emission (kg/kg-CO_2)
LQ (TR)	3,846	0.139	0.00045
CM (PL)	489.4	1.089	0.00357
CO_2H (HTL)	2,193	0.243	0.00080

LQ: liquid CO_2; CM: compressed gas CO_2; CO_2H: CO_2 hydrate; TR: truck; PL: pipe line; HTL: hydrate tank lorry.

4.3. Total Cost of the CO_2 Supply System

Figure 9 shows the relation between the total cost of the CO_2 supply system and the transported distance of CO_2 for each method. As can be seen, these costs, including transportation, ranged from

15 to 25 yen/kg-CO_2 for a transportation distance of 40 km or less. The supply cost per unit of CO_2 of the pipeline transportation mode increased while the annual transport volume decreased. Figure 10 shows the relation between the total cost of the CO_2 supply system and the annual CO_2 transport volume in pipeline in the case of the distance at 40 km. According to this figure, the pipeline transportation cost at an annual CO_2 transport volume of 52,000 t was comparable to those obtained by the transportation of a cylinder truck or of a CO_2 hydrate tank truck. Additionally, the pipeline transportation cost at an annual CO_2 transport volume of about 70,000 t was significantly larger as compared to other transportation methods in this condition.

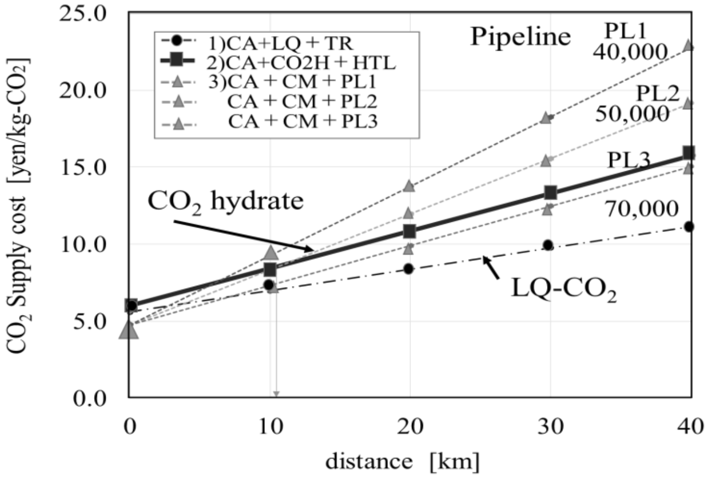

Figure 9. Relation between the total cost of the CO_2 supply system and the transported distance of CO_2 for each method.

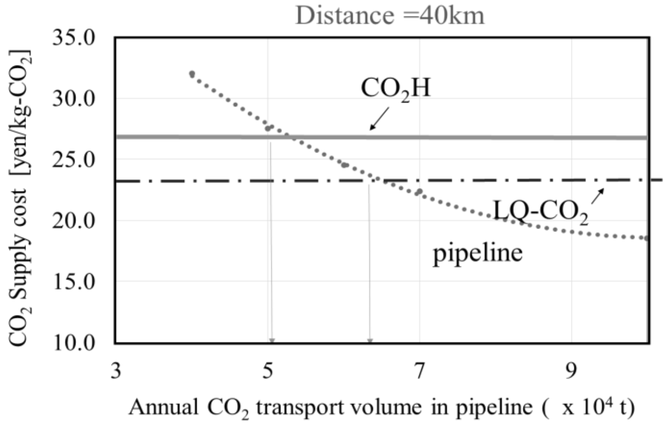

Figure 10. Relation between the total cost of the CO_2 supply system and the annual CO_2 transport volume in pipeline.

In this system, storage temperature of CO_2 hydrate in the container was assumed to be −20 °C under atmospheric pressure. Taking into account results of earlier studies on dissociation rates of CO_2 hydrate and CH_4 hydrate [18,19], CO_2 hydrate can be easily stored without its dissociation during the transportation process for several hours or up to a day. The potential of a natural gas hydrate pellet for long-term transportation of natural gas by means of gas hydrate has also been reported [20]. Further assessment will be required to compare the economic benefits of using pellet technology for CO_2 transportation.

4.4. Examining the Usefulness of the Supply of Cold via CO_2 Hydrate Transportation

In ordinary greenhouse cultivation, it is impossible to fertilize CO_2 because the cultivation house has to be ventilated in the daytime to prevent temperature from increasing inside. Since cold heat and CO_2 are simultaneously supplied, the utilization of CO_2 hydrates is expected to maintain an optimum temperature while fertilizing in the summer and without ventilating the greenhouse. Therefore, the possibility of CO_2 fertilization via CO_2 hydrate supply was evaluated by analyzing the cooling capacity of the CO_2 hydrates according to Equation (11). Generally, cold heat is also generated when CO_2 is supplied in a liquefied CO_2 cylinder. However, in view of the CO_2 supply rate and difficulty in taking out, this cold heat is not normally used at present. On the other hand, CO_2 hydrate can supply CO_2 and cold heat at the same time when hydrate is decomposed.

With regard to the amount of CO_2 fertilizer required, tomato cultivation was considered and the value was obtained from the literature [4]. The cold heat supplied by the CO_2 hydrates was calculated as the sum of the latent heat produced by CO_2 hydrate decomposition, the amount of water generated by decomposition, and the sensible heat equivalent to 20 °C. The temperature of the CO_2 gas must increase from 5 to 25 °C for CO_2 hydrate formation. At this time, the cooling capacity was 12 W/m^2.

$$H_{cool} = \frac{w_{dem\_co2}}{100} / 3{,}600 \cdot H_{co2H} \cdot 1{,}000. \tag{11}$$

The solar radiation is strong during summer days. Since the solar heat flux was 1200 W/m^2 or less, and the cooling capacity of the air conditioner was 200 W/m^2 or less in this season, the cold heat supplied by the CO_2 hydrates seemed to be insufficient for the cooling capacity of the greenhouse.

However, when the sun's solar radiation is weak, such as the spring and autumn season's morning and evening, there is merit for a simultaneous supply of CO_2 and cold heat by CO_2 hydrate. Local cooling technologies (Figure 11) that provide a cooling effect to agricultural crops by cooling only specific parts of crop plants have been studied in recent years [20], so the technology of supplying CO_2 by hydrate has merits. In this case, photosynthesis is accelerated by fertilization of CO_2 because it can maintain an appropriate temperature near plants by local cooling, and yield increase of about 20% can be expected. Although the transportation method by CO_2 hydrate is inferior to the CO_2 transport volume, we considered that this method has sufficient effectiveness in this field in combination with local cooling technology or for use in spring and autumn.

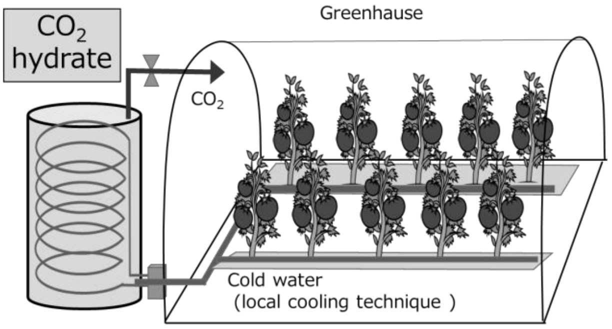

Figure 11. Utilization technology of CO_2 hydrate by combining with a local cooling method.

5. Conclusions

In this study, the feasibility of several systems using CO_2 or CO_2 hydrates supplied from industrial to agricultural areas was quantitatively evaluated from the viewpoint of profitability and CO_2 emission reduction. According to this analysis, the total CO_2 supply costs including transportation ranged from 15 to 25 yen/kg-CO_2 when the transportation distance was 50 km or less. Pipeline transportation costs at an annual CO_2 transport volume of about 70,000 t were comparable to those of a cylinder truck or a CO_2 hydrate tank truck. Among them, the cost of the hydrate-based method increased with the transport distance in contrast to the liquefied CO_2 approach. However, the technology of supplying CO_2 hydrate has merit, for example, by using a local cooling technique for cooling specific parts of agricultural products. In this case, photosynthesis is accelerated by fertilization of CO_2 because it can maintain an appropriate temperature near plants via local cooling, and a yield increase of about 20% can be expected. The CO_2 supply system presented herein supplied CO_2 at a low cost and with low CO_2 emissions, and the feasibility of the proposed system was shown from the viewpoint of profitability and CO_2 emission reduction.

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Author Contributions: S. Matsuo, S. Takeya, H. Umeda, and T. Fujita conceived and designed the experiments; S. Matsuo and S. Takeya analyzed the data; S. Matsuo, H. Umeda, and T. Fujita wrote the paper.

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

Latin symbols

T	Temperature (°C)
P	Pressure before compression (MPa)
γ	Ratio of specific heat of CO2 (-)
Y	Cost (yen)
E	Power consumption (J/s)
C	Constant value (-)
W	Weight (kg)
V	Capacity (m^3)
H	Heat (J)
N	Times (-)
D	Distance (km)
F	Factor (-)

Subscripts

bst	Boosting
liq	Liquefaction
tr	Truck
cyl	Cylinder
m	Molecules $_2$
gas	Gas filling
CO_2H	CO_2 hydrate
lo	Light oil
fc	Fuel consumption
mnt	Maintenance
em	Emission of light oil
tank	Tank lorry
pl	Pipeline
ann	Annal transport volume
dem	Demand for CO_2
lab	Labor

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