PERSPECTIVE ON THE USE OF AIR-SOURCE HEAT PUMPS TO REDUCE CO_2 EMISSIONS FROM GREENHOUSES BASED ON LIFE CYCLE ASSESMENT

Masashi Hanagata, General Manager, Tokyo Electric Power Company, Japan
Fumiyuki Goto, Chief Researcher, Central Research Institute of Electric Power Industry, Japan
Kazuhiro Shoji, Chief Researcher, Central Research Institute of Electric Power Industry, Japan
Hideyuki Mano, Assistant Manager, Tokyo Electric Power Company, Japan
Toyoki Kozai, Professor, Chiba University, Japan

Abstract: In protected horticulture, the use of heat pumps in place of combustion heaters, which are widely used in Japan is expected to achieve energy conservation, cost reductions and CO_2 emissions reduction. We estimated the amount of CO_2 emissions from energy and so on inputted per plant body in the raising of seedlings and cultivation of tomatoes in greenhouses. Based on LCA, CO_2 emissions can be reduced by 6.31 kilograms per plant body on average in cases where both heat pumps and combustion heaters are used together as heat sources compared with those cases where only combustion heaters are used. This is equivalent to a 38% reduction. In cases where all combustion heaters are replaced by heat pumps, an estimated 65% reduction is to be expected. Moreover, we found that the temperature and high CO_2 concentrations in greenhouses were maintained at levels suitable for the growth of tomatoes by closing the roof windows of greenhouses and cooling the greenhouses with heat pumps during the winter daytimes. These results provide multiple usages of heat pumps in greenhouses.

Key Words: heat pump, CO_2 reduction, greenhouse, life cycle assessment, tomato

1 INTRODUCTION

Japan's tomato crop amounts to about 732,800 tons per year (2008), accounting for about one-third of the total of fruit-vegetables harvested in the country (MAFF 2010). The total area devoted to the cultivation of tomatoes in Japan is about 12,500 hectares, and most of the area is used for protected horticulture (MAFF 2007). In addition, most tomatoes produced in Japan are eaten raw (MAFF 2010).

Japan lies in the Asian monsoon climate zone, and its climatic conditions are characterized by high temperatures and humidity during the summer and low temperatures during the winter. About 96% of greenhouse heat requirements are fulfilled by combustion heaters that use kerosene, fuel oil and others (MAFF 2009). On the other hand, heat pumps have not been widely disseminated to date, though it is widely recognized that the use of heat pumps is effective as the energy efficiency (coefficient of performance; COP) of a heat pump is high. In recent years, however, the COP of a heat pump has further increased. Additionally, it is generally easier to install air-source heat pumps compared with ground-source or water-source heat pumps. For such reasons, heat pumps have been increasingly introduced by general households as well as in a wide range of fields and applications such as for business and industrial use (HPTCJ 2007, Hanagata 2007). In the future, heat pumps are also expected to come into wider use in the field of agriculture with an aim to promote energy conservation (IEA 2010).

Furthermore, efforts to reduce greenhouse gases in recent years have extended into multiple areas. The field of agriculture is no exception. Efforts to reduce CO_2 emissions are also required in this field. The field of protected horticulture consumes a large amount of fossil energy, accounting for a large share of CO_2 emissions in the entire agricultural field (Oikawa 2007). Heat pumps are regarded as an effective tool from the viewpoint of CO_2 emissions reduction as their CO_2 emissions per energy gained are less than that of combustion heaters.

However, though there are examples of the LCA study in those cases where combustion heaters or air heaters that use fuel oil, kerosene and others as heat sources for protected horticulture, the study on the effects of CO_2 emissions reduction via heat pump utilization from the viewpoint of LCA has to date not been widely reported (Hosoi 2001).

On the other hand, LCA studies on tomatoes, which have been reported to date, show that the cultivation period has the largest effect on CO_2 emissions throughout the life cycle of tomatoes from seeding to transportation (Roy et al. 2008, Nishizono and Moteki 2007, Shiraki et al. 2006, Yoshikawa et al. 2006). For example, the percentage of cultivation is estimated to be about 85%, according to Shiina (2007).

The functions of heat pumps include cooling, dehumidification and others, in addition to heating. In reality, however, heat pumps are mainly used for heating. Their dehumidification and cooling functions are just partly used for floriculture such as rose cultivation (Shimaji 2011). When the serviceability of cooling and dehumidification functions of heat pumps is made clear in the future, the fields and scope of heat pump utilization are expected to be drastically expanded.

This study is aimed at: (1) from the viewpoint of LCA, in order to find the effect of the introduction of heat pumps to reduce CO_2 emissions, comparing CO_2 emissions from the conventional method of cultivation by using combustion heaters and that from the method of cultivation by replacing the heat source to heat pumps within the phase from the raising of seedlings to the cultivation of tomatoes based on hearings on CO_2 emissions in the respective cases; and (2) finding the effectiveness of CO_2 fertilization in cases where greenhouses are cooled with their roof windows closed during daytime in the winter in order to contribute to the development of cultivation methods that make use of the ability (including cooling and dehumidification) of heat pumps to the greatest extent.

2 METHODOLOGY

2.1 Target and scope of evaluation

The system boundary as the target scope of LCA is shown in Figure 1. As mentioned in the introduction above, the focus of LCA is placed on the raising of seedlings and cultivation. This study is aimed at identifying the difference in CO_2 emissions between combustion heaters and that of heat pumps within the target scope. Therefore, we conducted research on the relevant factors including fuel usage, electricity usage and the quantities of fertilizers and agricultural chemicals, which are assumed to change with the difference in heat sources. For information, cultivating works with tractors and the usage of polyvinyl multi-films were excluded from the target scope as there is little difference regardless of the heat sources.

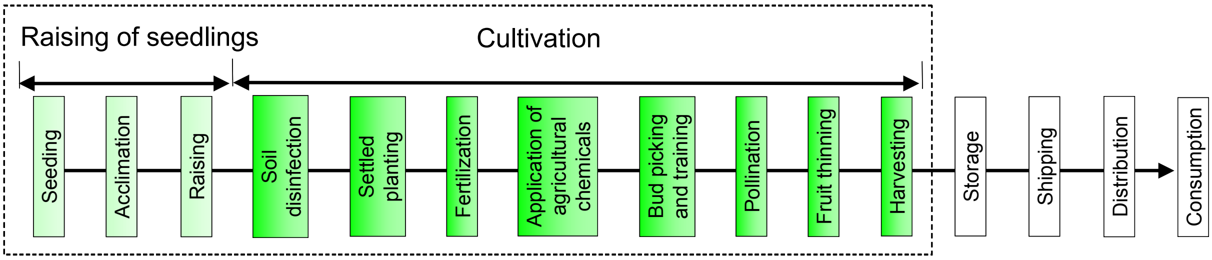


Figure 1: System boundary

Raising of seedlings and cultivation of tomatoes are covered by this study (the scope surrounded by dashed lines)

Four farm households in the Kanto district were used as targets for this study on cultivation. Of these households, the greenhouses (660-1,700 square meters per greenhouse) of three households were covered by hard films, and the tomatoes were cultivated by soil culture. The seedlings were planted from early August to late August, and the tomatoes were harvested from late September to October through late June in the following year. The remaining one household had a glass greenhouse (1,170 square meters), and was engaged in water culture. All of the four households installed heat pumps in March 2009, and the study periods were one year (April 2008 to March 2009) before the installation of heat pumps and one year (April 2009 to March 2010) after the installation of heat pumps. None of the households relied solely on heat pumps, all of them used both heat pumps and fuel fired combustion heaters in combination. The ratio of electric power consumption to total energy consumption for heating ranged between 16% and 52% (26% on average).
As for the raising of seedlings, we conducted a study on specialized producers.

It should be noted that the functional unit in conducting LCA analysis is defined as one plant body from the raising of seedlings to cultivation. This is because the continuity from the raising of seedlings to cultivation is considered from a life-cycle point of view.
Table 1 shows the CO_2 emission intensities used in the study.

Table 1: CO_2 emission intensity

Electricity	0.339	kg-CO_2/kWh	Website of Tokyo Electric Power Company http://www.tepco.co.jp/eco/environment/provision/outline/outline03-j.html
Kerosene	2.49	kg-CO_2/L	Ministry of the Environment and Ministry of Economy, Trade and Industry; List of calculation methods and emission factors for greenhouse gas emissions
Fuel oil A	2.71	kg-CO_2/L	Ministry of the Environment and Ministry of Economy, Trade and Industry; List of calculation methods and emission factors for greenhouse gas emissions
Elemental fertilizer	9.0	g-CO_2/yen	National Institute for Agro-Environmental Sciences (NIAES) Manual for Life Cycle Assessment of Agricultural Practices in Japan, November 2003
Combined fertilizer	5.9	g-CO_2/yen	National Institute for Agro-Environmental Sciences (NIAES) Manual for Life Cycle Assessment of Agricultural Practices in Japan, November 2003
Organic fertilizer	2.4	g-CO_2/yen	National Institute for Agro-Environmental Sciences (NIAES) Manual for Life Cycle Assessment of Agricultural Practices in Japan, November 2003
Agricultural chemicals	3.8	g-CO_2/yen	National Institute for Agro-Environmental Sciences (NIAES) Manual for Life Cycle Assessment of Agricultural Practices in Japan, November 2003

2.2 Measurements in greenhouses

We used two greenhouses of identical size, which are located about 800 meters above sea level, halfway up Mt. Akagi in Gunma Prefecture about 100 kilometers north away from Tokyo. The size of the greenhouses is 6.5 meters in width, 12.6 meters in depth and 2.15 meters in height, and the roof top is 3.76 meters high. The depth of the greenhouses lies in a north-south direction. The greenhouses have one layer of thermal insulating curtain (polyvinyl alcohol and polyethylene). One of the greenhouses has two heat pumps (SFYP140A made by Daikin Industries, Ltd., Japan), and the other greenhouse has no heat pump. Moreover, CO_2 was supplied (20 liters per minute) from a CO_2 gas cylinder to maintain CO_2 concentrations in the greenhouses at about 1,000 ppm. CO_2 concentrations were measured by a non-dispersive infrared sensor (Vaisala GMP343B, Finland). The amount of electricity consumed by heat pumps was measured by a multi-meter (WVP-WE made by Watanabe Electric Industry Co., Ltd., Japan). The measurement was conducted on fine days in late December 2010 in the greenhouses containing no crops.

3 RESULTS

3.1 CO_2 emissions from the raising of seedlings

To identify the CO_2 emissions from the raising of seedlings, we interviewed specialized seedling producers. One of the producers whom we interviewed produced about 7 million tomato seedlings a year in greenhouses where hot-water heaters equipped with boilers that use fuel oil A or kerosene were installed. CO_2 emissions from inputted energy and materials were 0.012 kilograms per plant body (seedling). Of the 0.012 kilograms, emissions from kerosene accounted for 0.0046 kilograms (38%), that from fuel oil A 0.0034 kilograms (28%), from electricity, 0.0033 kilograms (28%), from fertilizer, 0.0006 kilograms (5%), and from agricultural chemicals, 0.0002 kilograms (2%) (Figure 2). Compared with the cultivation phase described below, the percentage of CO_2 emissions from fertilizers and agricultural chemicals of the total emissions was as high as about 7%.

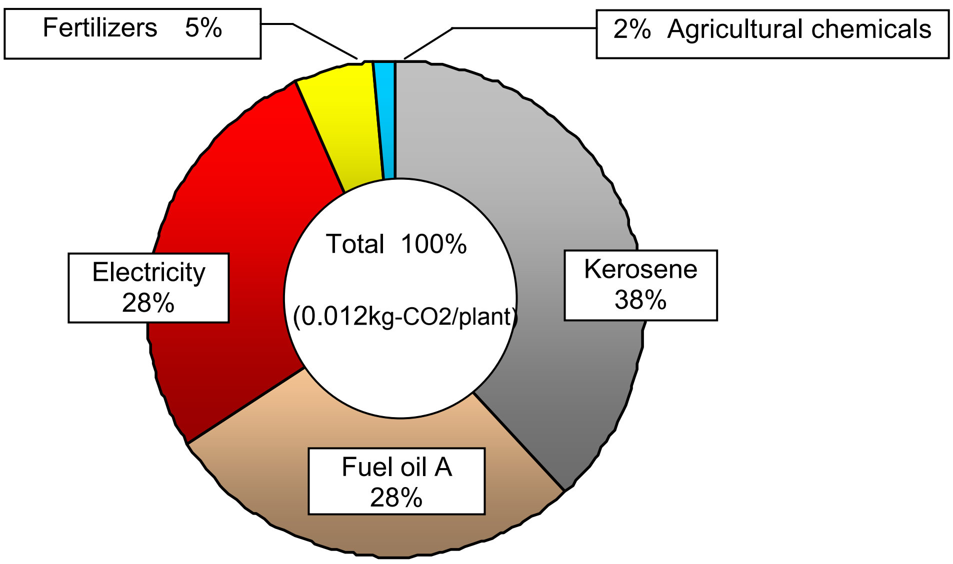


Figure 2: Ratio of CO_2 emission sources in the raising of seedlings

3.2 CO_2 emissions from cultivation

We conducted a study on the farm households mentioned above to grasp the area of their greenhouses, the number of plant bodies, the amount of energy consumption, and the quantities of fertilizers and agricultural chemicals. Based on this data, we calculated CO_2 emissions before and after the introduction of heat pumps. As a result, it was found that fuel oil consumption and electricity consumption before the introduction of heat pumps were 5.76 liters and 2.45 kWh, respectively, per plant body on average during the cultivation period. After the introduction of heat pumps, the consumption amount was 2.69 liters and 8.54 kWh, respectively. As for the quantities of fertilizers and agricultural chemicals, no significant difference was recognized before and after the introduction of heat pumps in the study (Table 2).

Table 2: Comparison of CO_2 emissions from fertilizers and agricultural chemicals before and after the introduction of heat pumps (during cultivation)

Emission source	Before	After
Fertilizers	0.155	0.122
Agricultural chemicals	0.200	0.182
Total	0.355	0.304

(Unit: kg-CO_2/plant)

Based on the aforementioned results, we calculated the amount of CO_2 emissions per plant body in the cultivation phase. The CO_2 emission amount per plant body was 16.80 kilograms on average before the introduction of heat pumps, and the figure decreased to 10.49 kilograms after the introduction of heat pumps (Table 3).

As for CO_2 emissions prior to the introduction of heat pumps, about 93% of total CO_2 emissions during cultivation derived from combustion heaters and about 2% derived from fertilizers and agricultural chemicals.

We calculated the total amount of CO_2 emissions by adding CO_2 emissions during the raising of seedlings to CO_2 emissions during cultivation. The total amounts are 16.82 kilograms and 10.50 kilograms on average, respectively, before and after the introduction of heat pumps. Consequently, it was shown that CO_2 emissions per plant body were reduced by 6.31 kilograms via the introduction of heat pumps as part of the heating equipment during the period from the raising of seedlings to cultivation, and that the reduction rate was about 38% on average (Figure 3).

Table 3: Comparison of CO_2 emissions (during cultivation)

	Fuel oil A only (before introduction of HP)	Hybrid (after introduction of HP)	HP only
CO_2 emissions (kg-CO_2/plant)	16.80	10.49	5.5*

* Estimated value from Ohyama and Kozai (2008)

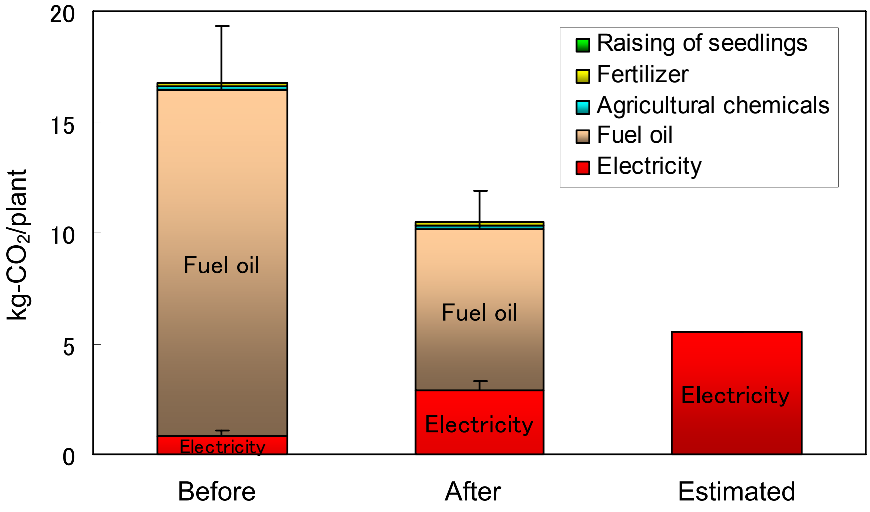


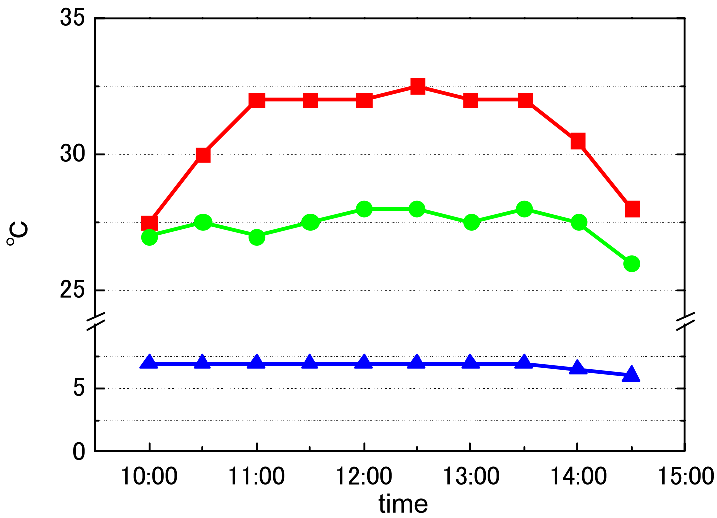
Figure 3: CO_2 emissions per plant body before and after introduction of HP (during the raising of seedlings and cultivation)

The rightmost bar represents the value of trial calculation in the case where all heating appliances are replaced by heat pumps. (Mean ±S.E, N=4)

3.3 Environmental changes in greenhouses at the time of cooling during winter

3.3.1 Greenhouse temperature

In summer, of course, and also generally in winter (from November to around March), the temperature in greenhouses during fine weather escalates substantially and even exceeds the needed temperature suitable for the growth of plants in some cases. In such cases, the suitable temperature is maintained usually by opening roof windows to let in the cold outside air. Therefore, if the temperature in greenhouses can be maintained at a suitable level minus opening roof windows by making use of heat pumps, the productivity of tomato cultivation is expected to rise without wasting CO_2 fertilization.
Figure 4 shows the changes in temperatures inside and outside the greenhouses on a fine day in late December 2010 (10-minute average amount of solar radiation at midday = 557 W per square meter).



(●) represents those cases where heat pumps are operated with roof windows closed; (■) represents those cases where heat pumps are not operated with roof windows closed; and (▲) represents the outside temperature.

Figure 4: Changes in temperatures inside and outside the greenhouses

The temperature of the outside air during the measurement period remained at about 7℃. The temperature in the greenhouse, where no heat pumps have been installed and its roof windows are closed, continued to rise over time and reached around 33℃ at about 11:00 a.m. The temperature was kept at about 33℃ until 1:30 p.m. Then, the temperature sharply decreased. On the other hand, the temperature inside the greenhouse where heat pumps were operated was kept at about 27℃, though its roof windows were shut.

3.3.2 CO_2 concentrations

We measured the time required for CO_2 concentrations in the greenhouses to become equal to that of the outdoors (≒ 380 ppm), after CO_2 concentrations in the greenhouses were increased to about 1,000 ppm at the time when the measurement was started (Figure 5).

The average wind velocity outdoors during a 10 minute period from midday on the measurement day was 4.1 meters per second. In those cases where roof windows were closed, the CO_2 concentrations slowly decreased and took about three hours to become almost equal to outdoor CO_2 concentrations. In cases where roof windows were opened, on the other hand, it took only about 15 minutes to become almost equal to outdoor CO_2 concentrations.

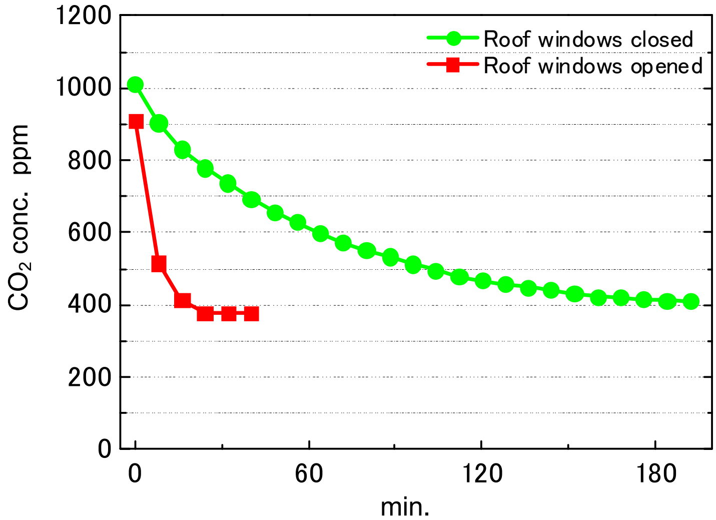


Figure 5: Changes in CO_2 concentrations in the greenhouses

Time-varying changes in CO_2 concentrations in greenhouses in those cases where roof windows are opened (■) and closed (●) were measured. The CO_2 concentrations were measured at the point near the centre of the greenhouses at a height of 150 centimetres from the ground.

The frequency of ventilation in the greenhouse in this experiment (N: the value that is calculated by dividing the amount of ventilation per hour in the greenhouse by V as the volume of the greenhouse. Unit [1/h]) was calculated by Formula (1) (Aitken-Christie et al. 1995).

$$N = \frac{1}{t_2 - t_1} \times \ln \frac{C_1 - C_{out}}{C_2 - C_{out}} \qquad (1)$$

Where, C_1 and C_2 represent indoor CO_2 concentrations at the time of t_1 and t_2, respectively, and C_{out} represents the CO_2 concentrations outside the greenhouse.

As a result, N = 1.0 time per hour in cases where roof windows were closed, and N = 10.6 times per hour in cases where roof windows were opened.

(R) as the speed of CO_2 leaked out of the greenhouse was calculated by Formula (2).

$$R=V \times N \times (C_{in} - C_{out}) \quad (2)$$

Where, C_{in} represents the CO_2 concentrations inside the greenhouse.

The speed of CO_2 leakage slowly decreased in those cases where roof windows were closed. However, the initial speed in those cases where roof windows were opened was about ten times higher than those cases where roof windows were closed.

4 DISCUSSION

As described above, we analyzed CO_2 emissions derived from the raising of seedlings and the cultivation of tomatoes as the target scope from the viewpoint of LCA. As a result, it was found that CO_2 emissions per plant body totaled 16.82 kilograms under the conventional method of cultivation that makes use of combustion heaters. Of this total, the raising of seedlings accounted for 0.012 kilograms and cultivation for 16.80 kilograms. CO_2 emissions were found to be overwhelmingly larger in the cultivation phase. It was also found that CO_2 emissions can be reduced by 38% on average by introducing heat pumps as a heating source in the cultivation phase (Figure 3).

For reference, the greenhouses targeted for this study used heat pumps and combustion heaters in combination. In the future, however, it may be possible for greenhouses to be sufficiently heated by heat pumps only. According to Tong et al. (2010), as a result of the actual measurement of the COP of heat pumps in small greenhouses, it was reported that the average COP was 3.3 in those cases where greenhouse temperatures were maintained at 16℃ when the outside temperature fluctuated between -5℃ and 0℃. In addition, according to Ohyama and Kozai (2008), when the heating temperature in greenhouses is set at 15℃ and COP at 3, CO_2 emissions from heat pumps during the cultivation period amount to 11 tons in 1,000 square meters. Based on this data, for example, in cases where all of the greenhouses studied at this time, which had an average planting density of 2,000 seedlings over 1,000 square meters, are heated by heat pumps, CO_2 emissions per plant body would be 5.5 kilograms (Figure 3). As the CO_2 emissions of fuel oil origin used by combustion heaters are 15.62 kg-CO_2 per plant body (the value calculated by deducting CO_2 emissions from fertilizers, agricultural chemicals and so on from 16.80 kg-CO_2 per plant body) in this study, the expected amount of reduction in CO_2 emissions is 10.12 kg-CO_2 per plant body and its reduction rate is about 65%.

It is known that the CO_2 concentrations in greenhouses decline during the daytime due to the active photosynthesis of crops, leading to an adverse impact on production. To prevent such impact, CO_2 fertilization is conducted in some cases. On the other hand, greenhouses have been ventilated by opening roof windows and others during the daytime even in the winter to retard the increase of temperature in greenhouses due to the incoming radiation of sunlight. Considering these points, if greenhouses with their roof windows closed can be cooled by heat pumps to restrain indoor temperature rise, it would be possible to make CO_2 fertilization more effective (Kozai 2010). Therefore, we conducted the experiment mentioned in Section 3.3 above, and we verified that it is possible to maintain CO_2 concentrations in greenhouses for many hours by operating heat pumps in a cooling mode, while maintaining the greenhouse temperature at a suitable level conducive to the growth of plants (Figure 4). Additionally, N as the frequency of ventilation became large as the roof windows of greenhouses were opened and consequently the speed of CO_2 leakage proportionally increased (Figure 5). Therefore, we were able to verify the significance of reducing the frequency of ventilation.

For the reasons indicated above, we propose the system shown in Figure 6 as the methods of the year-round raising of seedling and cultivation of tomatoes by making good use of heat pumps. This system is composed of the raising of seedlings in a closed-type environmentally controlled chamber where heat pumps and artificial light illumination are installed (Kozai 2010) and water culture in greenhouses is equipped with heat pumps. Its effect in reducing CO_2 emissions is considered very high.

The conventional method requires two months or longer for the raising of seedlings, including preparation works. As the raising of seedlings can be finished in about three weeks under the proposed system, it is possible to proportionally extend the cultivation period. In the closed-type environmentally controlled chamber, moreover, high-quality seedlings are expected to be stably produced without agricultural chemicals. Furthermore, as the proposed system actively makes use of cooling and dehumidification functions of heat pumps on a year-round basis, the occurrence of diseases is expected to be retarded, in addition to the effective use of CO_2 fertilization as mentioned above, and annual crops are expected to be higher. From now on, we plan to further verify the validity of the proposed system.

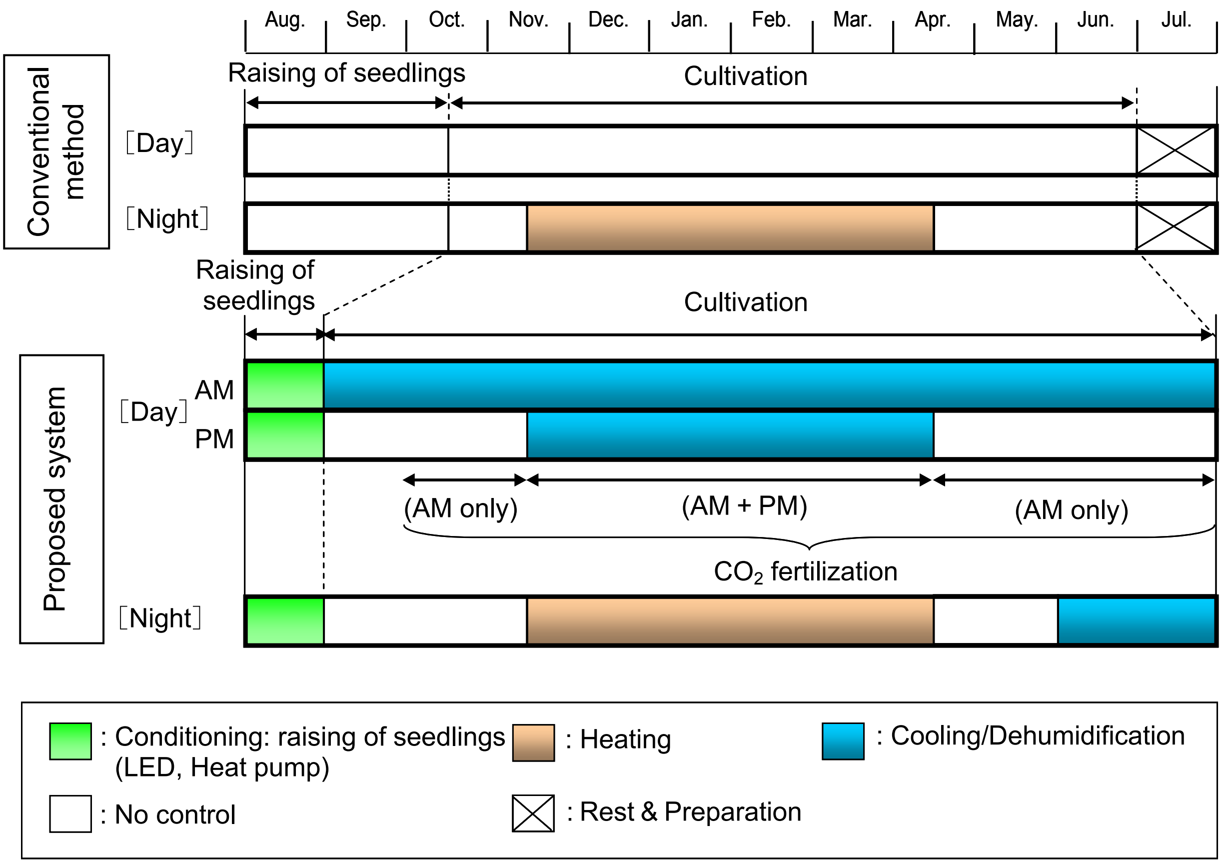


Figure 6: Year-round raising of tomato seedlings and cultivation using heat pumps

The efficient raising of seedlings within a short period is to be expected and to ensure a long period of cultivation throughout the year by making use of the various functions of heat pumps (dehumidification, cooling, etc.) in addition to the heating function.

5 CONCLUSIONS

Utilizing tomatoes as an example, we conducted research on the utilization of air-source heat pumps for protected horticulture in Japan and arrived at the following conclusions:

(1) In those cases where air-source heat pumps and combustion heaters were used together in combination, it was found that CO_2 emissions, from the viewpoint of LCA, were reduced by about 38% on average compared with those cases where only combustion heaters were used.

(2) In those cases where all combustion heaters were replaced by heat pumps, CO_2 emissions are expected to be reduced by about 65% compared with those cases of combustion heaters only.

(3) It was confirmed by actual measurements that using heat pumps to cool during the winter daytimes was effective in terms of CO_2 emissions and others.

Based on the aforementioned results, we proposed a new cultivation system that utilized heat pumps for protected horticulture.

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