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# Life Cycle $CO_2$ Emissions Analysis of a High-Tech Greenhouse Horticulture Utilizing Wood Chips for Heating in Japan

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**Abstract:** High-tech greenhouse horticulture offers efficient crop cultivation that is unaffected by outdoor climate. However, compared to conventional cultivation systems, energy requirements, such as greenhouse heating and control, are larger, and concerns about the associated increase in $CO_2$ emissions exist. Although several previous studies have analyzed $CO_2$ emissions from high-tech greenhouse horticulture, few have covered the entire life cycle. This study aimed to analyze $CO_2$ emissions from high-tech greenhouse horticulture for tomatoes in Japan across the entire life cycle. A hybrid method combining process and input–output analyses was used to estimate life cycle $CO_2$ (LC-$CO_2$) emissions. The emission reduction potential of replacing liquefied petroleum gas (LPG) for greenhouse heating with wood chips was also examined. The results show that LC-$CO_2$ emissions were estimated to be 3.67 kg-$CO_2$ per 1 kg of tomato, 55.6% of which came from the production and combustion of LPG for greenhouse heating. The substitution of LPG with wood chips has the potential to reduce LC-$CO_2$ emissions by up to 49.1%. However, the improved LC-$CO_2$ emissions are still higher than those of conventional cultivation systems; thus, implementing additional measures to reduce LC-$CO_2$ emissions is crucial.

**Keywords:** high-tech greenhouse horticulture; life-cycle assessment; renewable energy; wood chips; hybrid method; process analysis; input–output analysis; climate change



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## 1. Introduction

In Japan, horticultural crops and their processed foods account for the largest share of annual food expenditures per household [1]. Horticultural crops are indispensable to the daily lives of citizens, and a long-term stable supply is required. Concerns exist regarding the aging farmer population and climate change affecting the supply of horticultural crops. For example, in recent years, the number of horticultural farmers has decreased because of the aging population, and the cultivation area has also decreased [2]. Additionally, the effects of climate change, such as crop physiological disorders due to high temperatures and heavy rainfall, have been recognized in the field of horticultural agriculture, and there are concerns that these negative effects will increase further in the future owing to more severe natural disasters [3].

High-tech greenhouse horticulture, characterized by advanced environmental control technology, is gaining attention as a system that ensures systematic and stable crop production throughout the year [4]. This method could contribute to stable crop quality and supply and reduce labor load [4–6]. In Japan, the Ministry of Agriculture, Forestry, and Fisheries (MAFF) has developed a "base of next-generation greenhouse horticulture" in 10 locations nationwide. These model plants utilize advanced technology from the Netherlands, where technological advancements in greenhouse horticulture have flourished [6].

The expansion of high-tech greenhouse horticulture in Japan comes with the use of various devices for environmental control. This results in an increase in direct and indirect input energy compared to open-field cultivation and conventional greenhouse horticulture, raising concerns about elevated $CO_2$ emissions [7]. Greenhouse systems in Japan, which predominantly rely on fossil fuels, such as heavy oil and liquefied petroleum gas (LPG), for heating [8], necessitate measures to reduce $CO_2$ emissions. Therefore, the introduction of renewable energy to replace fossil fuels has attracted attention, especially those utilizing local renewable energy sources which is promising from the sustainability perspective in rural areas. For example, the "Strategy for Sustainable Food Systems MIDORI" [9], formulated by MAFF as a mid- to long-term policy for food, agriculture, forestry, and fisheries, states that to achieve zero $CO_2$ emissions in those industries by 2050, the government will promote local renewable energy usage and shift from fossil fuels in horticulture. Hence, analyzing $CO_2$ emissions throughout the life cycle, including assessing the potential reduction linked to utilizing renewable energy to replace fossil fuels, and exploring measures to reduce $CO_2$ emissions in high-tech greenhouse horticulture becomes imperative.

Few studies have analyzed $CO_2$ emissions from high-tech greenhouse horticulture and their reduction potential using renewable energy from a life-cycle perspective. Kikuchi et al. [10] analyzed greenhouse gas (GHG) emissions from a tomato hydroponic system at a university experimental plant in Japan and quantitatively demonstrated the impact of renewable energy resources and energy-saving technologies, such as utilizing unused heat from plants and improving the energy consumption efficiency of air conditioning heat pumps, on reducing GHG emissions. Marttila et al. [11] estimated the GHG emissions for multiple tomato and cucumber hydroponic systems in Finland using different heating systems and revealed that the use of wood chips, biogas, and industrial waste heat reduced GHG emission. Almeida et al. [12] estimated GHG emissions for a tomato hydroponic system in northern Italy. They quantitatively showed that GHG emissions could be reduced using renewable energy resources, such as canola oil and municipal solid waste, instead of natural gas for heating.

With a limited life-cycle scope, several studies have analyzed $CO_2$ emissions and their reduction potential using renewable energy for high-tech greenhouse horticulture. Torellas et al. [13] estimated GHG emissions for floriculture and tomato hydroponics in the Netherlands and tomato hydroponics in Hungary. They revealed that using renewable energy and energy-saving technologies, such as geothermal energy and combined heat and power (CHP), effectively reduces GHG emissions. Ntinas et al. [14] estimated GHG emissions for a tomato hydroponic system in an experimental plant located at a university in Germany and showed that solar heat can contribute to GHG reduction. Nasser et al. [15] estimated $CO_2$ emission reductions associated with using energy-saving equipment and introducing heat pumps powered by hydroelectricity. They quantitatively showed that the reductions in GHG emissions were greater in colder regions than in other regions.

Chicco et al. [16] quantified the GHG emission reductions associated with replacing fossil fuels by using heat energy from artificial quarry lakes for greenhouse heating in Italy. Maureira et al. [7] conducted a GHG emission analysis of tomato hydroponics for high-tech greenhouse horticulture in Washington, USA, and found that CHP is important for GHG emission reduction in high-tech greenhouse horticulture. They also mentioned the possibility that renewable electricity can contribute to reducing GHG emissions.

Several previous studies have analyzed $CO_2$ emissions from high-tech greenhouse horticulture and their reduction potential using renewable energy. However, some problems exist in these studies.

First, only a few studies have analyzed $CO_2$ emissions from an entire life-cycle perspective. Many studies have focused on $CO_2$ emissions associated with energy consumption during cultivation, and few have comprehensively considered emissions associated with the design and construction of plants, as well as the distribution and sale of harvested crops.

Second, these studies were mostly conducted outside Japan, and none were conducted on commercial plants in Japan. For realistic $CO_2$ emission reduction measures in Japanese high-tech greenhouse horticulture, we need information derived from an analysis that considers specific conditions of commercial plants in Japan, encompassing climate, crops, equipment configuration, and the potential use of renewable energy.

Third, these studies employed only process analysis to estimate $CO_2$ emissions. Since various products and services are used in constructing and operating high-tech greenhouse horticulture, $CO_2$ emissions associated with the use of these products and services should be comprehensively evaluated. However, ascertaining the physical quantities of several products and services may be challenging when conducting such analyses. Therefore, a hybrid method that combines process and input–output analyses should be employed to analyze high-tech greenhouse horticulture. This method is effective as it can estimate $CO_2$ emissions using both physical quantity and economic value data. However, no study has applied a hybrid method to analyze $CO_2$ emissions from high-tech greenhouse horticulture.

We aimed to apply the hybrid method to analyze the life-cycle $CO_2$ (LC-$CO_2$) emissions of commercial high-tech greenhouse horticulture in Japan and to quantify the potential for reducing LC-$CO_2$ emissions using wood biomass energy for heating. Based on the hydroponic cultivation of tomatoes, a typical crop grown in high-tech greenhouse horticulture, we estimated LC-$CO_2$ emissions. Additionally, we analyzed the LC-$CO_2$ emission reduction potential of wood chips for heating greenhouses. The MAFF has introduced woody biomass [6] to develop the "base of next-generation greenhouse horticulture" and is expected to be a local renewable energy source in Japan.

## 2. Materials and Methods

Initially, the analysis focused on the high-tech greenhouse horticulture, outlining details like equipment configuration and scale. Following this, analysis conditions, such as system boundaries and functional units, were established. Subsequently, LC-$CO_2$ emissions were estimated using a hybrid method that combined process analysis and input–output analysis, providing a breakdown of emissions. The study then delved into assessing the potential for reducing LC-$CO_2$ emissions by estimating the impact of utilizing wood chips as a heating energy source, thereby analyzing the potential for emission reduction through renewable energy.

### *2.1. Plant to Be Analyzed*

#### 2.1.1. Overview

The plant to be analyzed in this study is mainly based on important information from the Hyogo Prefecture Base (HPB) of "next-generation greenhouse horticulture" by MAFF. The facility configuration, size, and other details were determined using publicly available information on the HPB [17–20]. Table 1 shows the details of the plant analyzed.

**Table 1.** Details of the analyzed plant.

| Site | Greenhouse Type | Crops Grown | Cultivation Method | Cultivated Area | Yield | Principal Equipment and Facilities |
|---|---|---|---|---|---|---|
| Hyogo Prefecture | Venlo-type greenhouse | Tomato | Hydroponics | 3.6 ha | 1176 t/year | • Greenhouse interior<br>• equipment Energy-supply facility Seedling production system Warehouse<br>• for collection/shipping Administrative office |

The plant to be analyzed was located in Hyogo Prefecture (Figure 1). A hydroponic cultivation system, in which crops are grown in circulating liquid fertilizer without soils, in a Venlo type greenhouse was installed. The Venlo type greenhouse is a multi-span greenhouse developed in the Netherlands. The cultivation area was 3.6 hectares. The annual yield was 1176 tons, and the cultivation period was from the beginning of September to the end of July of the following year, with greenhouse heating from October to the beginning of June. Regular shipments started in early October, approximately one month after the start of cultivation. Figure 2 shows the monthly mean daily maximum and minimum temperatures at a weather station of Japan Meteorological Agency closest to the plant.

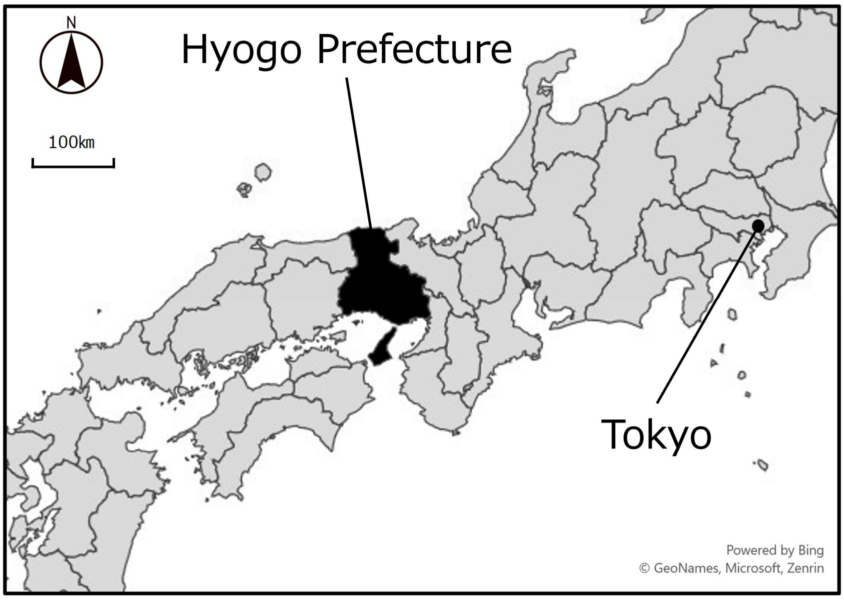


**Figure 1.** Location of Hyogo Prefecture (Microsoft product screen shot reprinted with permission from Microsoft Corporation).

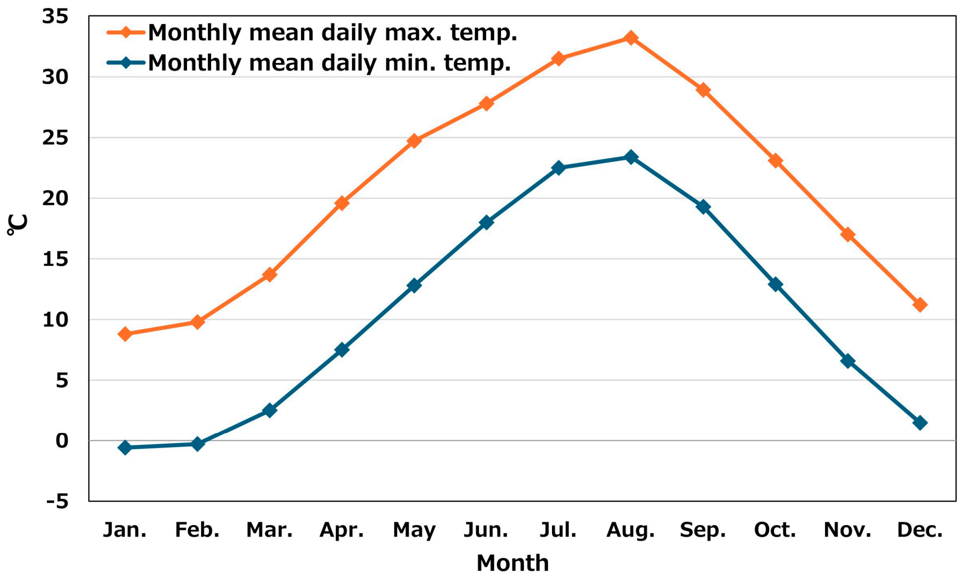


**Figure 2.** The monthly mean daily maximum and minimum temperatures (1990–2020) at a weather station of Japan Meteorological Agency closest to the plant (with reference to [21]).

The plant comprised greenhouses, seedling production systems (artificial light and sunlight), warehouses for collection or shipping, energy-supply facilities, and administrative offices. The artificial light-type seedling production system was a primary closed-type seedling production system used to grow seedlings purchased from nursery companies. The sunlight seedling supply system was a secondary system located in greenhouses. The warehouse for collection/shipping was a facility for sorting, packaging, and shipping harvested tomatoes. The energy-supply facility included a boiler, a boiler room for heating, and various other equipment, such as piping and tanks. The administrative office served as the hub to manage and operate various aspects of the facility.

2.1.2. Cultivation System

The cultivation system of the analyzed plant, as shown in Figure 3, employed the system of HPB [17]. This method used a circulating rock wool culture with a hanging gutter system. Water sources included rainwater and tap water. The greenhouse was heated by pipes (hot water circulation system), and the pipes were used as running rails for aerial work platforms and pesticide-spraying robots. LPG was used as the fuel for heating. In addition, ventilation systems, thermal screens, shading screens, and various gauges, such as temperature and humidity meters, were installed, and multiple pieces of equipment were controlled by an integrated environmental control system.

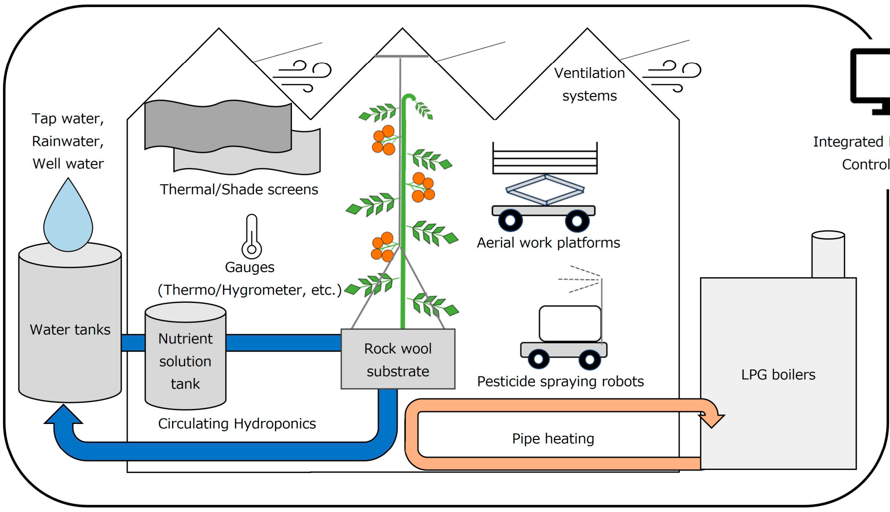


**Figure 3.** Cultivation system of the analyzed plant (with reference to [17]).

## *2.2. Analysis Condition*

In this study, the system boundary was broadly divided into construction and operation phases, as shown in Figure 4. The construction phase encompassed the design, construction work, manufacturing, and installation of each facility. The operational phase included cultivation activities, such as growing and harvesting tomatoes, packaging, transportation from the plant to the wholesaler, sales from the wholesaler (including intermediary wholesalers) to the retailer, and sales by the retailer to the consumer.

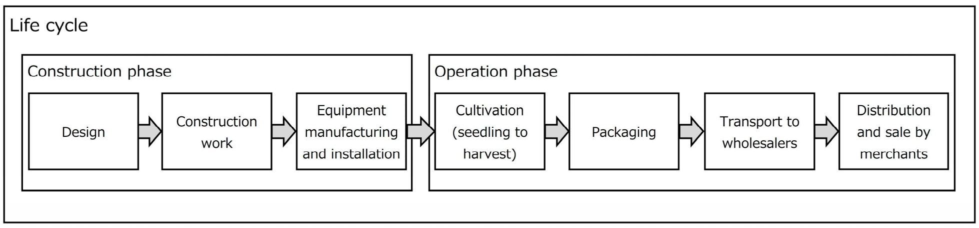


**Figure 4.** System boundary of this study.

The functional unit was the weight of the product (1 kg of tomatoes). In this study, only $CO_2$ was analyzed because $CO_2$ accounts for more than 90% of GHG emissions in Japan and is required to be reduced [22].

The evaluation period was set at 20 years. The useful life was assumed to be 20 years for each building, including the greenhouse [23], and 10 years for other facilities (equipment and materials) based on the average statutory useful life in Japan [24]. The annual replacement of rock wool with the substrate and other consumable products were assumed.

### 2.3. Estimation of Life Cycle $CO_2$ Emissions

#### 2.3.1. Calculation Method

This study estimated LC-$CO_2$ emissions using a hybrid method that combines process and input–output analyses. Direct $CO_2$ emissions associated with the combustion of fuels directly consumed for heating, transportation, and other equipment, as well as $CO_2$ emissions associated with fuel production activities, were estimated using process analysis. Indirect $CO_2$ emissions associated with the production of input products other than fuels and services were estimated using input–output analysis.

In the process analysis, direct $CO_2$ emissions were estimated by multiplying the direct consumption of each fuel (LPG, diesel, and gasoline) by the $CO_2$ emission intensity of combustion and production for each fuel and summing them (Equation (1)). The direct consumption of each fuel was estimated as follows: The LPG consumption for greenhouse heating was determined by dividing the actual annual heat demand (31,011 GJ/year) by its lower heating value. The annual heat demand was the average from 2016 to 2018 at the HPB [17]. The diesel fuel consumption for transporting tomatoes from the plant to the wholesaler was determined using an improved ton-kilometer method [25]. The distance from the plant to the wholesaler was assumed to be 100 km, and two 2-ton trucks were used for transport. The consumption of each fuel for processes other than greenhouse heating and transport was determined by dividing the consumption cost of each fuel by its respective unit cost. The consumption cost of each fuel was assumed according to the method described in Section 2.3.2,

$$E_D = \sum_{i=1}^{n} FC_i \times (e_{f,i} + e_{p,i}) \tag{1}$$

where $E_D$: direct $CO_2$ emission, $i$: fuel type, $FC$: amount of fuel consumption, $e_f$: $CO_2$ emission intensity of fuel combustion [26], and $e_p$: $CO_2$ emission intensity of fuel production [27].

Indirect $CO_2$ emissions were estimated using Equation (2),

$$E_I = \mathrm{e}^T (\mathrm{I} - \mathrm{A})^{-1} \mathrm{f} \tag{2}$$

where $E_I$: indirect $CO_2$ emissions, e: emission intensity vector of input-output sectors [28,29], $T$: transposition, $(\mathrm{I} - \mathrm{A})^{-1}$: Leontief inverse matrix, and f: final demand vector. From Equation (2), the $CO_2$ emitted to meet the final demand was calculated. The estimation method for the final demand vector is described in Section 2.3.2. In the input–output analysis, the 2015 Input–Output Tables for Japan with 390 sectors [30] were used.

Based on the above, this study estimated LC-$CO_2$ emissions ($LCCO2$) using Equation (3).

$$LCCO2 = E_D + E_I \tag{3}$$

#### 2.3.2. Determination of Final Demand Vector

The final demand vector was determined separately for the construction and operation phases according to the procedure shown in Figure 5. First, the total costs of both phases, including fuel costs, were assumed. The total costs were then classified and categorized into primary items. Next, each primary item was matched to a sector in the input–output table, and the amount was allocated to the corresponding sector. Primary items that could not be directly matched to sectors in the input–output table were subdivided into secondary items, and their costs were prorated. Each secondary item was then assigned to a sector in the input–output table, and the costs were recorded in the corresponding sector. Secondary items that could not be assigned to a sector were further subdivided into tertiary items, and costs were prorated and assigned to the sector in the input–output table. Finally, the amounts were summed for each sector of the input–output table, and the final demand vector was determined by excluding the fuel costs from the total. The final demand was based on the producer's prices. Tables 2 and 3 list the costs for the construction and operation phases, respectively. These costs were estimated according to the procedure shown in Figure 5. Table 4 provides information on the materials used to estimate each cost. For the cost estimation, we used data provided by the farmers and heat suppliers, as well as data from publicly available information [13,17–20,30–41]. The total cost of the construction phase was estimated based on publicly available information on the project plan of the HPB [19]. In the operation phase, costs were calculated for each primary item based on the estimated production costs in high-tech greenhouse horticulture [36,37], cost information provided by the farmer, and statistics from MAFF [41]. The sum of these costs was given as the total cost for the operation phase.

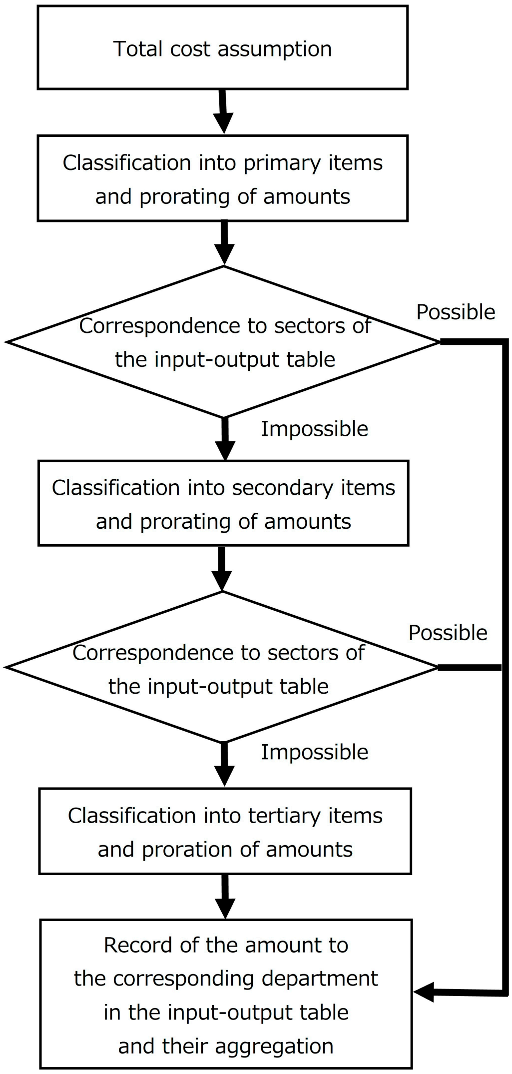


**Figure 5.** Flow for the final demand vector determination.

**Table 2.** Construction phase cost items.

| Primary Item | Secondary Item | Tertiary Item | Composition |
|---|---|---|---|
| Greenhouse | | | 49% |
| | Greenhouse materials | Glass, Steel, Aluminum, Concrete | |
| | Greenhouse construction | Other building materials, Construction equipment, Labor, etc. | |

**Table 2.** *Cont.*

| Primary Item | Secondary Item | Tertiary Item | Composition |
|---|---|---|---|
| Greenhouse interior equipment | | | 26% |
| | Heating pipes | | |
| | Aerial work platforms | | |
| | Shade screens | | |
| | Thermal screens | | |
| | Self-propelled sprayers | | |
| | Growing beds | | |
| | Rock wool | | |
| | Nutrient solution supply system | Tanks, Pumps, Gauges, etc. | |
| | Disinfection equipment | | |
| | Nutrient solution supply and drainage pipes | | |
| | Iron removal equipment | | |
| | Drip irrigation system | | |
| | Environmental control computer | | |
| | Heat storage tank | | |
| | Circulation fans | | |
| | $CO_2$ application equipment | | |
| | Raw water tank | | |
| | Rainwater tank | | |
| | Electricity receiving facility | | |
| Artificial light seedling production system | | | 1% |
| | Prefab storage materials/construction | Building materials, Construction equipment, Labor, etc. | |
| | Growing racks | | |
| | Cell trays | | |
| | LED lights | | |
| | Nutrient solution supply system | Tanks, Pumps, Gauges, etc. | |
| | Air conditioners | | |
| | Air blowers | | |
| Sunlight seedling supply system | | | 2% |
| | Assumed to be the same as "Greenhouse" | | |
| Warehouse for collection/shipping | | | 2% |
| | Warehouse materials/construction | Building materials, Construction equipment, Labor, etc. | |
| | Weight sorter | | |
| | Packing machines | | |
| | Long type container carts | | |
| | Short type container carts | | |
| | Forklifts | | |
| Energy-supply facility | | | 13% |
| | Boiler room materials/construction | Building materials, Construction equipment, Labor, etc. | |
| | Boilers and other equipment | LPG boilers, Pipes, etc. | |
| | Other construction (electrical work, etc.) | | |
| Administrative office | | | 2% |
| | Warehouse materials/construction | Building materials, Construction equipment, Labor, etc. | |
| Transport vehicle (2-ton truck) | | | 1% |
| Design | | | 4% |
| Total | | | 100% |

**Table 3.** Operation phase cost items.

| Primary Item | Secondary Item | Tertiary Item | Composition |
|---|---|---|---|
| Materials | | | 3% |
| | Seedlings | | |
| | Fertilizers | | |
| | Pesticides | | |
| | Rock wool | | |
| | Other materials | Farm implements, Consumables, Clothing, etc. | |
| Water and electricity | | | 1% |
| | Water supply | | |
| | Electricity | | |
| LPG | | | 15% |
| Maintenance | | | 1% |
| | Spare parts, Machine repair, etc. | | |
| General management | | | 2% |
| | Communication, Office supplies, etc. | | |
| Depreciation | | | 14% |
| Property tax | | | 1% |
| Labor cost | | | 10% |
| | Salaries | | |
| | Wages | | |
| Packaging Materials | | | 2% |
| | Plastic packaging | | |
| | Cardboard boxes | | |
| Transport (facility to wholesaler) | | | 1% |
| | Diesel fuel | | |
| | Driver wages | | |
| Distribution and sale | | | 48% |
| | Sales commissions | | |
| | Commercial margin | | |
| Total | | | 100% |

**Table 4.** Information on materials used for cost estimation.

| Primary Item | Reference Materials for Total Costs and Primary Item Costs | Reference Materials for Secondary and Tertiary Item Costs | Notes |
|---|---|---|---|
| Construction phase | | | |
| Greenhouse (incl. Sunlight seedling supply system) | [18,19] | [13,32,33] | |
| Greenhouse interior equipment | [18,19] | [17–20,33,34] | |
| Artificial light seedling production system | [18,19] | [34–36] | |
| Warehouse for collection/shipping | [18,19] | [17,20,34], Input coefficients in the input–output table [30] | |
| Energy-supply facility | [18,19] | [17], Data provided by the heat supplier | |
| Administrative office | [18,19] | Input coefficients in the input–output table [30] | |
| Transport vehicle (2-ton truck) | [31] | | |
| Design | [18,19] | | |

**Table 4.** *Cont.*

| Primary Item | Reference Materials for Total Costs and Primary Item Costs | Reference Materials for Secondary and Tertiary Item Costs | Notes |
| --- | --- | --- | --- |
| Operation phase | | | |
| Materials | [36,37], Data provided by the farmer | [36,37], Data provided by the farmer, Input coefficients in the input–output table [30] | |
| Water and electricity | [36,37] | Input coefficients in the input–output table [30] | |
| LPG | [17,38] | | |
| Maintenance | [36,37] | Data provided by the farmer | |
| General management | [36,37] | [39] | |
| Depreciation | See Notes. | | Calculated using the straight-line method according to the useful life (see Section 2.2). |
| Property tax | See Notes. | | The property tax for each year was set at 1.4% of the amount of remaining fixed asset less depreciation, and the average amount over 20 years was recorded. |
| Labor cost | [17,40] | [17,40] | |
| Packaging Materials | [36,37], Data provided by the farmer | Data provided by the farmer | |
| Transport (facility to wholesaler) | See Notes. | See Notes. | Diesel fuel costs were estimated from its consumption estimated using the improved ton-kilometer method (see Section 2.3.1). Driver wages were estimated based on the expected number of operating days for the trucks. |
| Distribution and sale | [41] | | |

### *2.4. Reduction Potential for LC-$CO_2$ Emissions by Utilizing Wood Chips*

In this study, we assumed that LPG was used as the fuel for heating greenhouses. However, as mentioned above, the use of local renewable energy in high-tech greenhouse horticulture is expected to progress toward realizing a decarbonized society. This study analyzed the potential for LC-$CO_2$ emissions reduction associated with using wood chips as heating energy. Changes in the LC-$CO_2$ emissions were estimated by varying the ratio of LPG substitution per unit heat rate using wood chips. The LC-$CO_2$ emission reductions were estimated by varying the wood chip ratio to 50% and 100%, assuming that only LPG (wood chip ratio of 0%) was used as the base case. This quantitatively demonstrated the LC-$CO_2$ emission reduction potential associated with using renewable energy for heating, using wood chips as an example.

The $CO_2$ emissions associated with the consumption of wood chips were calculated using Equation (1); however, the emissions during combustion were considered carbon neutral. This study also considered the changes in $CO_2$ emissions during the construction phase. Therefore, the final demand related to the item "boilers and other equipment" in the construction phase (Table 2) was changed according to the increase or decrease in the wood chip ratio. The installation cost of the wood-chip boiler (including the production cost of the boiler and other equipment) was assumed based on the data provided by the heat supply operator and varied according to the wood-chip ratio. Similarly, the cost of installing an LPG boiler was assumed to increase or decrease according to the wood-chip ratio. This study assumed that installation costs would increase proportionately to the 0.7 power of the boiler output to account for economies of scale.

## 3. Results and Discussion

### *3.1. Life Cycle $CO_2$ Emissions*

Table 5 shows the estimated LC-$CO_2$ emissions of high-tech greenhouse horticulture and their composition by item. The items in Table 5 correspond to those in Tables 2 and 3. LC-$CO_2$ emissions were estimated at 3.67 kg-$CO_2$/kg, of which the largest source was emissions from the LPG combustion for heating, accounting for 46.7% of the total emissions. Additionally, emissions during LPG production accounted for 8.8% of the total.

**Table 5.** LC-$CO_2$ emissions of high-tech greenhouse horticulture and their breakdown.

| Primary Item | Secondary/Tertiary Item | Emissions (kg-$CO_2$/kg) | Ratio |
|---|---|---|---|
| Construction phase | | | |
| Greenhouse | Glass | 0.07 | 1.8% |
| (incl. Sunlight seedling supply system) | Steel | 0.06 | 1.8% |
| | Aluminum | 0.02 | 0.6% |
| | Concrete | 0.005 | 0.1% |
| | Greenhouse construction | 0.01 | 0.4% |
| Greenhouse interior equipment | Heating pipes | 0.05 | 1.3% |
| | Aerial work platforms | 0.03 | 0.9% |
| | Shade screens, Thermal screens | 0.02 | 0.5% |
| | Self-propelled sprayers | 0.01 | 0.2% |
| | Growing beds, Rock wool | 0.01 | 0.2% |
| | Others | 0.02 | 0.4% |
| Artificial light seedling production system | | 0.004 | 0.1% |
| Warehouse for collection/shipping | | 0.01 | 0.1% |
| Energy-supply facility | Boiler room materials/construction | 0.02 | 0.5% |
| | Boilers and other equipment | 0.01 | 0.2% |
| | Other construction (electrical work, etc.) | 0.005 | 0.1% |
| Administrative office | | 0.01 | 0.2% |
| Transport vehicle (2-ton truck) | | 0.004 | 0.1% |
| Design | | 0.003 | 0.1% |
| Subtotal | | 0.35 | 9.6% |
| Operation phase | | | |
| Materials | Seedlings | 0.01 | 0.2% |
| | Fertilizers | 0.10 | 2.8% |
| | Pesticides | 0.01 | 0.2% |
| | Rock wool | 0.04 | 1.1% |
| | Other materials | 0.04 | 1.1% |
| Water and electricity | Water supply | <0.001 | <0.1% |
| | Electricity | 0.36 | 9.7% |
| LPG | LPG (combustion) | 1.72 | 46.7% |
| | LPG (production) | 0.32 | 8.8% |
| Maintenance | | 0.02 | 0.5% |
| General management | | 0.02 | 0.6% |
| Packaging Materials | Plastic packaging | 0.05 | 1.4% |
| | Cardboard boxes | 0.02 | 0.5% |
| Transport (facility to wholesaler) | Diesel fuel | 0.07 | 1.8% |
| Distribution and sale | | 0.55 | 15.0% |
| Subtotal | | 3.32 | 90.4% |
| Total | | 3.67 | 100% |

The next largest source was emissions from distribution and sales, accounting for 15.0% of the total. These are $CO_2$ emissions associated with the production activities of wholesalers, intermediate wholesalers, and retailers. The energy consumption associated with the transportation and refrigeration of tomatoes by each merchant results in $CO_2$

emissions. Previous studies on LC-$CO_2$ emissions of high-tech greenhouse horticulture did not quantify $CO_2$ emissions during distribution and sales but indicated that the impact of these emissions cannot be ignored. Figure 6 shows the change in $CO_2$ emissions, assuming direct sales to retailers rather than sales through wholesalers and intermediary wholesalers, which is common in Japan. The figure shows the LC-$CO_2$ emissions by the direct sales ratio to retailers and the share of emissions attributable to distribution and sales in the total emissions. In the base case, $CO_2$ emissions from distribution and sales were 0.55 kg-$CO_2$/kg, accounting for 15.0% of the total. However, in the 50% direct sales case, they were 0.37 kg-$CO_2$/kg, accounting for 10.7% of the total. Finally, in the 100% case, the emissions were 0.20 kg-$CO_2$/kg, accounting for 6.0% of the total. Thus, the potential for a decrease in $CO_2$ emissions with an increase in the ratio of direct sales to retailers was quantitatively demonstrated. The main reason for the decrease in $CO_2$ emissions is the reduction in energy consumption associated with the transport of tomatoes and other sales activities between the respective merchants by not involving wholesalers and intermediary wholesalers.

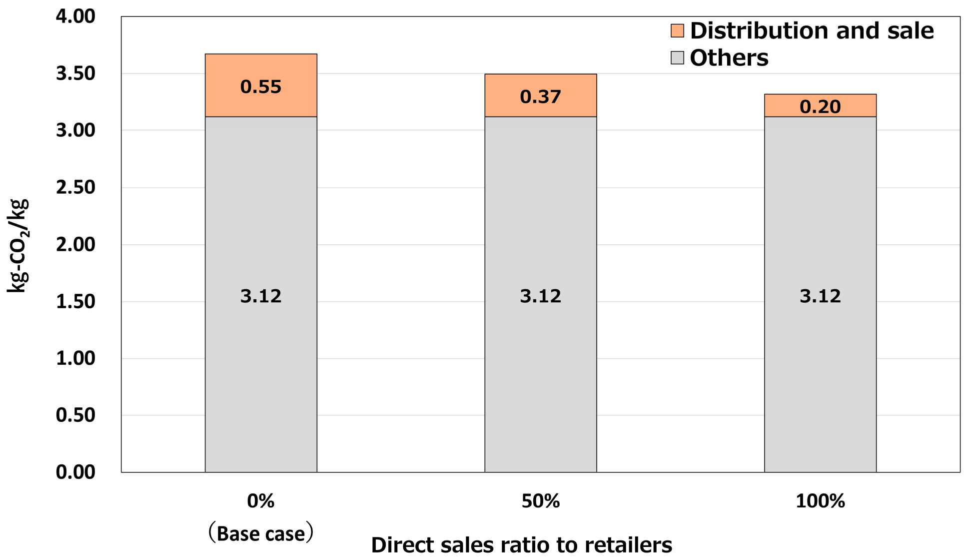


**Figure 6.** LC-$CO_2$ emissions by direct sales ratio to retailers.

After distribution and sale, electricity was the next largest emission source, which accounted for 9.7% of the total emissions. This is because electricity is consumed to operate and control various electronics and equipment in high-tech greenhouse horticulture. $CO_2$ emissions from electricity consumption are affected by the power supply composition ratio of the electricity used. This study assumes the use of electricity generated following the current power supply mix in Japan; however, the results may vary depending on differences in power supply composition.

Additionally, as primary items, materials in the operational phase accounted for 5.4% of the total, of which fertilizers accounted for 2.8%, which was the largest percentage of any item related to materials. Greenhouses account for 4.7% of the total, with glass and steel accounting for the largest share (1.8%). Greenhouse interior equipment accounted for 3.5% of the total, of which heating pipes laid inside the greenhouse accounted for 1.3%, and aerial work platforms used for various tasks inside the greenhouse accounted for 0.9%, which is a relatively large share. Packaging materials accounted for 1.9% of the total (plastic packaging: 1.4%, cardboard boxes: 0.5%). Further, emissions from diesel fuel consumption during transport (plant-to-wholesaler) accounted for 1.8% of total emissions.

### *3.2. LC-$CO_2$ Emission Reduction Potential of Utilizing Wood Chips for Heating*

Figure 7 shows the LC-$CO_2$ emissions by wood chip ratio (base case, 50%, and 100%) and their breakdown (energy-supply facility, LPG, wood chip (production), and others).

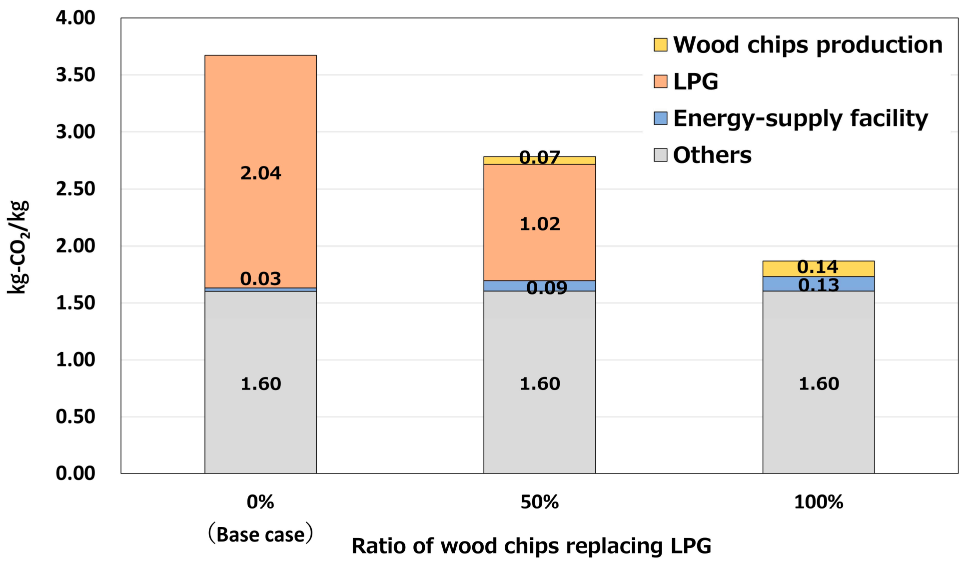


**Figure 7.** LC-$CO_2$ emissions by wood chip ratio and their breakdown.

The LC-$CO_2$ emissions can be reduced by 49.1% more than the baseline by assuming a wood chip ratio of 100% during heating. This was due to the limited increase in $CO_2$ emissions from wood-chip production and the larger reduction in $CO_2$ emissions from LPG production and combustion. Since heaters using woody biomass take time to enter stable combustion after the fuel ignition, they are generally operated in hybrid systems that combine fossil fuel combination [42]. A wood chip ratio of 50% indicated a 24.2% LC-$CO_2$ emission reduction potential relative to the base case. Thus, depending on the situation at each plant, promoting the use of renewable energy for heating as much as possible is effective in reducing $CO_2$ emissions.

Figure 7 shows that the $CO_2$ emissions of the energy-supply facilities gradually increased as the wood-chip ratio increased. This is because the introduction of wood chips requires the construction or expansion of energy-supply facilities, such as wood-chip boilers and silos.

In this study, wood chips were assumed to be a renewable energy source for heating. However, if other renewable energy sources, such as geothermal energy [13,16] and biogas [11], are utilized, the $CO_2$ emission reduction potential may be different from the estimated results of this study. Therefore, considering the type of renewable energy available and the supply potential of each plant is crucial when conducting the analysis.

### *3.3. Comparison of Results with Previous Studies*

Table 6 shows the estimated LC-$CO_2$ emissions for each case in our study alongside the results from previous tomato studies mentioned in the Introduction section. Marttila et al. [11] reported results of 3.52 kg-$CO_2$ eq./kg with only natural gas for heating and 0.86 kg-$CO_2$ eq./kg when relying solely on wood chips. Almeida et al. [12], whose system boundaries closely align with ours, reported results of 3.59 kg-$CO_2$ eq./kg when using only natural gas for heating and 2.28 kg-$CO_2$ eq./kg for a scenario where 49% of the heating demand was met by canola oil. Comparing these results with our base case, the 50% and 100% wood chip ratio cases generally showed similar trends in this study. Although their results do not exactly match those of our study, the discrepancies can be attributed to differences in the system boundaries and cultivation conditions, such as heat demand and varieties of cultivated tomatoes.

**Table 6.** Comparison of estimation results with previous studies.

| Literature | | Country | System Boundary * | $CO_2$ Emissions [kg-$CO_2$ eq./kg] | Renewable Energy Used for Heating | Other Energy Used for Heating | Fossil Fuel Substitution Rate per Heat Unit by Renewable Energy | GHGs | Yield [kg/m$^2$] |
|---|---|---|---|---|---|---|---|---|---|
| This study | Base case | Japan | C-F-P-T-D | 3.67 | - | LPG | - | $CO_2$ | 32.7 |
| | 50% wood chips | | | 2.78 | Wood chips | | 50% | | |
| | 100% wood chips | | | 1.87 | | - | 100% | | |
| Marttila et al. [11] | | Finland | C-F-P-T | 6.52 | - | Peat | - | Multiple GHGs | 41 |
| | | | | 4.39 | - | Natural gas for CHP | - | | |
| | | | | 4.26 | - | Oil | - | | |
| | | | | 3.52 | - | Natural gas | - | | |
| | | | | 3.02 | - | District heating | - | | |
| | | | | 1.81 | Biogas | - | 100% | | |
| | | | | 1.19 | - | Industrial waste heat | - | | |
| | | | | 0.86 | Wood chips | - | 100% | | |
| Almeida et al. [12] | | Italy | C-F-P-T | 3.59 | - | Natural gas | - | Multiple GHGs | 38 |
| | | | | 2.28 | Canola oil | | 49% | | |
| | | | | 1.37 | Municipal solid waste | | 39% | | |
| | | | | 2.69 | - | Natural gas for CHP | - | | |
| Ntinas et al. [14] | | Germany | C-F | 2.5~4.1 | - | Natural gas, Electricity | - | $CO_2$, $CH_4$, $N_2O$ | 24.5 |
| | | | | −0.7~1.9 | Solar heat | | Multiple cases | | |
| Torrellas et al. [13] | | Hungary | C-F | 5.00 | - | Natural gas | - | $CO_2$, $CH_4$, $N_2O$ | 48 |
| | | | | 0.44 | Geothermal heat | - | 100% | | |
| | | The Netherlands | | 0.78~2.00 | - | Natural gas for CHP | - | | 56.5 |
| Maureira et al. [7] | | USA | F | $0.86 \pm 0.06$~$0.96 \pm 0.06$ | - | Natural gas for CHP | - | $CO_2$, $N_2O$ | $60.2 \pm 10.7$~$71.6 \pm 2.7$ |
| Nasser et al. [15] | | Norway | F | 0.52~0.92 | - | Natural gas | - | $CO_2$ | 35.6~40.3 |
| | | | | 0.32~0.48 | Hydroelectric energy | | Multiple cases | | |

* C: Construction/Structure, F: Farming, P: Packaging, T: Transport, D: Distribution and sale.

Other previous studies [7,13–15] reported different results when estimating $CO_2$ emissions. In high-tech greenhouse horticulture, $CO_2$ emissions may differ depending not only on the system boundaries in the analysis but also on the crop yield per unit area, equipment configuration, and climatic conditions in the region where the plant is located. These factors may have influenced the differences in the result of each study. Therefore, analyzing the $CO_2$ emissions of high-tech greenhouse horticulture under various conditions is crucial.

Next, we compared the estimated LC-$CO_2$ emissions from conventional tomato cultivation in Japan. Nemoto [43] estimated $CO_2$ emissions in several cases using different transport methods and distances, considering the entire process from tomato cultivation to sales activities at the store. Similar to this study, assuming that tomatoes are transported from the cultivation plant to the wholesaler by truck over a distance of about 100 km each way, the emissions were estimated to be 0.63 kg-$CO_2$/kg for open-field cultivation and 1.23 kg-$CO_2$/kg for conventional greenhouse horticulture (heated). Yoshikawa et al. [44] analyzed the average LC-$CO_2$ emissions of tomatoes consumed in Japan from cultivation to transport and estimated them to be 0.97 kg-$CO_2$/kg. Owing to the differences in system boundaries and other analytical conditions, the results of these studies cannot be compared with those of this study. However, based on the estimation results of both previous studies, reducing the LC-$CO_2$ emissions of high-tech greenhouse horticulture to the same level as those of conventional cultivation methods may be challenging, even with a 100% wood-chip ratio.

## 4. Conclusions

This study analyzed LC-$CO_2$ emissions from high-tech greenhouse horticulture in Japan, using tomato hydroponic cultivation as a case study and employing a hybrid method that combined process and input–output analyses. The research also analyzed the potential $CO_2$ emission reduction by substituting LPG with wood chips as a heating energy source for greenhouses.

The results showed that 55.6% of LC-$CO_2$ emissions were attributed to the combustion and production of LPG for heating. Further, replacing LPG with wood chips reduced LC-$CO_2$ emissions by up to 49.1%. Additionally, the distribution and sale processes, involving retailers, wholesalers, and intermediary wholesalers, contributed to 15.0% of total $CO_2$ emissions—an aspect that was overlooked in the previous studies. Shifting sales channels to direct sales to retailers demonstrates a potential reduction of up to 9.6% in LC-$CO_2$ emissions. However, the study acknowledges the site-specific nature of its findings due to variations in facility configurations and cultivation conditions across different plants.

This study quantitatively demonstrated the effectiveness of replacing fossil fuels with renewable energy sources for heating to reduce LC-$CO_2$ emissions in high-tech greenhouse horticulture. However, even with such measures, the LC-$CO_2$ emissions of this approach are still higher than those of conventional cultivation systems. Therefore, contributing to a decarbonized society requires comprehensive measures to further reduce $CO_2$ emissions throughout the life cycle, beyond utilizing renewable energy for greenhouse heating.

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