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Proposal of Agro-Industrial Integration Heat Transport System Using High-Performance Medium for the Realization of a Sustainable Society

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Abstract: The aim of this study is to propose an agro-industrial heat transport system from industrial to agricultural areas for horticultural facilities with high heat demand to fill the problematic gap in the current heat transport system, and to derive by simulation the conditions under which this system can be used economically as well as environmentally. In this study, HASClay was used as a high-performance medium. HASClay has the ability to supply carbon dioxide (CO_2) at the same time as heat and dehumidify the inside of the house, so it can be expected to increase the yield in addition to reducing the environmental load by using heat. The simulation results show that the proposed system of supplying heat to a large greenhouse in HASClay in 20-ton containers would have an economic budget similar to that of the previous system, but with an environmental impact of about 80% less tomatoes and 84% less chrysanthemum fuel than the previous system of heating with fuel oil. On the other hand, the analysis showed that the power of the fan could be reduced as an improvement of the heat transport problem using HASClay. As a countermeasure, the use of natural energy and the change of the fan for heat supply from a damper system to an inverter system to control the air volume were considered. For transport to the 10a scale, which has environmental advantages, a system was proposed in which the heat from the HASClay is divided into mini-tanks and transported to stations envisaged in each region, where it is collected by the agricultural producers. In summary, the authors concluded that our proposal for an agro-industrial fusion system based on the transport of heat using HASClay is an effective method for the realization of a sustainable society. The environmental benefits of the project are likely to attract participation from the industrial sphere in order to meet future demands for CO_2 reductions.

Keywords: high-performance media; heat transport; agro-industrial integration; HASClay; CO_2 application; dehumidification

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Citation: Matsuo, S.; Suzuki, M.; Shimazu, T. Proposal of Agro-Industrial Integration Heat Transport System Using High-Performance Medium for the Realization of a Sustainable Society. *Energies* **2022**, *15*, 1211. https://doi.org/10.3390/en15031211

Academic Editors: Paula Fernández González and María José Presno

Received: 30 December 2021
Accepted: 4 February 2022
Published: 7 February 2022

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1. Introduction

Greenhouse gases, which cause global warming, have become an issue. In Japan, measures such as the adoption of renewable energy are being considered to reduce greenhouse gas emissions by 26% in 2030 compared to 2013 [1]. Various studies have been carried out to reduce greenhouse gas emissions. For example, in the Asian region, it was found that emission reductions of approximately 50% to 90% are required, with the largest reductions in Malaysia and Thailand, where at least 50% of the primary energy supply must come from low-carbon sources such as renewable energy and nuclear power [2]. In the verification of decentralized energy systems, a comprehensive evaluation model was developed to provide a basis for future evaluation of decentralized energy system construction [3]. An approach for improving the efficiency of biomass use [4], comparing macro energy scenarios, and quantifying the impact on economic and social development for Kosovo and China regions has been proposed [5,6].

However, it is difficult to reduce carbon dioxide (CO_2) emissions simply by extending the development of conventional technologies, and innovative thinking is needed. Among these, CO_2 reduction through inter-plant and inter-industrial networks is considered to be one of the ways to solve these problems [7]. A considerable amount of unused waste heat exists in factories and industries such as electric power, chemicals, and steel, and effective use of this unused waste heat in other fields has a significant effect on energy conservation and reduction of greenhouse gas emissions. Offline heat storage transport system is a technology to bridge these gaps, and some examples of using various heat storage materials have already been reported [8,9]. In this report, a system is proposed for off-line transport of waste heat generated from waste incineration plants, etc., which is stored in tanks filled with latent heat storage material and transported by vehicles. A simple transfer type latent heat storage system has been developed that is smaller than a conventional trans-heat container, to reduce the number of vehicles required and the space required for installation and delivery, thus reducing the initial and running costs and promoting the use of waste heat [10,11]. Then, it was analyzed from the three viewpoints of energy requirement, exergy loss, and CO_2 emission that affect the heat source and heat storage material in this system. As a result, when supplying hot water with a waste heat temperature of 200 °C, supply water temperature of 50 °C, transportation distance of 20 km, container loading weight of 2.4 to 104 kg, and 50 °C, Kerosene is used as the energy requirement of this system using erythritol. It is reported that the exergy loss is 8.1% and the CO_2 emission is 20.2%, which is a reduction of 7.7% compared to the conventional system [12,13].

The authors have targeted heat transport systems that transport unused energy from the industrial area to the agricultural area in order to reduce CO_2 emissions, reduce cultivation costs and increase yields. Although CO_2 emissions from agriculture, forestry, and fisheries industries account for only around 3% of Japan's total emissions, it is still considered to be an issue to be resolved [14]. In agriculture, efforts to reduce methane and nitrogen emissions are also required. Methane emission reduction technologies include paddy irrigation management and improved fertilizer use, while nitrogen emission reduction technologies include slow-release fertilizers and nitrification inhibitors, but there is a need to continue to establish technologies and develop new emission reduction technologies [15]. In Japan's agricultural sector, particularly in facility gardening, a large amount of fuel oil is still used for heating to reduce costs, and this conversion has become a major concern. In facility horticulture, utility power costs such as heating costs account for 20–30% of total costs and have a significant impact on profits. Therefore, the use of unused energy from industrial areas is an effective measure to solve the problem of reducing CO_2 and cultivation costs in the agricultural area. Although heat transportation systems are effective in reducing CO_2, some concerns have been identified, such as improving the density of heat storage materials and finding ways to reduce transportation labor costs [16,17].

In this study, a heat transport system from the industrial area to the agricultural area, notably for horticultural facilities with high heat demand, was envisioned. In particular, it was considered to overcome the economic problems by providing added value other than heat by using a functional medium instead of simply transporting heat. HASClay is an inorganic moisture-absorbing and -desorbing material that is a composite composed of amorphous aluminum silicate and low crystalline clay, which is synthesized from an inexpensive industrial raw material. It has high repeatability and has a larger adsorption amount than other adsorbents at a relative humidity of 40% or more [18]. HASClay has also been applied to the development of open adsorption heat storage heat pump systems. HASClay can use low-temperature waste heat, and the storage and heat dissipation characteristics of the packed bed have already been clarified [19,20]. A simulation model of the adsorbent heat storage tank has been proposed by comparing the calculation results of heat storage and heat storage with the experimental results [21]. From the hydration enthalpy value obtained from the calorific value measurement experiment and the water vapor adsorption isotherm of HASClay, the heat of hydration for each relative vapor pressure at the time of water vapor adsorption to HASClay can be obtained [22,23]. Demonstration tests of offline heat transport systems were conducted using HASClay adsorbents [24]. It was confirmed that the regeneration efficiency of 90% or more was stored by storing heat in the cogeneration system, transporting the heat storage material to the swimming center by a trailer truck, and supplying it as a heat raising heat source such as pool water.

On the other hand, various energy and environmental assessments have been considered in agricultural production processes. Yamamoto et al. defined the concept of carbon-related energy, which links energy consumption and CO_2 emissions [25]. Hori et al. assessed the energy required to produce 1 kg of vegetables as the environmental impact of consumption of major vegetables [26,27]. This shows that the energy required to produce 1 kg of tomatoes in a winter–spring greenhouse requires 4241 kcal–11,948 kcal of heat to be obtained from external sources, depending on the type of greenhouse. As an energy saving technology, the use of biomass and thermal storage environmental control systems for tomato production systems have been reported [28,29]. In a study of agricultural production and energy, it was found that although agricultural production should inherently aim at efficient use of solar energy, the input auxiliary energy in actual production is as high as 38% of the total, 22.6% for vegetables and 23.3% for fruit trees [30]. In addition, as the environmental burden in the production and transportation process of vegetables, the direct and indirect CO_2 emissions were estimated by commodity and time period based on vegetable production costs and wholesale market and trade data, and a comparison of eco-efficiency was made using nutrient content as the functional unit [31]. As a result, the total CO_2 emissions from the production and transportation of domestically produced vegetables were about 5.8 million tons, and the emissions per kg of vegetables were 280 g CO_2 for production and 130 g CO_2 for transportation. By category, the CO_2 emissions of root vegetables were relatively low, while those of fruit vegetables were high [32]. The life cycle assessment (LCA) of vegetable production has also been discussed [33,34]. According to this, the utility costs are more than twice as high for winter production as for summer, and it is clear that greenhouses are essential for the production of summer vegetables in winter, and that the supply of heat by heating has a very high environmental impact. Nishizono et al. investigated LCA of vegetables, including not only the production but also the energy required for distribution [35,36]. As a result, the production energy of vegetables in Gunma Prefecture was approximately 11,000 kJ/kg. The distribution energy, when considering the shipment from Gunma to Tokyo, was about 400 kJ/kg, a much smaller value than the production energy. It was considered that local production and consumption of vegetables could reduce the environmental impact by 20–40% in terms of energy.

The structure of this study is as follows. The aim of this study is to propose an agro-industrial heat transport system from industrial to agricultural areas for horticultural facilities with high heat demand to fill the problematic gap in the current heat transport described above, and to derive by simulation the conditions under which this system can be used economically as well as environmentally. Therefore, instead of simply transporting heat, we consider using a high-performance heat storage material to provide additional value at the same time as heat and overcome the economic problem of concern. HASClay was used as a high-performance medium. HASClay has the ability to supply CO_2 at the same time as heat and dehumidify the inside of the house, so it can be expected to increase the yield in addition to reducing the environmental load by using heat. If this proposed system can reduce CO_2 emissions in an economically viable way in the agricultural sector, it will enable the industrial world to benefit from the heat that has been emitted, and it will encourage more people from the industrial section to enter into these proposals. Furthermore, in the agricultural field, if this system can reduce the utility cost, which accounts for 20% to 30% of the total cost of crops, it will be of great benefit to introduce this system, and as a result, it will be a win–win relationship for both parties.

In the analysis, first, an agro-industrial area was assumed. Next, the cost and energy of the heat supply and transport from the industrial area to HASClay was calculated. In the agricultural area, the heat demand of different products, CO_2 application and dehumidification are calculated. As a case study to test the effectiveness of the system, 2 ton and 20 ton trucks, tomato and chrysanthemum crops, 20 a and 200 a greenhouses, and winter and summer seasons were chosen. As the method of transporting heat, the case of transporting only heat and the case of transporting heat and CO_2 by HASClay were assumed. The simulation results are analyzed in terms of cost and economy to investigate the suitable conditions for the heat transport in the HASClay. Furthermore, based on the results obtained, the effectiveness of the proposed system and its improvements are discussed.

2. Assumption of Target Area

2.1. Outline of the Target Area

Here, based on the data of a core city [37,38] with a population of about 60,000 in Japan that actually exists, it was assumed that there would be an industrial area in which major industries such as the automobile industry exist, and where Japan's leading agricultural area exists within an area of about 40 km. The following assumptions were made for the industrial and agricultural areas. In the industrial area, we envisioned an industrial area where steelworks, automobile factories, power plants and related factories exist. Therefore, it is possible to recover waste heat and CO_2 from boilers and exhaust gas removal equipment, and it is thought that the supply of heat transportation from this area can be sufficiently satisfied. As for agricultural areas, it was assumed that institutional horticulture would cultivate suburban vegetables such as tomatoes, cucumbers and melons, and flowers such as chrysanthemums and carnations; furthermore, vegetables such as cabbage, broccoli, and lettuce are cultivated in outdoor cultivation. As for the cultivation scale, it is assumed that there are small greenhouses such as 10 a and large greenhouses of 200 a scale.

The effectiveness of the agricultural–industrial fusion system using HASClay in this assumed area was verified (Figure 1). In this area, we previously conducted a feasibility study assuming CO_2 transportation from the industrial area to the agricultural area [39]. The study compared the transport of CO_2 by conventional cylinders with that by CO_2 hydrates. Gas hydrate, also called a water clathrate compound, is a hydrogen-bonded cage-like structure of water molecules in which molecules of other substances enter [40,41]. This substance has the characteristic of being produced under high pressure, as typified by methane (CH_4) hydrate and CO_2 hydrate [42,43]. Here, we examined a case study of transporting CO_2 and CO_2 hydrate supplied from an industrial area to an agricultural area and using them in agriculture. The CO_2 supply cost was about 15 to 25 JPY/kg-CO_2 when the transportation distance was 50 km or less. In addition, the pipeline transportation cost when the annual CO_2 transportation volume is about 70,000 tons is about the same as that of cylinder cars and CO_2 hydrate tank cars. Among these, the hydrate method is different from the liquefied CO_2 method, and the cost increases as the transportation distance increases. However, although CO_2 transport is an effective use of emitted gas, it has been found that it does not contribute much to the reduction of CO_2 in the region. Therefore, we have decided to consider simultaneous transportation of heat and CO_2 this time. The data used for the simulation of CO_2 transport can be used for this analysis.

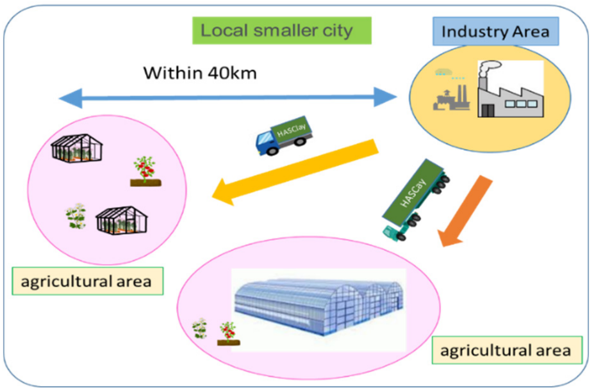
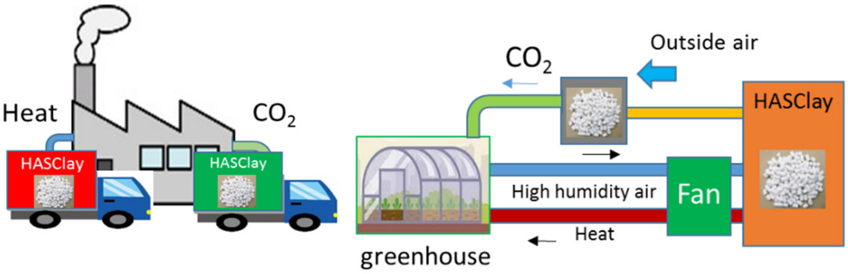


Figure 1. Overview of agricultural–industrial fusion heat transport system.

2.2. Heat Transport and Its Supply Method

HASClay is a highly functional heat storage material that can be used as an unused low-temperature heat source at 100 °C or lower, and there are some examples of heat transport [18]. This adsorbs (dries) heat in high-temperature exhaust gas during heat storage, as well as moisture, and releases heat during heat dissipation after transportation. That is, it is possible to dehumidify the greenhouse while supplying heat. HASClay also adsorbs CO_2 from exhaust gases, adsorbing about 3% of CO_2 by weight during heat storage. The CO_2 adsorbed on the HASClay is released at the same time as heat, and once adsorbed on zeolite, CO_2 can be supplied by airflow during the day when photosynthesis occurs. Therefore, the use of HASClay can be considered to increase crop production through CO_2 application and dehumidification in the greenhouse and heat.

Figure 2 shows a method for supplying and discharging heat and CO_2 in this heat storage material. In the heat supply, a two-stage system, that is, a system in which the heat supplied from the boiler exhaust gas is adsorbed and then CO_2 is adsorbed from the exhaust gas, enables simultaneous supply of heat, CO_2 and heat. In this case, it was assumed that the exhaust gases used to store CO_2 were equipped with desulphurization and other facilities that would not affect agricultural use. On the other hand, in the heat emission in the agricultural area, heat and CO_2 are regenerated by first sending the high-humidity air in the greenhouse to the heat storage medium by fan. Then, the heat is sent to the greenhouse, and CO_2 is adsorbed by another adsorbent again, and CO_2 is supplied by the outside air when CO_2 addition is required.



(**a**) Heat and CO_2 storage (**b**) Heat and CO_2 emissions

Figure 2. Heat and CO_2 supply and emission methods by HASClay, (**a**): case where heat and CO_2 are stored, (**b**): case where heat and CO_2 are emitted.

3. Calculation of Supply in the Industrial Area

3.1. Heat Supply Cost

Table 1 shows the conditions for calculating the cost of heat supply. For heat supply, it was assumed that exhaust gas would be supplied from a steel mill in an industrial area. The amount of heat that can be recovered from the exhaust gas is calculated by the following equation.

$$\begin{aligned}\text{Recoverable heat }(\mathrm{W}) = {} & \text{Exhaust gas amount }\left(\mathrm{m}^3/\mathrm{s}\right) \\ & \cdot \text{Exhaust gas specific heat }\left(\mathrm{J}/\mathrm{m}^3\ {}^\circ\mathrm{C}\right)\text{ (exhaust gas temperature} \\ & - \text{heat storage material recovery temperature) }({}^\circ\mathrm{C})\end{aligned} \quad (1)$$

Table 1. Calculation conditions (heat supply cost).

Category	Detail Item	Value	Unit
Truck	Cargo bed volume	61,374	(L)
	Maximum loading	2000	(kg)
HASClay heat transportation	Density	1.04	(kg/L)
	Heat storage density	588	(kJ/L)
	Loading capacity	1923	(L)
	Price of HASClay	1000	(JPY/kg)
	Number of times HASClay can be used	10,000	(times)
	Recovery temperature of HASClay	100	(°C)
	Amount of heat that can be transported by 2 ton truck	0.374	(MJ/s)
Heat supply	Amount of exhaust gas	17,000	(Nm^3/h)
Exhaust gas	Exhaust gas temperature	180	(°C)
	Specific heat of exhaust gas	0.25	($\mathrm{kcal}/\mathrm{Nm}^3\cdot{}^\circ\mathrm{C}$)
	Recovery temperature of heat storage material	100	(°C)
Heat storage capacity	Recoverable heat	0.395	(MW)

Based on the exhaust gas volume of 17,000 Nm^3 /h, the exhaust gas temperature of 180 °C and the recovery temperature of the husk clay of 100 °C shown in Table 1, the recoverable heat is calculated to be 0.395 MW. For HASClay, the amount of heat that can be carried in a container is calculated by the following equation.

$$\begin{aligned}&\text{Transport heat quantity }(\mathrm{kJ}) \\ &= (\text{Maximum load weight}(\mathrm{kg})\ /\ \text{Heat storage density }(\mathrm{kg}/\mathrm{L})) \\ &\cdot \text{Heat storage capacity }(\mathrm{kJ}/\mathrm{L})\end{aligned} \quad (2)$$

As a result, the amount of heat that a 2 t truck can carry is 0.374 MW. The amount of heat stored from the exhaust gas was 0.395 MW, and the heat storage time is about 1–2 h, which is not so long. On the other hand, the amount of CO_2 adsorbed at the same time is assumed to be about 200 kg, considering that 1% of 2 tons of HASClay is recovered from the exhaust gas from the device that separates and recovers several tons of CO_2 per day.

3.2. Transportation Costs

Table 2 shows the conditions for calculating the heat transport cost. Transportation costs, fixed costs, and HASClay heat dissipation electricity costs were calculated. The transportation cost was calculated by the following Equation (7).

$$\begin{aligned}&\text{Transportation }\cos\mathrm{t}\ (\mathrm{JPY}) \\ &= (\text{Transportation distance }(\mathrm{km})/\text{Fuel consumption }(\mathrm{km}/\mathrm{L})) \\ &\cdot \text{Light oil }\cos\mathrm{t}\ (\mathrm{JPY}/\mathrm{L})\end{aligned} \quad (3)$$

Fixed costs consist of labor costs, truck insurance costs, HASClay costs, and depreciation costs. Depreciation is the sum of truck costs, heat storage equipment costs, and heat dissipation equipment costs. Labor costs are calculated from labor costs and working hours, and HASClay costs are calculated from HASClay costs and their transportation capacity. The electricity cost for the heat dissipation equipment of HASClay is calculated by the following equation.

Table 2. Calculation conditions (transportation cost).

Category	Detail Item	Value	Unit
Transportation cost	Container weight 1	2000	(kg)
	Truck fuel consumption	10	(km/L)
	Container weight 2	200,000	(kg)
	Truck fuel consumption	4	(km/L)
	Number of containers	2	(pieces)
	Travel distance	16	(km)
	Diesel fuel charge	120	(JPY/L)
Fixed cost	Labor cost	250,000	(JPY/month)
	Amortization period	10	(year)
	HASClay price	1000	(JPY/kg)
	Cost of air blowing fan	500,000	(JPY)
Electricity costs for heat dissipation	Fan power	10.08	(kJ/MJ)
	Unit cost of electric power	5.744	($\times 10^{-3}$ JPY/kJ)
Cost of heavy oil heating equipment	Unit calorific value	39.1	(GJ/kl)
	Price of heavy oil	81.1	(JPY/L)
Calculation of CO_2 emissions factor	Diesel oil	2.619	(kg-CO_2/L)
	Electricity consumption	0.143	($\times 10^{-3}$ kg-CO_2/kJ)
	Heavy oil	2.71	(kg-CO_2/L)

The amount of CO_2 emitted by the heat transport system by HASClay was calculated as the sum of the amount emitted by truck transportation and the amount emitted by the power consumption of heat dissipation equipment. Emissions from the truck and emissions from the power consumption of the heat dissipation device were calculated by the following equations, respectively [8]. The CO_2 emissions of heavy oil heating equipment are measured assuming that they are emitted only by heavy oil combustion.

$$\begin{aligned}\text{Electricity } \cos\text{t (JPY)} \\ &= \text{Heat dissipation (MJ)}\cdot \text{Fan power (kJ/MJ)} \\ &\cdot \text{Unit price of power (JPY/kJ)}\end{aligned} \tag{4}$$

$$\begin{aligned}\text{Emissions from truck } (\text{kg} - \text{CO}_2) \\ &= (\text{Transportation distance (km) / Fuel consumption (km/L)}) \\ &\cdot \text{Light oil CO}_2 \text{ emission factor } (\text{kg} - \text{CO}_2/\text{L})\end{aligned} \tag{5}$$

$$\begin{aligned}\text{Emissions of heat dissipation equipment } (\text{kg} - \text{CO}_2) \\ &= \text{Heat dissipation heat (MJ)}\cdot \text{Fan power (kWh / MJ)} \\ &\cdot \text{CO}_2 \text{ emission factor } (\text{kg} - \text{CO}_2/ \text{ kWh})\end{aligned} \tag{6}$$

4. Calculation of Demand in the Agricultural Area

4.1. Heating Demand for Heat Transport

As the climate of the region is similar to the average conditions in Japan, from the analysis it was estimated that the heat demand for heating in this region is from January to April and from November to December. Based on this heating demand, the fan power cost for heat dissipation of HASClay, which is a fixed cost of the transportation system, is calculated. Table 3 shows the yield, sales, and heavy oil consumption per unit area of major crops according to the survey data of Higashimikawa [38]. Tomatoes had the highest production per unit area, almost four times that of chrysanthemums. The production value per unit area was higher for strawberries and tomatoes. These results indicate that CO_2 application has a significant effect on increasing the production of tomatoes in particular. The cost of heavy oil required for production, the amount of heat, and the amount of CO_2 emitted were calculated based on these data.

Table 3. Production, sales, and heavy oil usage for each crop.

Cultivated Varieties	Production per Area (kg/a/year)	Profit per Area (JPY/a/Year)
Tomato	1019	31.9
Strawberry	422	36.8
Melon	224	9.20
Chrysanthemum	280	9.97
Cabbage	526	1.93
Broccoli	199	0.80
Cabbage	526	1.93

Figure 3 shows the amount of heavy oil used for production per crop per unit area. According to this, the highest amount of heavy oil used in crop production is chrysanthemum, which is 1.4 times that of tomato.

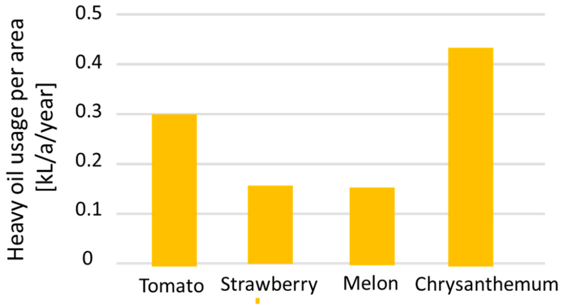


Figure 3. Amount of heavy oil used for production per crop per unit area.

Figure 4 shows a comparison of the amount of heavy oil used between fruits and flowers in crop production per unit area and the amount of CO_2 emitted by the use. This result also suggests that the amount of heavy oil used is higher than that of fruits, and that the production of flowers requires high energy for heating. The amount of CO_2 emitted by the flowers is about twice that of the fruits. These are important factors in comparing the energy required for production of each crop in the analysis of later case studies.

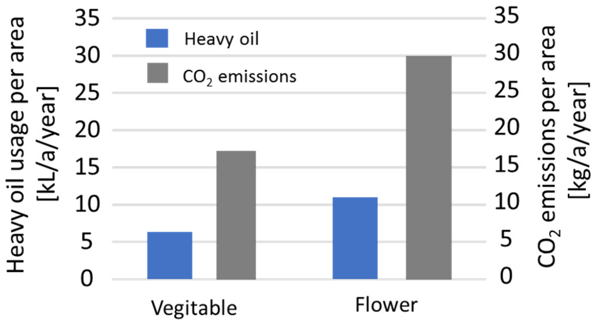


Figure 4. A comparison of the amount of heavy oil used between fruits and flowers in crop production per unit area and the amount of CO_2 emitted by the use.

4.2. CO_2 Demand

The amount of CO_2 required for the growth of each crop was calculated [44]. In this calculation, the dry weight of the yield is first calculated. Carbon weight is then calculated from the ratio of carbon weight to dry matter weight. Then, the amount of CO_2 required to satisfy the carbon weight is calculated. Here, the water content of the plant was assumed to be 90%. Table 4 shows the results of calculating the CO_2 requirements of six varieties of chrysanthemum, tomato, melon, strawberry, broccoli, and cabbage. From these results, it can be seen that melon, strawberry and chrysanthemum have high CO_2 content, but tomato has low CO_2 content.

Table 4. Calculation result of CO_2 required for crops.

Cultivated Varieties	Dry Matter Content per 1 kg (kg)	Carbon Content (kg)	CO_2 Equivalent (kg)
Tomato	0.08	0.03	0.13
Melon	0.15	0.08	0.27
Strawberry	0.12	0.05	0.18
Cabbage	0.10	0.04	0.15
Broccoli	0.10	0.04	0.15
Chrysanthemum	0.11	0.04	0.16

Finally, the amount of CO_2 fertilizer required in this area was calculated from the yield of each crop. CO_2 application is generally applied by burning kerosene or liquefied carbon dioxide cylinders. The general method of application is to compensate for the lack of CO_2 in the greenhouse, which has been squeezed for heat retention, and maintain the concentration at 500 ppm. According to Ref. [11], the amount of CO_2 fertilizer applied in winter is approximately 18 kg for 10 a and 360 kg for 200 a, and these amounts will be covered by the CO_2 carried by HASClay this time. From the analysis in the previous chapter, it is considered that these are sufficiently satisfied.

4.3. Effect of Increasing Yield by CO_2 Application and Dehumidification

Many works in the literature have documented the effect of carbon dioxide application on increasing revenue. For example, in tomato cultivation, yield increases by 19% when the carbon dioxide concentration in the greenhouse is 350 ppm, and by 16% when the concentration is 450 ppm [45]. In the case of chrysanthemums, it has been reported that the use of carbon dioxide gas in winter ring cultivation increased the weight of cut flowers by about 20% and the number of flowers shipped by 13% [46]. Regarding the estimation of dehumidifying effect, a regional survey revealed that tomatoes increase the yield in winter by 30% by reducing fruit cracking and hygroscopic diseases and dehumidification of the greenhouse in chrysanthemums controls the decrease in flowering rate due to increased dew condensation during the rainy season.

In consideration of these, as shown in Table 5, it was hypothesized that the effect of CO_2 application increased by about 30% for tomatoes and about 10% for chrysanthemums when fertilized at a CO_2 concentration of 500 ppm in winter. Since the greenhouse is open during the day, except in winter, the effect of CO_2 application was expected to be less than in winter. Dehumidification, on the other hand, was projected to enhance yield by 10% for chrysanthemums and 30% for tomatoes.

Table 5. Increased effect of product production by CO_2 application and dehumidification.

Varieties	Season	Percentage Increase (-)
<CO_2 application>		
Tomato	Winter	1.30
Tomato	Summer	1.10
Chrysanthemum	Winter	1.10
Melon	Summer	1.20
Strawberry	Winter	1.20
<Dehumidification>		
Tomato	Winter, Summer	1.10
Chrysanthemum	Winter, Summer	1.10

5. Case Study for Simulation

Based on the above calculation formula, the effectiveness of the proposed system was examined by simulation. Figure 5 and Table 6 give an overview of the case studies assumed in the simulation and their conditions. Here, it is assumed that the heat of the industrial area is transported to the facility horticulture in the agricultural area, and the facilities are not adjacent to each other, and the moving distance is assumed to be 16 km. As for the cultivation facility, a greenhouse group of 10 a and a larger greenhouse group of 200a are assumed, and 2 t and 20 t trucks are considered to be transported accordingly. Considering that cultivars can be cultivated throughout the year as much as possible, tomatoes were selected for fruits and vegetables, and chrysanthemums were selected for flowers. The heat supply method is assumed to be the case where only heat is transported by HASClay in winter (HC1) and the case where heat and CO_2 are supplied at the same time (HC2). Furthermore, it is assumed that HASClay is supplied for dehumidification and CO_2 application in summer in addition to heat and CO_2 supply in winter (HC3). In the heat transport of HASClay, it was assumed that all the heat obtained by burning heavy oil would be covered by the heat transport of HASClay. For reference, the conventional method of supplying heat by a boiler without transporting heat (HO) was also envisioned.

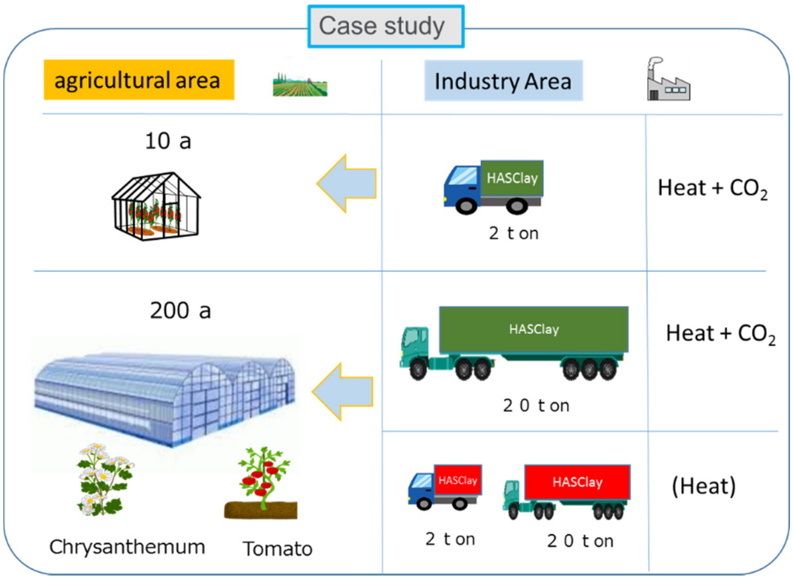


Figure 5. Overview of the case study used in the simulation.

Table 6. Simulation conditions.

<Conditions 1> :	Crop type, season, transport distance, etc.		
Crop type	Tomato, Chrysanthemum		
Cultivation season	Winter:	1, 2, 3, 11, 12,	(month)
	Summer:	5, 6, 7, 8, 9, 10	(month)
Transport Distance	16		(km)
Greenhouse size	10, 200		(a)
Truck size	2000, 20,000		(kg)
<Conditions 2> :	Heat supply method		
HC1	Heat	Winter	
HC2	Heat + CO_2	Winter	
HC3	Heat + CO_2,	Winter, Summer	
(HO)	Heat (from heavy oil)	Winter	

The results of the simulation were evaluated using the following formula. As shown in Equation (7). The production of the crops was calculated by adding the amount obtained from the production per unit area of the crop and the assumed planting area, and the amount increased by CO_2 application and dehumidification. As shown in Equations (8) and (9), the energy used for crop production and its cost were calculated from the total of HASClay's transportation process and fan power for heat supply in the agricultural area. CO_2 emissions were calculated from the sum of the energy used for heat transfer and fan power for crop production, as shown in Equation (10).

$$\begin{aligned}&\text{Amount of production}(\text{kg})\\&\quad=\text{Production per unit area}\cdot\text{Assumed planted area}\\&\quad+\text{Increased yield by } CO_2 \text{ application}\end{aligned} \tag{7}$$

$$\text{Productive energy (J)} = \text{Transportation energy} + \text{Fan operating energy} \tag{8}$$

$$\begin{aligned}&\text{Cost of Productive energy (JPY)}\\&\quad=\text{Transportation } \cos\text{t} + \text{Fan lectricity } \cos\text{t}\end{aligned} \tag{9}$$

$$\begin{aligned}&CO_2 \text{ emissions } (\text{kg} - CO_2)\\&\quad= CO_2 \text{ emissions from Transportation energy } (\text{kg} - CO_2)\\&\quad+ CO_2 \text{ emissions from Fan operating energy } (\text{kg} - CO_2)\end{aligned} \tag{10}$$

In the evaluation of the proposed system, economic and environmental aspects were assessed. In terms of economic efficiency, the cost per unit of energy used in production and the production cost per unit of production were used as indicators, as shown in Equations (11) and (12). For the environmental aspects, the energy input to produce 1 kg of the product and the associated CO_2 emissions were used to assess them as shown in Equations (13) and (14). Each of the values calculated from these equations was compared with the results calculated by the conventional method.

$$\begin{aligned}&\text{Production } \cos\text{t per production energy (JPY/J)}\\&\quad= \text{Cost of generation energy (JPY)/Productive energy (J)}\end{aligned} \tag{11}$$

$$\begin{aligned}&\text{Production } \cos\text{t per 1 kg production (JPY/kg)}\\&\quad= \text{Cost of productive energy (JPY)/Amount of production (kg)}\end{aligned} \tag{12}$$

$$\begin{aligned}&\text{Energy per 1 kg production (J/kg)}\\&\quad= \text{Productive energy /Amount of production (kg)}\end{aligned} \tag{13}$$

$$\begin{aligned}&CO_2 \text{ emissions per 1 kg production}(\text{kg} - CO_2/\text{kg}) =\\&\quad= CO_2 \text{ emissions from productive energy } (\text{kg} - CO_2)\\&\quad/\text{Amount of production (kg)}\end{aligned} \tag{14}$$

6. Simulation Results and Discussion

6.1. Simulation Results for Economic Aspects

Figure 6 shows the results of a comparison of production costs per productive energy when heat and CO_2 are simultaneously transported by HASClay in winter (HC2). As a comparison, the figure also shows the calculation results for the conventional method of heating with heavy oil (HO). In this case, when the results of the analysis are greater than the energy cost of the case using heavy oil (HO), it is judged to be economically unfeasible. From this result, it can be seen that the energy cost of both tomato and chrysanthemum is higher on the scale of 10 a than on the scale of 200 a, and large-scale heat transport is effective for heat supply using HASClay.

Therefore, Figures 7 and 8 show the results of comparing the production costs per production volume of tomato and chrysanthemum for the case of 200 a scale, which is expected to be economical. Here, HC1 shows the case where only heat is transported by HASClay in winter, HC2 shows the case where heat and CO_2 are supplied simultaneously, and HC3 shows the case where HASClay is supplied for dehumidification and CO_2 application in summer in addition to the supply of heat and CO_2 in winter. These results show that the production cost of chrysanthemum is higher than that of tomato. This is probably due to the fact that the cultivation of chrysanthemum requires the use of more heavy oil than that of tomato, as can be seen in Figure 3 above. With regard to the difference in the method of transport, it can be seen that the production cost of HC1, where the heat is simply changed from heavy oil to husk clay, is higher in both cases than in the case where the heat is supplied by conventional heavy oil. In the case of HC2, where heat and CO_2 are supplied together, the cost per unit of production is lower due to the yield effect of CO_2 application, showing the merits of the simultaneous supply of CO_2. Furthermore, it can be seen that the production cost of the case (HC3), in which HASClay was transported for CO_2 application/dehumidification in the summer, is also low, as is the case with HC2. This suggests that the heat transport of HASClay, which was previously only used in winter, has the advantage of being able to supply heat all year round. In particular, the reduction of energy costs in economic terms in tomatoes is small, but for chrysanthemums it was found that the CO2 application and dehumidification by transporting husk clay can reduce utility costs by about 10–20% compared to the conventional heavy oil.

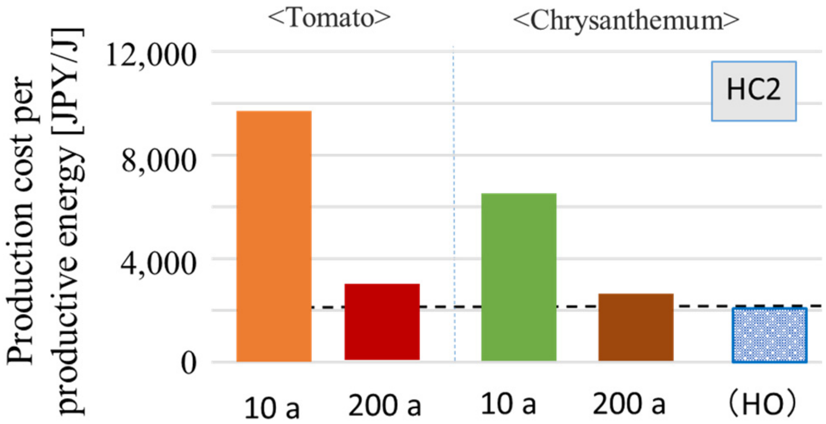


Figure 6. Comparison of production cost results per productive energy. (HC2: the case where heat and CO_2 are supplied simultaneously, (HO): the case of heating with fuel oil, which is the conventional method).

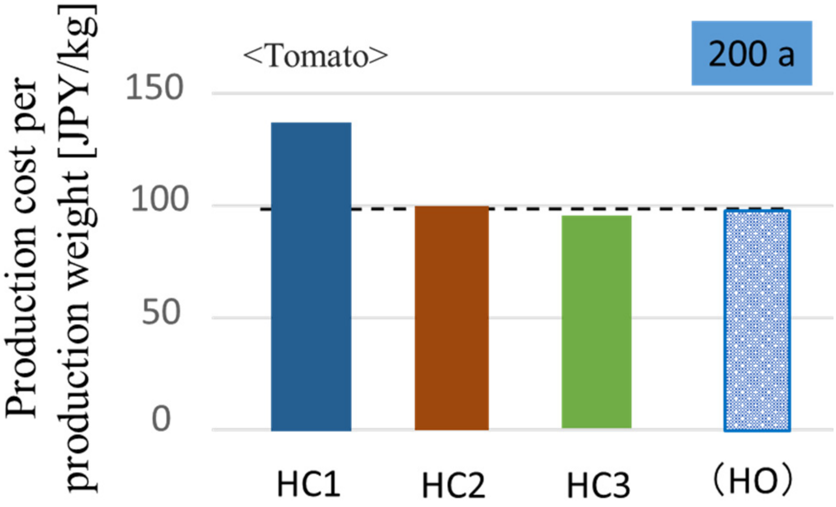


Figure 7. Comparison of production cost results per production weight (Tomato). (HC1: the case where only heat is transported by HASClay in winter, HC2: the case where heat and CO_2 are supplied simultaneously, HC3: the case where HASClay is supplied for dehumidification and CO_2 application in summer, (HO): the case of heating with fuel oil, which is the conventional method).

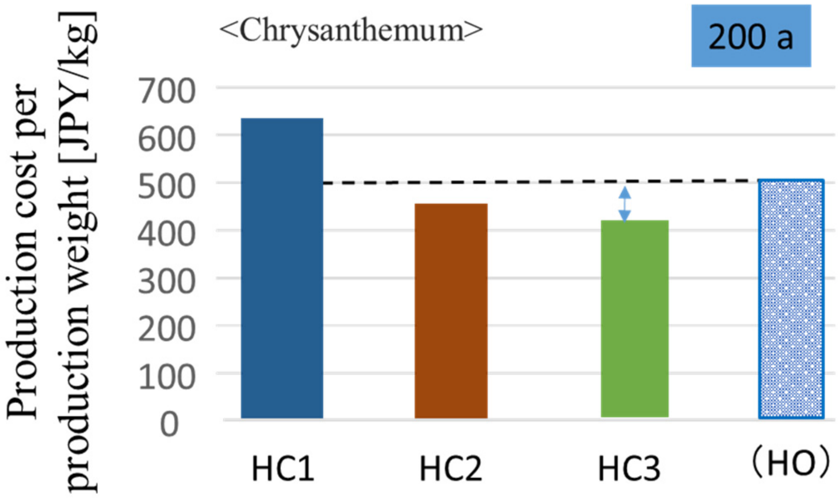


Figure 8. Comparison of production cost results per production weight (Chrysanthemum, HC1: the case where only heat is transported by HASClay in winter, HC2: the case where heat and CO_2 are supplied simultaneously, HC3: the case where HASClay is supplied for dehumidification and CO_2 application in summer, (HO): the case of heating with fuel oil, which is the conventional method).

6.2. Simulation Results for Environmental Aspects

Next, from the perspective of environmental energy, energy per production weight, CO_2, was evaluated. Figures 9 and 10 show a comparison of the production energy required to grow 1 kg of tomato and chrysanthemum in different transport methods and cultivation preferences. Here, as a comparison, HO is the case of heating with fuel oil, which is the conventional method, (A) is the case of growing tomatoes in a conventional greenhouse without heating energy in winter, and (B) is the case of growing tomatoes in summer [26].

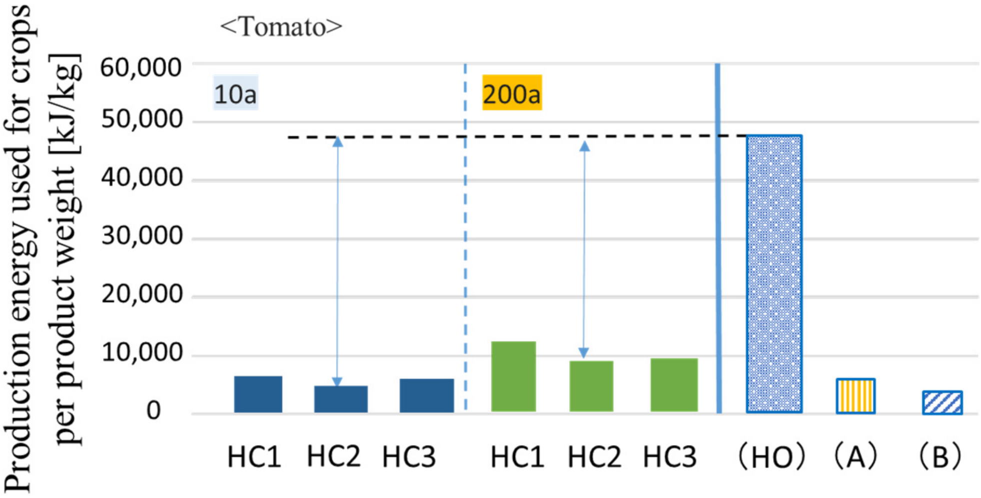


Figure 9. Comparison of productive energy results per production weight (tomato). (HC1: the case where only heat is transported by HASClay in winter, HC2: the case where heat and CO_2 are supplied simultaneously, HC3: the case where HASClay is supplied for dehumidification and CO_2 application in summer, (HO): the case of heating with fuel oil, which is the conventional method, (A) the case of growing tomatoes in a conventional greenhouse without heating energy in winter, (B) the case of growing tomatoes in a conventional greenhouse in summer).

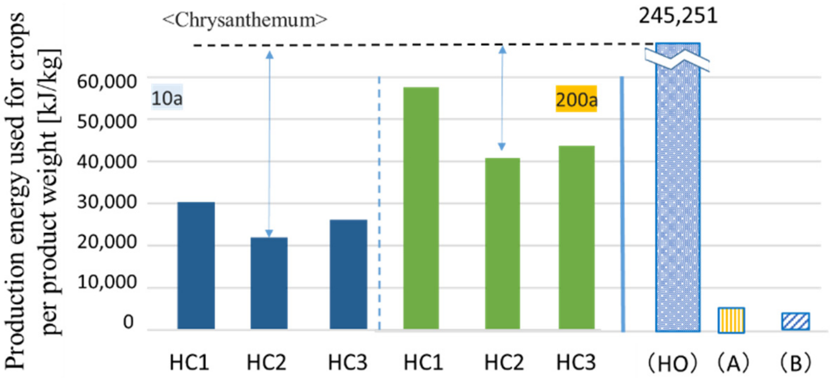


Figure 10. Comparison of productive energy results per production weight (chrysanthemum). (HC1: the case where only heat is transported by HASClay in winter, HC2: the case where heat and CO_2 are supplied simultaneously, HC3: the case where HASClay is supplied for dehumidification and CO_2 application in summer, (HO): the case of heating with fuel oil, which is the conventional method, (A) the case of growing tomatoes in a conventional greenhouse without heating energy in winter, (B) the case of growing tomatoes in a conventional greenhouse in summer).

These results show that even in this case, the production costs of chrysanthemums are higher than those of tomatoes. In particular, the use of heavy oil to supply heat for chrysanthemums has a high environmental impact. In contrast to the previous economic results, the smaller 10 a scale produced less productive energy per production weight than the 200 a scale. Compared to the conventional use of heavy oil, the productive energy of tomatoes is reduced by 10–20% and that of chrysanthemums by 8–16% with the use of HASClay, which shows that the heat transport by HASClay is very effective from an environmental point of view. It should be noted that the energy produced by transporting HASClay in summer (HC3) was higher than in winter only (HC2), suggesting a slight environmental burden.

Figure 11 shows the results of CO_2 emissions per weight of tomato and chrysanthemum produced in the case of simultaneous heat and CO_2 transport by HASClay (HC2). According to this, it can be seen that the cultivation of chrysanthemums by burning heavy oil (HO) has a large amount of CO_2 emissions per production weight as in Figure 10 above, and the environmental effect of heat transport by HASClay is large. The CO_2 emissions per unit of production weight of HASClay transported to the cultivation of 200a of chrysanthemum are significant, and it is considered that measures to reduce CO_2 emissions will be necessary in the practical application of the proposed system in the future.

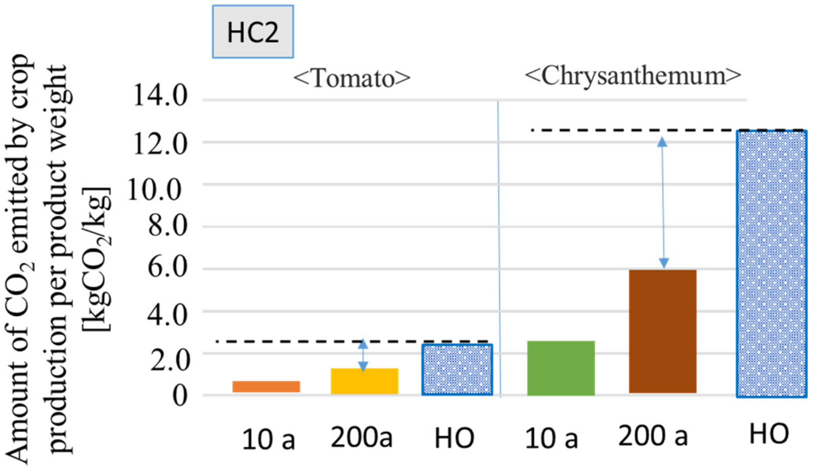


Figure 11. Comparison of CO_2 emission results per production weight. (HC2: the case where heat and CO_2 are supplied simultaneously, (HO): the case of heating with fuel oil, which is the conventional method).

7. Discussion

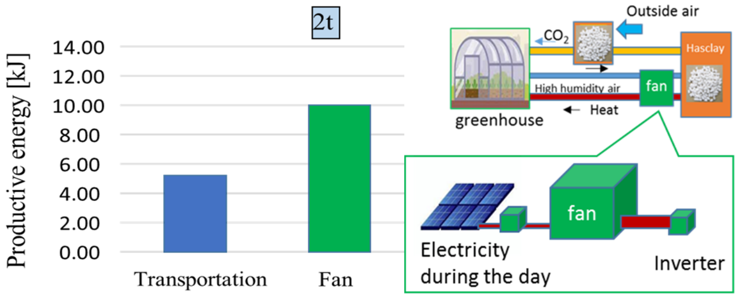
7.1. Discussion of Simulation Results

The simulation shows that the proposed system of supplying heat to a large greenhouse in Haskley in 20-ton containers would have an economic budget similar to that of the previous system, but with an environmental impact of about 80% less tomatoes and 84% less chrysanthemum fuel than the previous system of heating with fuel oil. This will be a great advantage for the industrial area in the future, because the unused heat can significantly reduce CO_2 in the agricultural area. In particular, the transport of heat by means of the huskley ensures that the demand for heat can be met throughout the year, unlike conventional transport in industrial areas.

On the other hand, the issue of transportation using this HASClay was also considered. From an economic point of view, the simultaneous transport of heat and CO_2 by means of HASClay overcomes the economic concerns of the conventional method, but it is necessary to further reduce the cost of heat transport in order to create benefits for the agricultural area. Due to the high heat requirements per unit weight in cultivation, the environmental impact of chrysanthemums is still twice as high as that of tomatoes, even assuming a large-scale transport system in HASClay, and the transport system needs to be improved. The use of 2-ton trucks to transport heat to a 10a greenhouse in HASClay is not economically viable, although it has environmental benefits. However, it is essential to transport the heat at this scale for practical use, so it is necessary to propose a new transport method.

7.2. Consideration of the Reduction of Transportation Costs and Heat Transportation Systems to Small-Sized Greenhouses

Improvements to the above-mentioned transportation problem by HASClay was considered. First, the improvement of heat transport cost by HASClay was considered. Figure 12a shows a comparison of production energy in a 2 t truck as an example. From this, it can be seen that it is important to reduce the power of the fan as an environmental measure. One possible solution to this problem is to replace this electricity with renewable energy, as shown in Figure 12b. If electricity is stored during the day and used for heat at night, the utility bill will be reduced accordingly. From the technical point of view, it is possible to reduce the electricity consumption by about 20% by using an inverter to control the air flow according to the season and temperature, instead of the conventional damper-type fan used to supply heat to the HASClay [19]. These improvements are directly linked to the reduction of CO_2 emissions and energy costs, so their realization will be effective for improving environmental aspects.



(**a**) Transport system by 2 t truck (**b**) Fan system improvements

Figure 12. Proposed improvements to the system to reduce the environmental impact. (**a**): Comparison of energy consumption by heat transport with a 2 tonne truck (**b**): Overview of the improvement of the fan system.

Next, transport to the 10a scale, which has environmental advantages, was studied. In the case of supplying heat to each small greenhouse with one 2 t truck, the transportation cost would be the same as the number of trucks, which is not a solution for the current situation. Therefore, a new method of transporting heat to small greenhouses is proposed, as shown in Figure 13, taking advantage of the effectiveness of HASClay's large-scale heat transport. The heat from the HASClay is supplied in mini-tanks, rather than containers, and is not transported directly to the 10a greenhouses, but to stations that are designed for each region in this system. This station is considered to be suitable for a harvest center that collects cultivated crops. Then, on the way back from the delivery of the harvested crops, individual agricultural producers bring back the mini-tanks that store heat to their respective greenhouses and use them. This is expected to reduce the increase in transport costs and will enable the supply of heat to smaller greenhouse sizes with environmental benefits.

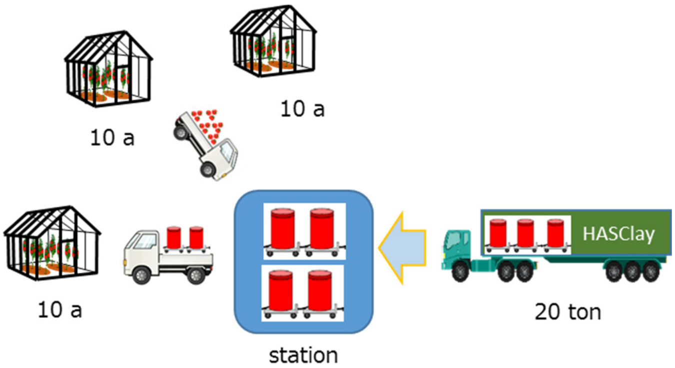


Figure 13. Proposal for a heat supply system for a 10a greenhouse.

In summary, the authors conclude that our proposal for an agro-industrial fusion system based on the transport of heat using HASClay is an effective method for the realization of a sustainable society. This will be of great advantage for the industrial area in the future, because the unused heat can significantly reduce CO_2 in the agricultural area. In particular, the transport of heat by means of the HASClay ensures that the demand for heat can be met throughout the year, unlike conventional transport in industrial areas. The environmental benefits of the project are likely to attract participation from the industrial sphere in order to meet future demands for CO_2 reductions. If the economic aspects of the project are further explored, it is hoped that the number of users from the agricultural sector will increase and that a sustainable policy will be developed that does not rely on subsidies. Furthermore, it will be important to continue to look at technological improvements, such as the development of new solutions such as heat pipes [47] and the generation of electricity from low and medium temperature industrial surplus heat [48], as in the case of this inverter. As shown in the example of system-wide evaluation including crop production, distribution, and consumption [49], further studies for the formation of a heat transport network in which agriculture, industry and commerce are linked will be useful for implementation in the future.

8. Conclusions

The aim of this study is to propose an agro-industrial heat transfer system from an industrial area to an agricultural area for horticultural facilities with a high demand for heat, and to derive by simulation the conditions under which the system can be used economically as well as environmentally. Therefore, instead of simply transporting heat, it was considered to use a high-performance heat storage material to provide additional value at the same time as heat and overcome the economic problem of concern. HASClay was used as a high-performance medium. HASClay has the ability to supply CO_2 at the same time as heat and dehumidify the inside of the house, so it can be expected to increase the yield in addition to reducing the environmental load by using heat.

Consequentially, the simulation therefore shows that the proposed system of supplying heat to a large greenhouse in HASClay in 20-ton containers would have an economic budget similar to that of the previous system, but with an environmental impact of about 80% less tomatoes and 84% less chrysanthemum fuel than the previous system of heating with fuel oil. This will be of great advantage for the industrial area in the future because the unused heat can significantly reduce CO_2 in the agricultural area. In particular, the transport of heat by means of the HASClay ensures that the demand for heat can be met throughout the year, unlike conventional transport in industrial areas.

On the other hand, in order to overcome the problem of heat transport in HASClay, it was found that it is necessary to improve the system considering the environmental aspect and reduction of transport cost and to propose a new heat transport system to small greenhouses. Therefore, a countermeasure was considered. First, analysis revealed that it is important to reduce the power of the fan in order to improve the heat transport cost by HASClay. As a countermeasure, it is possible to replace these electric powers with natural energy, and to control the air volume according to the season and temperature by using an inverter from the conventional damper-type fan for the fan used for heat supply of HASClay. This turned out to be effective for reduction. Since these improvements directly led to CO_2 reduction and energy cost reduction, it was considered that their realization would be effective for environmental improvement. For transport to the 10a scale, which has environmental advantages, a system was proposed in which the heat from the HASClay is divided into mini-tanks and transported to stations envisaged in each region, where it is collected by the agricultural producers.

In summary, the authors concluded that our proposal for an agro-industrial fusion system based on the transport of heat using HASClay is an effective method for the realization of a sustainable society. The environmental benefits of the project are likely to attract participation from the industrial sphere in order to meet future demands for CO_2 reductions. If the economic aspects of the project are further explored, it is hoped that the number of users from the agricultural sector will increase and that a sustainable policy will be developed that does not rely on subsidies. In terms of future prospects, the introduction of new technologies and the further study of the formation of a heat transport network in which agriculture, industry and commerce are linked would be useful for future implementation.

Author Contributions: S.M., M.S., and T.S. conceived and designed the experiments; S.M. and M.S. analyzed the data; S.M. wrote the paper. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Acknowledgments: This study was carried out on the basis of data analyzed with the support of the "Agricultural–Industrial–Commercial Fusion System Demonstration Project", a project commissioned by Tahara city, Aichi Prefecture, Japan, in 2016. We also received a lot of support from Tahara city officials for data collection and community survey and Muraoka S. (graduate school of engineering, The University of Tokyo) for their efforts in the analysis. The authors express our deep appreciation to these parties concerned.

Conflicts of Interest: The authors declare no conflict of interest for the research study.

Nomenclature

HC1	The case where only heat is transported by HASClay in winter,
HC2	The case where heat and CO_2 are supplied simultaneously,
HC3	The case where HASClay is supplied for dehumidification and CO_2 application in summer in addition to the supply of heat and CO_2 in winter.
(HO)	The case of heating with fuel oil, which is the conventional method
(A)	The case of growing tomatoes in a conventional greenhouse without heating energy in winter.
(B)	The case of growing tomatoes in a conventional greenhouse in summer.

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