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Prediction Model for the Internal Temperature of a Greenhouse with a Water-to-Water Heat Pump Using a Pellet Boiler as a Heat Source Using Building Energy Simulation

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Abstract: Although smart farms are considered an alternative to traditional agriculture, they require large amounts of energy and high investment costs, hindering their efficient implementation. In the Republic of Korea, the energy supply is primarily for heating rather than cooling, necessitating the accurate prediction of the greenhouse internal temperature to determine the feasibility of agricultural management while using renewable energy. This study developed a model (TRNSYS) for predicting the internal temperature of a greenhouse using building energy simulation. A greenhouse heating experiment was conducted using a hybrid heating system simulated by TRNSYS to analyze the prediction model. The regression analysis of the experimental and simulation results revealed an R^2 and RMSE of 0.8834 and 3.61, respectively. A comparative analysis was conducted with the existing hot air heating system to evaluate the heating performance and economic feasibility of the hybrid system. Overall, the heating performance exhibited satisfactory results, whereas the economic analysis, based on life cycle cost, revealed a cost reduction effect of 9.45%. Hence, greenhouse heating using renewable energy can replace conventional fossil fuels with economic advantages. Moreover, the prediction of the internal temperature of the greenhouse will facilitate the design of a systematic smart farm business to prevent duplicate investment.

Keywords: heat pump; pellet boiler; greenhouse heating; TRNSYS; economic analysis

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1. Introduction

Smart farms are a current hot topic in global agriculture research and are increasingly investigated within the Republic of Korea (ROK), which has established a nationally led research project [1]. In the ROK, the development of third-generation smart farms, focusing on the energy system, is currently active after the first- and second-generation farms have been passed [2]. Besides smart farms, new and renewable energy also represents a major research topic as a means to achieve carbon neutralization [3–8]. These two issues have considerable overlap with the ROK's 2030 Greenhouse Gas (GHG) Reduction Roadmap. In particular, the ROK has pledged that the domestic agricultural sector's carbon emission reduction must account for 4.8% of the nation's total carbon emission reduction [9]. However, with the intensified interest in smart farms and carbon reduction, a need has arisen for the development of greenhouse heating technology using renewable energy. Currently, the ROK government supplies and recommends the use of geothermal heat pumps and pellet boilers as new and renewable energy systems for greenhouse heating [10]. However, the efficiency of geothermal heat pumps as a stable heat source is variable, as it depends on the amount of groundwater and the presence of a river near the greenhouse, while also requiring high initial investment costs [11]. Meanwhile, regarding pellet boilers, securing stable economic feasibility is challenging due to the price volatility of wood pellets as fuel [12–15]. Moreover, even if one opts for such a heating system, it is unclear whether it can meet the required heating performance for the regional location and climate. Meanwhile, the effective prediction of the internal temperature of a greenhouse heated with renewable energy can alleviate these challenges.

Many researchers mainly use the TRNSYS program to predict the thermal environment of greenhouses. TRNSYS is a building energy simulation program for thermal energy simulation analysis in residential and commercial buildings. Many researchers have used this program in many studies and conducted simulation studies on the heating load of the greenhouse and the greenhouse heating performance of the new system. The research cases of using TRNSYS related to greenhouses are as follows.

Ahamed et al. (2020) tried to predict the heating load using TRNSYS to evaluate the applicability of Chinese solar greenhouses in high latitudes in the northern hemisphere. Their newly developed TRNSYS model (CSGHEAT) found that the heating load result could be different from the existing model (CSG) by 33–68% depending on the greenhouse control based on solar radiation and the water generation rate [16]. Asa'd et al. (2019) used TRNSYS to investigate the energy performance of a solar greenhouse using rock-bed thermal storage. They measured the outlet temperature of the rock-bed thermal storage and the internal temperature of the greenhouse for one year, and compared the experimental values with the predicted values using TRNSYS. As a result of the comparison, they derived at an R^2 value of about 0.926, and announced that the above results were obtained using conditions such as the set temperature inside the greenhouse, greenhouse cover, and mechanical ventilation as parameters [17]. Banakar et al. (2021) modeled three types of greenhouses consisting of a natural ventilation greenhouse, a semi-closed greenhouse, and an ideal closed greenhouse using TRNSYS. A TRNSYS model was built for the three greenhouses, and the change in heating and cooling load according to the ventilation rate was confirmed. Compared to the natural ventilation greenhouse, it was confirmed that the heating load decreased by two times and the cooling load increased by three times in the ideal closed greenhouse. They confirmed that the heating and cooling load was highly dependent on the ventilation rate [18]. The above research cases used TRNSYS for the thermal energy analysis of greenhouses. Most of the greenhouse research cases using TRNSYS consisted of the prediction of the results through modeling and simulation, and comparisons between models. However, there were relatively few research cases in which the actual greenhouse composition and the TRNSYS model were configured and verified in the same way. Therefore, this study intends to model the actual greenhouse composition with TRNSYS and to verify it by comparing the experimental and predicted values. First, a hybrid heating system (a water-to-water heat pump system using a pellet boiler as a heat source, HPB), developed based on the results of previous studies, was selected as a greenhouse heating system [19]. Note, TRNSYS is a specialized building energy simulation (BES) program for analyzing thermal energy characteristics to predict the internal temperature of a greenhouse [18,20]. We intend to verify the results of the internal temperature prediction model developed with the BES program for HPB by comparing it with the experimental results. In addition, HPB conducted comparative experiments with a hot air heating system (HAH) using an air-to-air heat pump and radiator and conducted economic analysis.

2. Experimental

2.1. Summary of Greenhouse

The targeted greenhouse used in this study was located at the Kangwon National University (Chuncheon-si, Gangwon-do, Korea). The greenhouse area was 90 m^2 and represented a double-layer type. That is, the external greenhouse represented a glass greenhouse, and the internal greenhouse represented a plastic greenhouse. The floor area was 68.37 m^2 with a 121.44 m^2 covering area. The heating experiment was conducted with two greenhouses in a similar manner. The first greenhouse utilized a hybrid heating system powered by renewable energy, comprising a water-to-water heat pump with a pellet boiler as a heat source (HPB). In the second greenhouse, a hot air heating system comprising an air-to-air heat pump and radiator was applied (HAH; Figure 1). The dimensions of the greenhouse used in the experiment are presented in Figure 2 and Table 1.

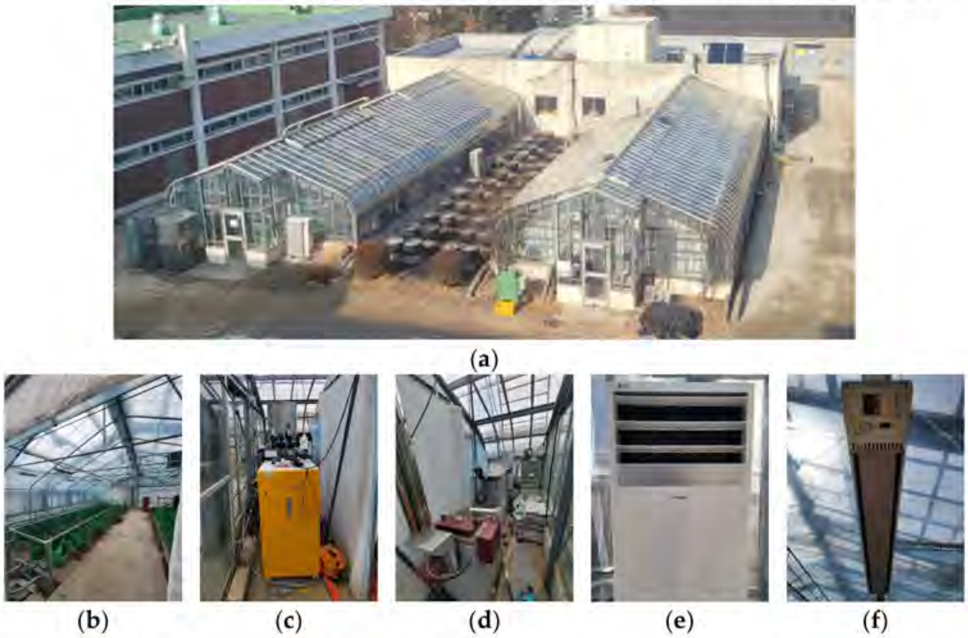


Figure 1. Heating device installation overview. (**a**) Photograph of the experimental greenhouse, (**b**) inside view of the greenhouse, (**c**) water-to-water heat pump and water tank, (**d**) pellet boiler, (**e**) air-to-air heat pump, (**f**) ceiling radiator.

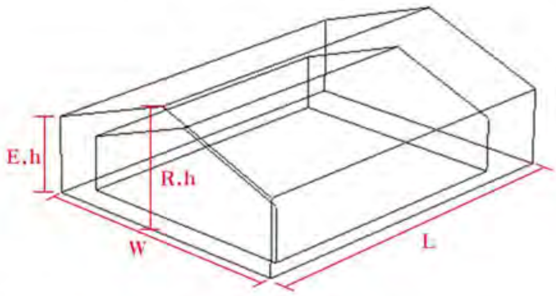


Figure 2. Schematic diagram of greenhouse.

Table 1. Greenhouse dimensions.

	Inside Greenhouse	Outside Greenhouse
W (Width), m	9.34	11.64
L (Length), m	7.32	8.52
E.h (Eaves height), m	1.70	2.40
R.h (Roof height), m	3.00	3.90

2.2. Experimental and Simulation Procedures

For the HPB, the thermal energy supply facilities applied to the greenhouse represented a hybrid heating system. It consisted of an 83,736 kJ/h class pellet boiler (KN-23D, Kyuwon Tech Co., Ltd., Gyeongsan-si, Gyeongsangbuk-do, Korea) (Table 2) and a 3RT-class water-to-water heat pump (3RT, Innergie Technologies Inc., Gwangju-si, Gyeonggi-do, Korea) (Table 3). This pump was customized with a capacity suitable for the internal greenhouse heating load. The pellet boiler was selected as the product with a minimum capacity available for purchase in the market and exhibited a relatively high heating capacity. The thermal energy supply device supplied thermal energy through convection and radiant heat transfer using a fan coil unit (FCU) and tube rail. Figure 3 depicts how the thermal energy of the constructed HPB was generated. For HAH, an air-to-air heat pump of 59,871 kJ/h class and 12 radiators of 4186 kJ/h class were utilized. The air-to-air heat pump was selected with a suitable capacity for the heating area standard. The radiator was intended to be used as an auxiliary heat source when heating is stopped during the defrosting process of an air-to-air heat pump. Moreover, the radiator was designed to exhibit a heating capacity similar to that of an air-to-air heat pump. The thermal energy supply devices were selected based on the greenhouse heating load, which was set to more than 41,860 kJ/h. Furthermore, the heating capacity of the heat energy supply devices was set high, as we anticipated an extremely cold season, which could be theoretically caused by anomalous climate conditions in the study area.

Table 2. Details of wood pellet boiler.

Type	Numerical Value
Model	K-23A
Pellet heating ability	96,279 kJ/h
Pellet water heating capacity	95,706 kJ/h
Highest pressure in use	1 kgf/cm^2
Irrigation capacity	90 L
Combustion method	Natural exhaust formula
Fuel consumption	6.15 kg/h
Type	Associative formula

Table 3. Details of water-to-water heat pump.

Type		Numerical Value
Model		COMPORT-A-03
Rated power source		380 V/3 Ph/60 Hz
Rated capacity	Cooling system	10,610 W
	Heating system	10,517 W
Operational power	Cooling system	3.41 A
	Heating system	5.26 A
Consumption power	Cooling system	1776 W
	Heating system	2839 W
Refrigerant		R-410A 2.3 kg
Equipment weight		230 kg

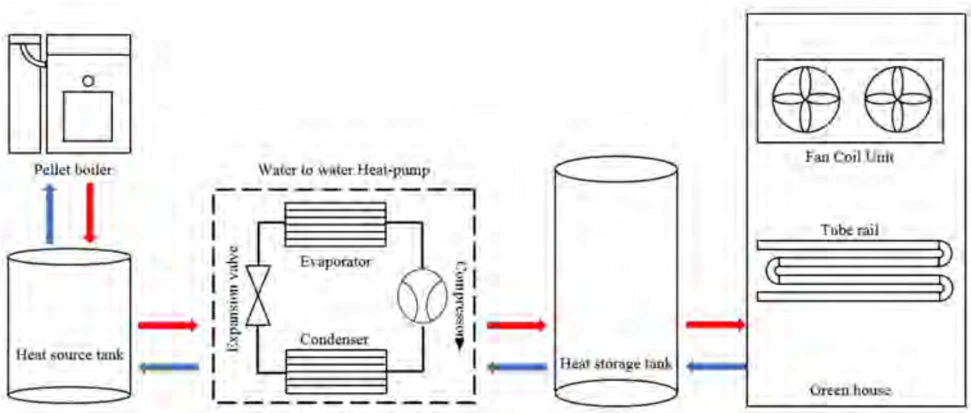


Figure 3. Schematic diagram of the water-to-water heat pump with a pellet boiler as a heat source.

The introduced HPB was tested according to the control logic (Figure 4). Of note, in the control logic sequence, the thermocouple first senses the temperature of the greenhouse and the heat source tank. The sensed value was compared with the set temperature range of the greenhouse heating and heat source tank to control the pellet boiler and the main heating pump using an on/off control [19]. The water-to-water heat pump allowed the storage tank to be maintained at 57 °C, which is the maximum heating water temperature of the heat pump used in this study. Moreover, the greenhouse heating temperature was set to 18–22 °C, and the heat source temperature was set to 20–25 °C. The range of heating and the heating source was set to prevent the breakdown and malfunction of equipment due to frequent on/off control. The air-to-air heat pump and radiator applied in the HAH were the commonly used types of air conditioners and radiant heat transfer heaters from the market. The inside of the greenhouse was heated to 22 °C, which was selected as the standard heating temperature for melons, which require the highest nighttime temperature among crops that can be grown in the ROK [21].

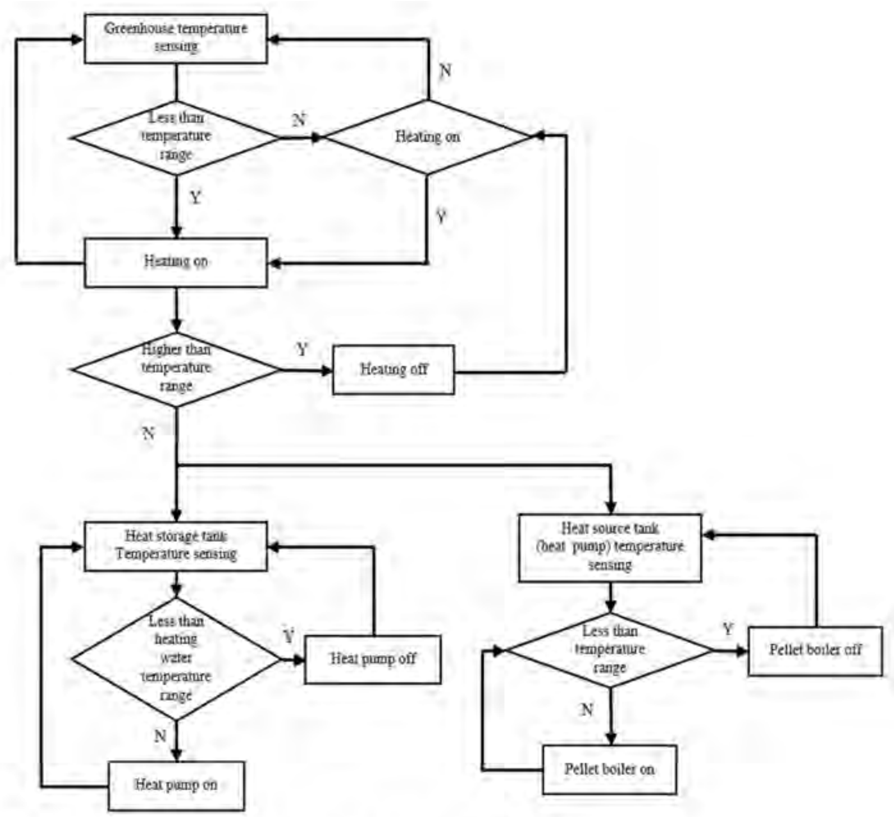


Figure 4. Control logic diagram of hybrid heating system.

2.3. Data Measurements

Temperature is the main data output for the prediction model in this study. Therefore, the temperature was measured for comparison between the experiment and the prediction model. To this end, thermocouples were installed in four places at the top and four at the bottom of the greenhouse. The thermocouples in the upper section were installed at a position of 2 m and 10 cm, while those in the lower section were installed 60 cm from the ground and the unit of the figures shown in Figure 5 is mm (Figure 5). Temperature data were recorded using a data logger (GL840, GRAPHTEC Co., Totsuka-ku, Yokohama, Japan). In addition, the temperature data were measured at intervals of 10 s, and the details of the thermocouple are shown in Table 4.

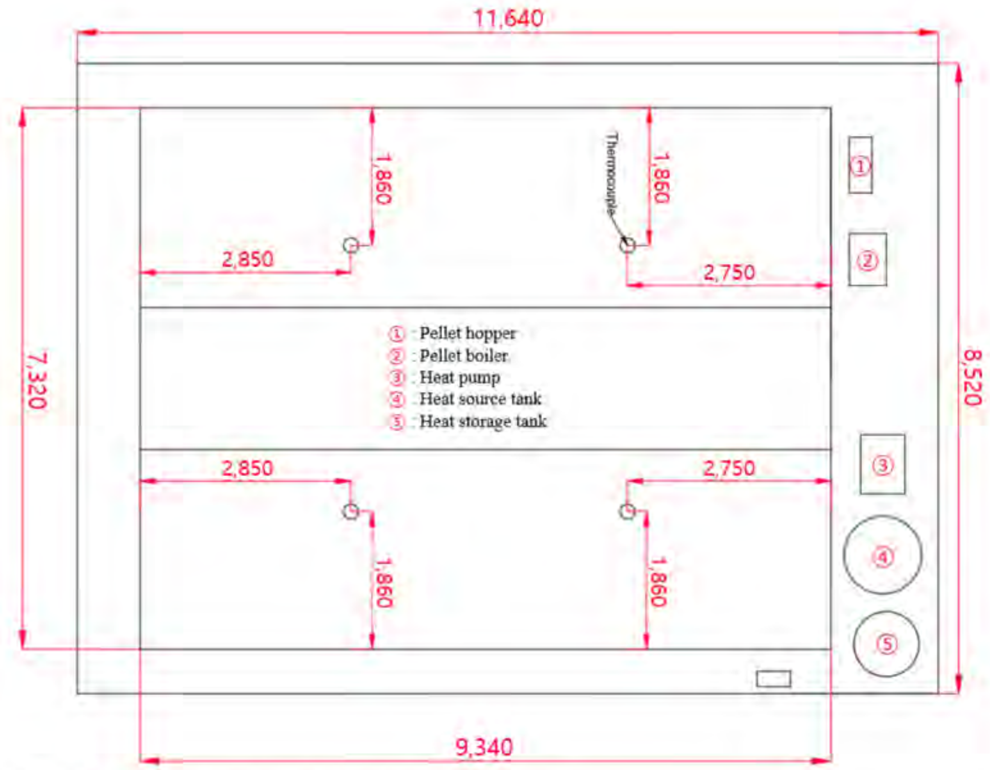


Figure 5. Thermocouple position for temperature data.

Table 4. Details of thermocouple.

Division	Specifications
Model	GTPK–02–17
Type (shape/unit of measurement)	Rod type/k-type
Temperature range	−50~200 °C
Sensor length	10 mm
Sensor thickness	3 Ø
Line length	2 m

The energy consumption was measured based on the power consumption used in each system and the pellet consumption used in the pellet boiler. The power consumption of the HPB was measured using a power analyzer (DW-6092, Lutron Electronic Enterprise C, Taipei City, Taiwan), and the pellet consumption was measured with a load-cell scale (HPS-300A, CAS Co.,Yangju-si, Gyeonggi-do, Korea). The energy consumption of the HAH was measured using an integrated energy meter (LD3410DRM-080, LS Electric Co., Anyang-si, Korea). Notably, the energy consumption measurements were conducted at 16:50 each day, as this did not affect the main heating time from 18:00 to 09:00 the next day.

2.4. Building Energy Simulation Modeling

TRNSYS (version 18, Solar Energy Laboratory, University of Wisconsin Madison, Madison, WI, USA) is a representative program used for thermal energy analysis related to buildings, including greenhouses. Various modules, called "Components", in TRNSYS related to piping, HAVC-related facilities, solar heat, geothermal heat, and energy can be used to set the model. The internal temperature prediction model for the greenhouse includes implemented radiation and convective heat transfer by pellet boiler, water-to-water heat pump, FCU, and tube rail. The greenhouse was implemented as a 3D model (Figure 6) using the SketchUp software (SketchUp Pro 2021; Trimble Inc., Sunnyvale, CA, USA), while the simulations were performed in conjunction with TRNSYS. The components used in the simulation are shown in Table 5, while the schematic diagram of the internal temperature prediction model is illustrated in Figure 7.

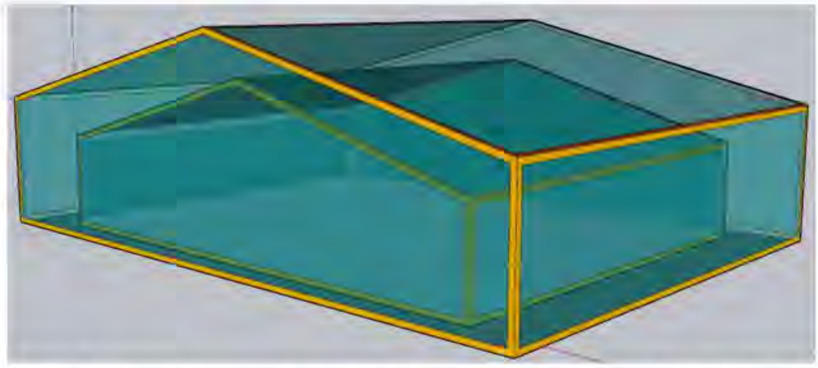


Figure 6. Three-dimensional modeling for multi-zone building in TRNSYS.

Table 5. Components in TRNSYS for the internal temperature prediction model.

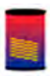
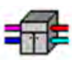
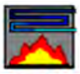
Icon	Content	Specification
 Type9c	Data reader	Simulation input of various data, including meteorological data
 Type16a	Radiation processor	Calculates various solar radiation data based on the measured solar radiation and locational data related to solar radiation
 Type33c	Psychrometric calculator	Calculates various humidity data using data such as dry-bulb temperature, relative humidity, absolute humidity, dew point temperature, and humidity air diagram
 Type69b	Sky temperature calculator	Determines the effective sky temperature for calculating longwave radiation exchange between an external surface and the atmosphere
 Type56	Multi-zone building	2D and 3D modeling of the target building to be analyzed within TRNSYS and interworking with external files
 Type137	Fan coil unit	Radiator- and fan-combined convection heat transfer component
 Type1231	Radiator	Radiator for radiant heat transfer by replacing the exposed pipe (tube rail) in the greenhouse
 Type156	Hot water storage tank	Heat storage tank with heat exchanger installed inside
 Type927	Water-to-water heat pump	Water-to-water heat pump

Table 5. *Cont.*

Icon	Content	Specification
 Type700	Boiler	Boiler components for replacement of pellet boilers
 Type2b	On/off controller	An on/off controller that controls by comparing sensing data and monitoring data
 Type14h	Scheduler	Scheduler for time-zone setting of on/off control
g-kg/kg	Equation	Calculator for data conversion and control signal operation

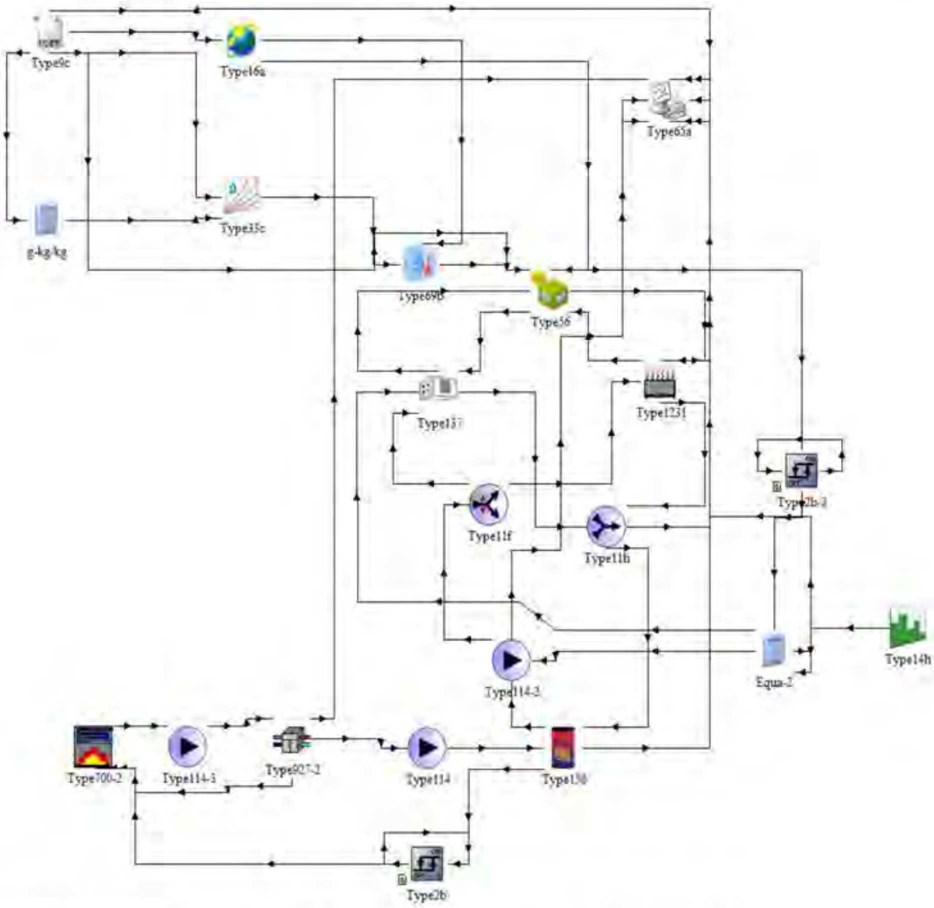


Figure 7. HPB using TRNSYS for the internal temperature prediction model.

The pellet boiler was operated as a heat source of the heat pump to continuously deliver 25 °C water, while the heat pump maintained the thermal storage tank at 57 °C. The pellet boiler was turned on/off by sensing the temperature of the heat storage tank. The heat pump was utilized to heat the storage tank throughout the experiment. The heat energy supply was controlled by the on/off signal of the heating main pump using the scheduler and monitoring the internal temperature of the greenhouse. The scheduler set the heating to begin at 18:00 and end at 09:00 the next day, while the meteorological data were recorded during the experimental period. The time standard was the local time in the ROK.

3. Analysis

3.1. Energy Balance of Hybrid System in TRNSYS

The proposed temperature prediction model of the greenhouse was designed to achieve energy balance (Figure 8).

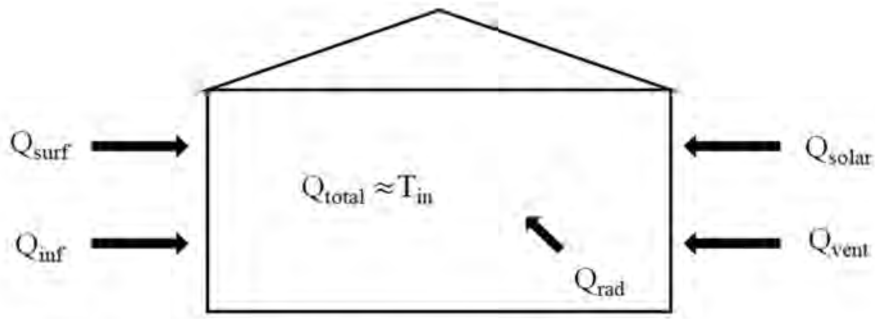


Figure 8. Energy balance of hybrid heating system in TRNSYS.

Q_{total} is the energy in the equilibrium state according to each energy input and is represented by Equation (1):

$$Q_{total} = Q_{inf} + Q_{surf} + Q_{vent} + Q_{rad} + Q_{soalr} \quad (1)$$

where Q_{inf} represents the energy gain and loss due to infiltration, Q_{surf} is the input and loss of thermal energy from the greenhouse cover area, Q_{vent} represents convective heat transfer using the forced flow fan of the FCU among the HPB used in this study, Q_{rad} is thermal energy gain and is the radiant heat transfer due to the tube rail—the radiator module used in the current study—and Q_{solar} represents the energy entering into the greenhouse due to solar radiation. The unit of energy for all Q mentioned here is kJ.

3.2. Regression Analysis for Validation of Experimental and Simulation Results

A regression analysis was performed by comparing the experimental and simulation results from 25 February to 19 March 2021. R^2 and RMSE were used as statistical indicators for comparative analysis and were calculated using Equations (2) and (3), respectively [22]:

$$r^2 = \left[\frac{n\left(\sum_{i=1}^{n} X_i Y_i\right) - \left(\sum_{i=1}^{n} X_i\right)\left(\sum_{i=1}^{n} Y_i\right)}{\sqrt{\left[\sum_{i=1}^{n} X_i^2 - \left(\sum_{i=1}^{n} X_i\right)^2\right]\left[\sum_{i=1}^{n} Y_i^2 - \left(\sum_{i=1}^{n} Y_i\right)^2\right]}} \right]^2 \quad (2)$$

where Y_i represents the ith measured value, X_i is the ith estimated value, and r^2 represents the coefficient of correlation.

$$\text{RMSE} = \sqrt{\left(\frac{1}{n}\sum_{i=1}^{n}\left(\frac{d_i}{Y_i}\right)^2\right)}, \quad (3)$$

where d_i represents the difference between the ith estimated and ith measured values, Y_i is the ith measured value, and RMSE represents the root-mean-square error.

3.3. Energy Consumption and Cost Calculation

The energy consumption of HPB and HAH is fundamentally directly related to the energy cost. Moreover, the energy cost substantially affects the economic analysis independent of initial investment cost, while representing an important factor in the actual greenhouse operation. Wood pellets and electric power were used as the energy sources in this study. The energy consumed by the pellets was calculated by multiplying the pellet consumption (kg) and the corresponding low calorific value (kJ/kg). Furthermore, the electricity consumption was converted by multiplying the amount of electricity measured by the power analyzer and the unit conversion factor for converting to kJ, as shown by Equation (4):

$$E_{total} = (\text{Pellet consumption} \times \text{LHV}) + (\text{Power consumption} \times \text{UCF}) \tag{4}$$

where E_{total} represents the total energy consumption (kJ), LHV is the lower heating value (kJ/kg), and UCF represents the unit conversion factor (power to kJ).

The energy price used in the study was based on the official price of wood pellets (0.29 USD/kg) according to the Korea Forest Service as of June 2019. The electricity price was based on the use of agricultural electricity (0.038 USD/kWh) when contracting 3 kW of contract power, according to the electricity rate calculation table of the Korea Electric Power Corporation (KEPCO, Naju-si, Jeollanam-do, Korea). Finally, the energy cost was calculated via Equation (5) using energy consumption and energy price:

$$EP_{total} = (\text{Pellet consumption} \times \text{PP}) + (\text{Power consumption} \times \text{EC}) \tag{5}$$

where EP_{total} represents the energy consumption price (USD), PP is the pellet price (USD/kg), and EC is the electricity charge (USD/kWh).

3.4. Heating Energy Load Calculation

Note that the heating load should be calculated in advance for a comparative analysis of the economic feasibility of HPB and HAH. To this end, the heating load calculation equations were introduced. Specifically, Equation (6) is the main equation to find the maximum heating load per hour. Equations (7)–(9) were used to calculate the heat transfer from the covering area, the heat transfer in the ventilation, and the heat transfer from the floor area, respectively. These are considered heat loss due to the covering area and ventilation and transmitted to the ground [23].

$$Q_g = A_g \times [q_t + q_v] + A_s \times q_s \times \text{fw} \tag{6}$$

$$q_t = \text{ht} \times (T_s - T_a) \times (1 - \text{fr}) \tag{7}$$

$$q_v = \text{hv} \times (T_s - T_a) \tag{8}$$

$$q_s = \text{hs} \times (T_s - T_a) \tag{9}$$

The factor values required for each equation are summarized in Table 6.

Table 6. Factors required to calculate the heating load.

Sign	Factor	Unit
Q_g	Maximum heating load	kJ/h
A_g	Covered area of a greenhouse	m^2
A_s	Floor area of a greenhouse	m^2
q_t	Transmission heat load per covered area of a greenhouse	kJ/m^2
q_v	Ventilation heat load per covered area of a greenhouse	kJ/m^2
q_s	Ground heat transfer load per covered area of a greenhouse	kJ/m^2
fw	Correction factor according to wind velocity	-
ht	Thermal perfusion ratio 18.84	kJ/m^2·h °C
T_s	Greenhouse internal set temperature	°C
T_a	Set ambient air temperature	°C
T_g	Ground temperature	°C

Table 6. *Cont.*

Sign	Factor		Unit
Sf	Safety factor	1.2	-
fr	Reduction rate of heating cover	0.71 (Triple screen)	-
hv	Ventilation heat coefficient	0.84	kJ/m^2·h·°C
hs	Ground heat transfer coefficients	1.02	kJ/m^2·h·°C

3.5. Economic Analysis (Life Cycle Cost (LCC))

From an economic perspective, we applied the life cycle cost analysis, a method for calculating the total cost invested during the durability period. We assumed that the initial investment cost considering self-pay, total initial investment cost, maintenance and repair cost, and total fuel cost were included in the life cycle cost analysis. The fuel cost per hour assumed the ratio of each type of energy used through the experiment. Equation (10) was applied for calculating the life cycle cost by considering the aforementioned items [11]:

$$\text{LCC} = \text{IIC}_{self} + (\text{IIC} \times \text{MCR}) + \left[\frac{\text{TEC}}{Q_g} \times \left(\text{Fuel cost} \times \frac{Q_g}{\text{LHV with used fuel ratio}}\right)\right] \quad (10)$$

where IIC represents the initial investment cost (USD), IIC_{self} is the initial investment cost self-pay (USD), MCR represents the maintenance cost ratio (%), TEC is the total energy consumption (kJ), Q_g is the maximum heating load (kJ/h), and LHV is the lower heating value of the wood pellets (kJ/kg). The various factor estimates used in the economic analysis are listed in Table 7.

Table 7. Factors involved in the economic analysis.

Divide	Pellet Boiler/Heat Pump	Air to Air Heat Pump/Radiator
Generating capacity	418,680 kJ/h (1 EA)/ 15RT (2 EA)	59,871 kJ/h (8 EA) 4320 kJ/h (74 EA)
Initial investment cost: total cost (USD)	43,654 (Pellet boiler 26,730, heat pump 16,924)	49,000
Initial investment cost: self-pay (USD)	7038	49,000
Maintenance cost ratio	10%	
Durability period (year)	10	
Fuel use ratio	Pellet boiler 78% Water-to-water heat pump 22%	Electricity 100%

In the economic analysis, we assumed that the size of the greenhouse was 1000 m^2. In this study, the experiment was conducted on a lab scale of about 90 m^2. However, it was determined that economic analysis should be conducted on a farm-scale scale to show meaningful analysis results when applied to actual farms. Therefore, the target greenhouse for economic analysis was selected to be 1000 m^2. Moreover, the maximum heating load per hour was found to be 407,216 kJ/h according to the heating load calculation formula. On this basis, the heating capacity of each energy device was selected. In addition, we considered a subsidy support project among domestic policies when using new and renewable energy in agriculture. Due to this, the initial investment cost considering self-pay was set at 16.1% of the total investment in the case of HPB. Considering that the subsidy support project has a self-pay rate of 20% when using wood pellets and 10% when using a heat pump, the total self-pay rate was 16.1%. However, as the existing HAH did not use renewable energy, the self-pay was set at 100%.

4. Results and Discussions

4.1. Comparison of Greenhouse Heating Experiment Results

The heating experiments were carried out for the period between 25 February 2021 and 19 March 2021, and were conducted in two greenhouses using HPB and HAH. The control method of the two systems was the on/off method for heating, and the setting temperature was 22 °C for melons. The HPB of the hot water heating method sets the temperature of heating to prevent breakdown and malfunction due to the frequent on/off switching of the device (Table 8).

Table 8. Heating experiment information.

Experiment	Period	Heating Method	Control Method	Set Heating Temperatures
HPB	25 February 2021 to 19 March 2021	Hot water heating (Convection and radiant heat transfer)	On/off	18–22 °C
HAH		Warm air heating (Convection heat transfer)	On/off	22 °C

Table 9 summarizes the results of the internal and ambient air temperatures of the greenhouse using HPB and HAH during the experimental period. The results of the internal and ambient air temperature were derived based on the 18:00 to 09:00 heating period. The experiment using HPB was heated to an average of 20 °C. Meanwhile, the HAH was heated to an average of 24 °C. The HPB was correspondingly heated to an average of the 18–22 °C range, which represented the setting range of heating temperature, while the HAH was heated slightly above the 22 °C setting temperature. This was determined by the difference in the position of the sensor input to the on/off control. A temperature sensor for the HPB was installed in the center of the greenhouse, whereas that of the HAH was located inside the blower, which was applied as a control. As a result, we identified only a slight difference.

Table 9. Internal temperature of greenhouse and temperature lifting during the heating time (18:00 to 09:00).

Experiment	Period	Greenhouse (HPB)	Greenhouse (HAH)	Ambient Temperature	
		Average Internal Greenhouse Temperature	Average Internal Greenhouse Temperature	Average	
				Max	Min
Week 1	25 February to 4 March 2021	20.3 °C	24.6 °C	4.3 °C	
				8.9 °C	1.7 °C
Week 2	5 March to 11 March 2021	20.7 °C	24.5 °C	5.5 °C	
				7.4 °C	3.6 °C
Week 3	12 March to 19 March 2021	20.2 °C	24.1 °C	9.8 °C	
				12.3 °C	8.4 °C

Both greenhouses reached temperatures within the setting range. Moreover, the internal temperatures were maintained within this range during the cold season (December to February). However, HAH exhibited more frequent on/off events compared with the HPB. This phenomenon was identified based on the pattern, where the hot air heating lacked heat retention compared with the hot water heating (Figure 9).

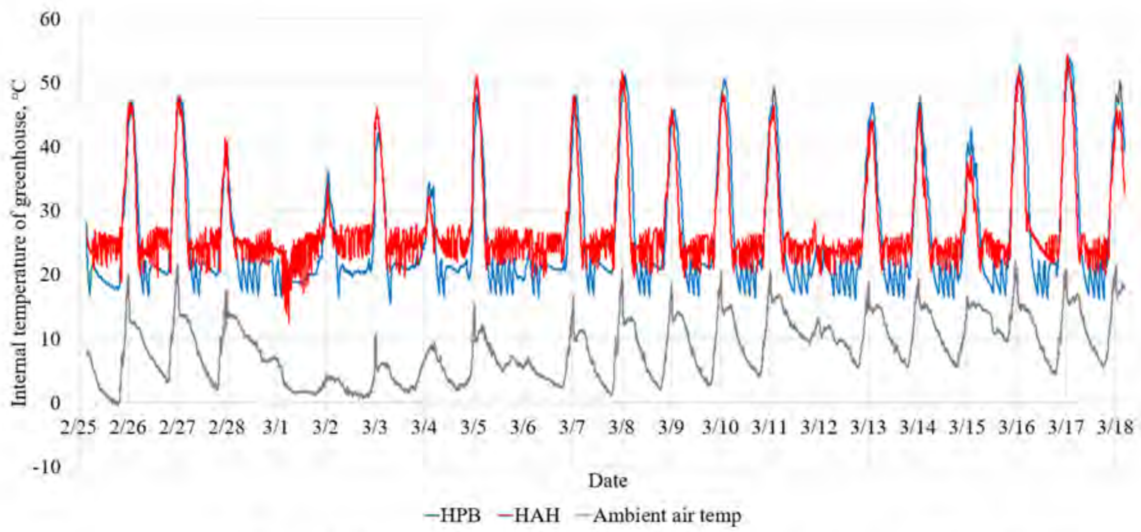


Figure 9. Comparison of heating test results for greenhouses using HPB and HAH.

4.2. Comparison of Internal Temperature Prediction Model Using TRNSYS and Experimental Results

Note that the HPB among the experiments conducted in this study was implemented in TRNSYS. Figure 10 shows the comparison between the experimental and simulation results. The experimental and simulation results exhibited similar tendencies. However, although the overall trend was similar, the simulation analysis values differed slightly in some cases. To elucidate the similarity and evaluate the agreement between the experiments and simulations, a regression analysis was performed.

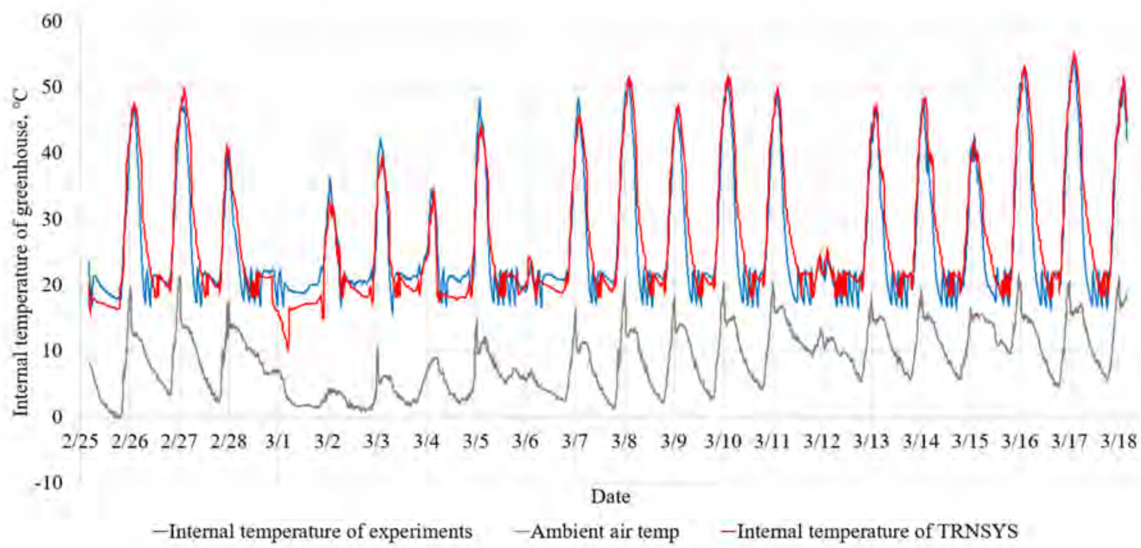


Figure 10. Comparison of results between experiment and simulation.

4.3. Regression Analysis

The regression analysis considered both the internal temperature prediction model and the actual experimental results, for which R^2 and RMSE were calculated. Specifically, the R^2 and RMSE estimates were derived to assess the similarity between the experiment and simulation. The resulting R^2 value was 0.8843, and the RMSE value was 3.61 °C. Although the R^2 was relatively high, the RMSE was based on temperature. Therefore, it is reasonable to suggest that further supplementation of the internal temperature prediction model for greenhouses is required. In particular, the RMSE results must be corrected by

3~4 °C in the simulation model. We also suggest that more accurate results can be obtained if additional meteorological data during the actual experiment period are added at the same location.

4.4. Comparison of Energy Consumption and Energy Cost

Figure 11 shows the amount of energy used in the heating experiment with the HPB and HAH. The amount of energy used by the HPB was generally lower than that of the HAH. The average energy consumption of the HPB was 531,455 kJ/day, and that of the HAH was 614,781 kJ/day, while the HPB demonstrated an energy-saving effect of 13.55% compared to HAH. The calculated energy costs were based on the energy consumption results (Figure 12).

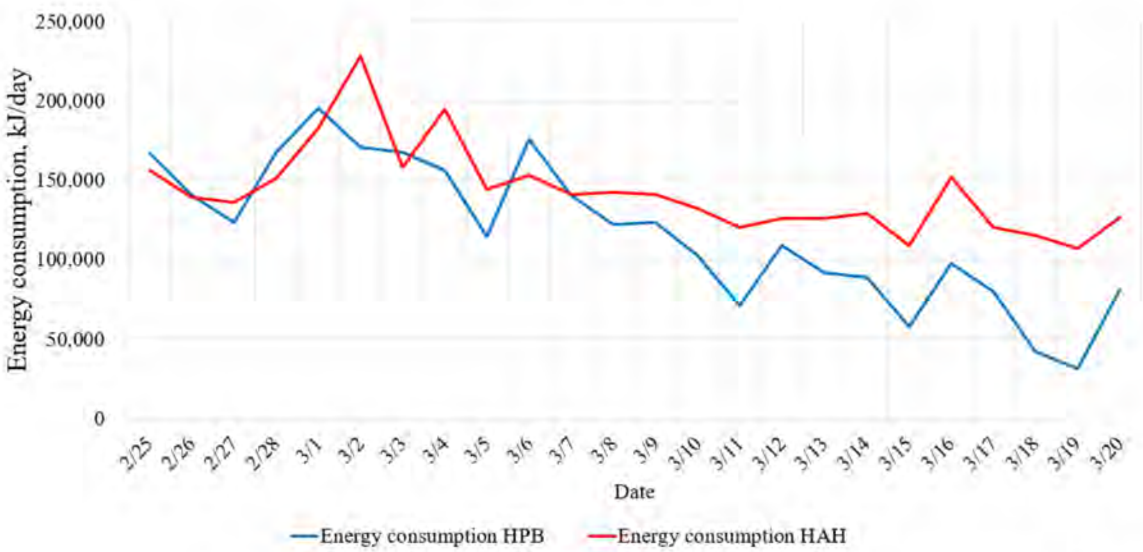


Figure 11. Comparison of greenhouse heating energy consumption between HPB and HAH systems.

Figure 12. Comparison of heating cost according to energy consumption of HPB and HAH systems.

Energy cost can be fundamentally derived from the actual price of pellets (0.29 USD/kg) and agricultural electricity price (0.038 USD/kWh) traded in the ROK. The average energy cost of using the HPB was 7.66 USD/day, and that for the HAH was 6.39 USD/day. The energy cost of the HPB was found to be 19.8% higher. This may have been due to the excessively low electricity price in the ROK. However, the energy cost alone was not sufficient to conclude which system was more economical. Therefore, a comparative analysis was performed for the HPB and HAH using LCC analysis to elucidate the economic feasibility.

4.5. Comparative Economic Analysis (Life Cycle Cost)

The greenhouse scale was assumed to be 1000 m^2 for the economic analysis of the HPB and HAH, and the life cycle cost analysis method was applied. The initial investment cost was based on self-pay, excluding subsidies from the "Renewable Energy Use Efficiency Project" implemented in the ROK. Moreover, the energy cost per hour was calculated to be the same as the energy use ratio used in the experiment. The results of the economic comparison analysis are summarized in Table 10.

Table 10. Comparative results of economic analysis using LCC (self-pay) for each system (HPB, HAH).

Division	HPB (Wood Pellet Boiler + Water-to-Water Heat Pump)	HAH (Air-to-Air Heat Pump + Radiator)
Fuel using ratio	Wood pellet boiler 78% Water-to-water heat pump 22%	Air-to-air heat pump 92% Radiator 8%
TEC	632,978,008 kJ	
Heating load per hour	407,216 kJ/h	
Annual heating time (h)	1554.4	
Fuel cost	Wood pellet: 0.29 USD/kg, electricity: 0.075 USD/kWh	
Fuel cost per hour (USD/h)	6.34	4.35
Operating expenses required for 10 years (Total investment cost) (USD)	102,990	72,514
Initial investment cost self-pay (USD)	7038	49,000
LCC (USD)	110,028	121,514

The LCC-based comparison revealed that the HPB exhibited 9.45% cost savings compared to the HAH. Moreover, the HPB was found to be more economical than the HAH despite the high energy cost per hour. Thus, it is reasonable to suggest that the advantage of the subsidy business according to the use of new and renewable energy played an important role in the initial investment cost. As the world is currently aiming for carbon neutrality, electricity production through new and renewable energy will be enhanced in the future.

5. Conclusions

This study developed the internal greenhouse temperature prediction model using a building energy simulation program (TRNSYS). The developed prediction model was established using BES and was evaluated through comparisons with the experimental results, while the heating experiment was conducted with a HAH to elucidate the economic feasibility of the HPB. The economic comparison analysis was performed using LCC analysis.

Our analysis revealed satisfactory results for the setting range for the heating, thereby confirming that greenhouse heating using renewable energy is efficient. The HPB was maintained at 20 °C and the HAH at 24 °C, which was higher than the 22 °C set temperature. This phenomenon was driven by differences in the location of the temperature sensor controlling the on/off of the HAH. In particular, the location of the experimental temperature measurement sensor differed from that of the control sensor. Moreover, the hot-air heating method was seemingly maintained higher at the top than at the bottom of the greenhouses.

The regression analysis indicated that, from the temperature perspective, the coefficient of determination (R^2) was high (0.8843), as was the RMSE (3.61 °C). Hence, the

RMSE was not conducive to crop growth. However, it had been anticipated that the RMSE value could be improved if the simple on/off control method was supplemented with a higher-level control method such as a PID control. Nevertheless, the developed internal temperature prediction model for the greenhouses was positively compared and verified through regression analysis. We confirmed that the HPB exhibited a 13.55% reduction effect compared to the HAH in terms of energy consumption; however, the cost was higher in terms of energy. This pattern was potentially driven by the excessively low agricultural electricity price in the ROK. However, the LCC-based economic comparative analysis revealed that the HPB exhibited an excellent cost reduction effect of 9.45% compared to the HAH based on self-pay.

Assuming that renewable energy accounts for a high proportion of electricity production in the future, electricity prices are expected to rise. Such an increase can further bolster the economic feasibility of HPB.

Taken together, the findings of this study demonstrate that the HPB is characterized by excellent economic efficiency as well as good heating performance. However, future studies should incorporate meteorological data from other regions to predict the internal temperature of greenhouses according to various regions and greenhouse types.

In addition, it suggests that additional studies are needed to verify not only the theoretical prediction using the existing TRNSYS, but also the prediction of the greenhouse internal environment and the actual experiment, such as this study. The results of this study can also suggest the validity of maximizing the use of new and renewable energies in line with the current global trend. In addition, through this study, small and medium-sized farms in the ROK can confirm the possibility of converting to a smart farm and economic feasibility, and it is judged that it will be able to contribute to the spread of smart farms using new and renewable energy.

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