agriculture

Article

Analysis on the Economic Feasibility of a Plant Factory Combined with Architectural Technology for Energy Performance Improvement

Yeweon Kim *, Hye-Ry Shin, Su-hyun Oh and Ki-Hyung Yu

Building Energy Research Department, Korea Institute of Civil Engineering and Building Technology, Ilsan 10223, Korea; hyeryshin@kict.re.kr (H.-R.S.); suhyunoh@kict.re.kr (S.-h.O.); raytrace@kict.re.kr (K.-H.Y.)
* Correspondence: yeweon.kim@kict.re.kr; Tel.: +82-31-910-0782

Abstract: In this study, a comparative economic analysis was conducted for typical greenhouses, plant factories with natural and artificial light, and those with only artificial light, based on the insulation, artificial light, and photovoltaic (PV) installation costs. In addition, the results of research on primary energy consumption and greenhouse gas (GHG) emissions from the use of fossil fuels were presented. By comparing the case-wise annual energy consumption, when all energy sources were converted into primary energy consumption based on the applied coefficients for collection, transport, and processing, to unify calculations for different fossil fuel energy sources, the case of the installed PV systems exhibited large reductions, of 424% and 340%, in terms of primary energy consumption and GHG emissions, respectively. Furthermore, electric heating resulted in higher primary energy consumption and GHG emissions than oil. When the economic analysis included the plant factory installation cost used to maintain the temperature required for plant growth in winter, the PV installation exhibited the highest cost; additionally, all plant factories showed an investment payback period of seven to nine years, which is comparable to typical greenhouses. Based on these results, we aim to reduce the use of fossil fuels for sustainable energy by combining architectural technology for improved energy performance in the agricultural environment.

Keywords: plant factory; natural light; artificial light; economic analysis; building energy-saving technology

check for updates

Citation: Kim, Y.; Shin, H.-R.; Oh, S.-h.; Yu, K.-H. Analysis on the Economic Feasibility of a Plant Factory Combined with Architectural Technology for Energy Performance Improvement. *Agriculture* **2022**, *12*, 684. https://doi.org/10.3390/agriculture12050684

Academic Editors: Riccardo Testa, Giuseppina Migliore, Giorgio Schifani and József Tóth

Received: 26 March 2022
Accepted: 6 May 2022
Published: 11 May 2022

1. Introduction

1.1. Research Background and Purpose

In the current year, which is also the first year of the implementation of the Paris Agreement, major countries have declared "carbon neutrality by 2050" [1], accelerating global solidarity on carbon neutrality. The South Korean government has also announced the "Korean New Deal" and established relevant mid- and long-term strategies. In particular, the government has made the installation and supply of renewable energy sources mandatory for a certain percentage of the energy used in the building sector, to reduce greenhouse gas (GHG) emissions, based on the green building activation plan.

However, the construction cost for renewable energy installation increases exponentially in cities with a high building density, and securing efficiency is also difficult. In rural areas, forests and farmland are being continuously damaged, with low land prices owing to renewable energy installations, and reckless development that is environmentally destructive. Greenhouses use fossil fuels, owing to the provision of tax-free oil and electricity by the government (out of the total greenhouse area of 52,393 ha, heating is used in 31%, with 89% based on oil heaters, for which 20,000,000 kL of tax-free oil is supplied annually) [2]. As a possible solution, the installation of photovoltaic (PV) systems is recommended for achieving efficient land use. However, instead of installing PV systems on farmland or forests, which may cause environmental damage, eco-friendly power generation based on agricultural PV systems that enable farming under natural light is preferable. In addition, it will be possible to increase the income of farmers and disseminate PV systems by installing PV systems, with the ability to use sunlight in farmlands for other purposes, and simultaneously performing agricultural activities.

The calculation of the carbon footprint of PV systems is given in the International Organization for Standardization (ISO 14040, 2006a [3], ISO 14044, 2006b [3]) and N. Gazbour and G. Razongles studied the calculation of environmental footprint in PV systems [4].

Previous studies on plant factories have focused on the application of IT technologies and plant productivity based on light sources, such as lighting systems, or based on cooling and heating [5], renewable energy [6], and ventilation environments [7–9].

In recent years, Graamans, Tenpierik, Dobbelsteen, and Stanghellini studied how to reduce the national cooling demand by applying suitable design methods in plant factories [10], as well as the use of renewable energy in plant factories to save energy. Jiang, Su, Shieh, Kuo, Lin TS, and Lin TT et al. [11] optimized solar power energy with the proposal of a two-step grid-linked solar power control system, with a boost-buck full-bridge design. In addition, a study of the profitability of plant factories was conducted by measuring the biomass conversion efficiency of plants in an economic design of artificial light factories, based on their biomass energy conversion efficiency [12].

This study aimed to analyze the energy savings and reduction in fossil fuel consumption against the additional installation cost incurred when the conditions required for plant growth are satisfied by applying architectural energy-saving technology and renewable energy systems (PV) to plant factories in rural areas.

1.2. Research Method

In this study, research was conducted on plant factories by applying four different environmental conditions required for growing the most popular winter-cultivated plant. The plant factory types were as follows: (i) a single glazed greenhouse, (ii) a glass greenhouse with installed PV modules that do not interfere with the solar radiation reaching the plants, (iii) a plant factory with increased greenhouse effect using glass and certain insulation materials that still conform to the solar radiation conditions, and (iv) a plant factory that increases the greenhouse effect using only insulation and that supplements the insufficient solar radiation with artificial light. In this paper, general single-glazed glass greenhouses of type (i) and facilities where the environment of plants, such as light and temperature, are artificially created according to the definition [13] by Dickson. D (ref) (ii–iv) are named as a plant factory. An economic feasibility analysis according to the conditions of glass greenhouses and plant factories and a comparative analysis from an environmental viewpoint were conducted.

2. Materials and Methods

2.1. Simulation Conditions

(1) Growth conditions for cultivated plants.

Strawberries (forcing culture), which have a high land productivity and require heating during the cultivation period, were selected as the cultivation crop, to analyze their economic efficiency based on the heating cost. Table 1 summarizes the required growth conditions for strawberries, including the cultivation period, appropriate daylight illuminance, light saturation point (the intensity of light at which the plant's photosynthesis rate stops increasing), and suitable lighting and heating conditions (using the data provided by the optimal environment setting guidelines of smart farms in the Rural Development Administration) [14].

Table 1. Strawberry cultivation conditions.

Category	Value	Remark
Cultivated crop	Strawberries	Forcing culture
Cultivation period	September 15th to December 31st	Heating period
Suitable daylight luminance (Lux)	15,000 to 40,000	Lighting control condition
Light saturation point (Lux)	40,000	Light comfort evaluation condition
Daylight hours (h)	06:00 to 18:00	Lighting schedule condition
Daytime set temperature (°C)	17 to 20	Temperature condition
Nighttime set temperature (°C)	10	Temperature condition

Owing to the difference between the daytime and nighttime growth temperatures for strawberries, the temperature conditions were set to 17 °C for daytime and 10 °C for nighttime.

These conditions satisfied the minimum conditions for strawberries to grow, and we assumed that the strawberry production was the same as the economic analysis of the building energy-saving element, which is the purpose of this study.

(2) Greenhouse overview.

For the control model, the typical glass greenhouse used for forcing culture in the winter in Korea was simulated. The specifications and geometry are defined according to the disaster-resistant facility standards for horticultural special facilities provided by the Rural Development Administration in Table 2 [15]. The specifications and geometry for energy simulation are shown in Figure 1. With regards to the region, the weather data DOE epw file of Gwangju, Jeollanam-do, located in southwest Korea, where strawberry cultivation is active, was used. All conditions were assumed to comply with the same environmental and spatial conditions (same site, same climatic conditions, etc.). According to the temperature conditions of the weather data, the heating device was assumed to run if the temperature was 17 °C or lower at daytime and 10 °C or lower at nighttime. It was assumed that renewable power was generated throughout the year, because renewable energy systems were installed in a building separate from that of the cultivated crops.

Table 2. Greenhouse overview.

Category	Value	Remark
Floor area	518 m^2	70 m × 7.4 m
Height	2.6 m	-
Region (weather data)	Gwangju, Jeollanam-do	DOE epw file
Renewable power generation period	January 1st to December 31st	-

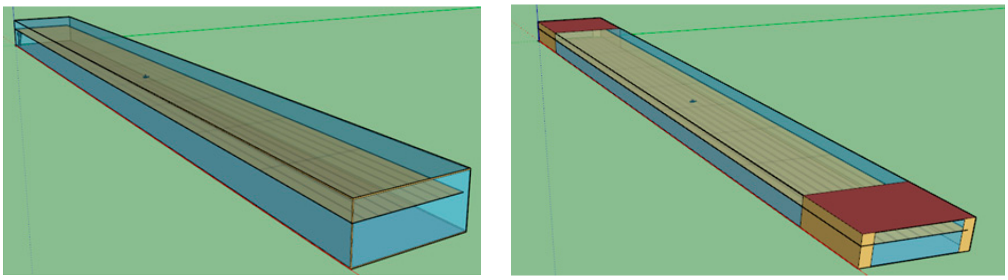

(**a**) (**b**)

Figure 1. Case geometry for simulation (**a**) Case 1, (**b**) Cases 2–4.

2.2. Case Study

Four case studies were conducted, i.e., three with installed insulation, artificial light, and PV systems, as shown in Figure 2 and Table 3, and one typical glass greenhouse installation. In Case 1, control conditions and oil boilers were used in a glass greenhouse. In Case 2, PV panels were installed in a glass greenhouse, and a certain percentage of the produced electricity was used as the energy source for the electric boilers. In Case 3, a few insulated walls were installed, without any PV system or lighting. Electricity was used as the heat source. In Case 4, adiabatic walls were installed on all sides by replacing the glass; additionally, natural light was replaced with LED (light emitting diode) lighting, and PV panels were installed as the energy source for lighting and heating. For this study, EnergyPlus was used for modelling and calculation.

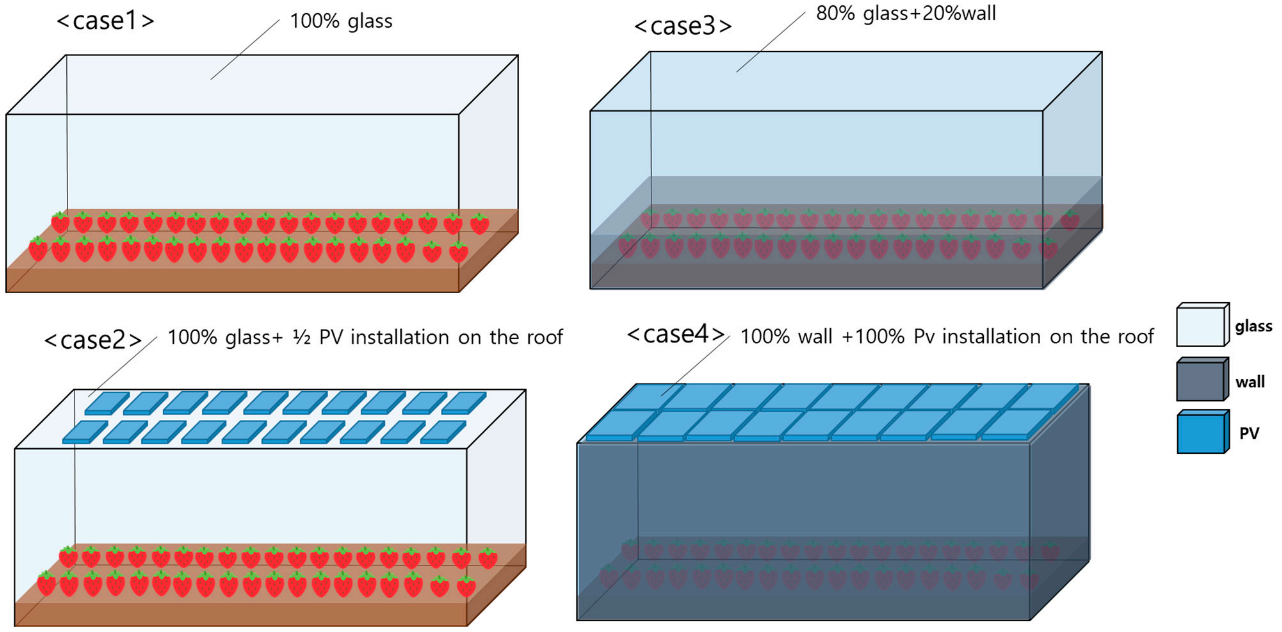


Figure 2. Model schematic diagram of different cases.

Table 3. Case study conditions.

Category	Adiabatic Conditions (U: W/m^{2}K, SHGC: 0~1)	Heating	PV Installation	Lighting Type and Quantity
Case 1	100% glass (U: 2.673, SHGC: 0.705)	Oil boiler (rated efficiency: 80%)	-	No lighting (Use of natural light)
Case 2	100% glass (U: 2.673, SHGC: 0.705)	Electric boiler (rated efficiency: 80%)	On the roof	No lighting (Use of natural light)
Case 3	20% wall (U: 0.47) + 80% glass (U: 2.673, SHGC: 0.703)	Electric boiler (rated efficiency: 80%)	-	No lighting (Use of natural light)
Case 4	100% wall (U: 0.47)	Electric boiler (rated efficiency: 80%)	On the roof	43.17 units of 15 W LED lamps (647.5 W)

2.2.1. Classification According to Adiabatic Conditions

In this study, the cases were defined according to adiabatic conditions. In Cases 1 and 2, a typical single glazed glass greenhouse was assumed. Accordingly, a U-value of 2.673 W/m^{2}K and a solar heat gain coefficient (SHGC) value of 0.703 were applied. In Case 3, a U-value of 0.47 W/m^{2}K and SHGC value of 0.703 were applied to the wall and glass, according to the 2009 "architectural standards and performance of eco-friendly houses" [16], which are the minimum building standards for energy performance in the housing sector. In Case 4, the walls were installed on all sides, and the same U-value as in Case 3 was applied.

2.2.2. Heating Equipment

Oil boilers, which are typical heating methods that use tax-free oil, were applied in Case 1, and electric boilers were applied in Cases 2–4, to compare energy source switching with the use of PV systems.

2.2.3. Classification According to Lighting

Plant factories can be categorized into those with natural, natural and artificial, and artificial light. Plants are cultivated using natural sunlight in plant factories. Artificially lit plant factories are closed establishments, where light sources such as fluorescent lamps, LEDs, HEFL (hybrid electrode fluorescent lamp), and high-pressure sodium lamps are used without sunlight. Plant factories with natural and artificial light are hybrid systems in which sunlight is the main light source, while artificial light is used as a supplement on cloudy days or in the evening. In this study, cultivation under natural light without artificial lighting was assumed for Cases 1–3. In Case 4, a plant factory with artificial light was assumed by installing 43 15 W-LED lamps to satisfy the lighting conditions with an appropriate illuminance of 40,000 lux during the daytime, as natural light was blocked by insulation.

2.2.4. PV Installation Condition

In Case 2, although a PV system was installed in a typical glass greenhouse, it was assumed that the solar radiation condition was satisfied by adjusting the space between the PV panels (half of the roof). In Case 4, it was assumed that PV modules were installed on the roof of a closed plant factory.

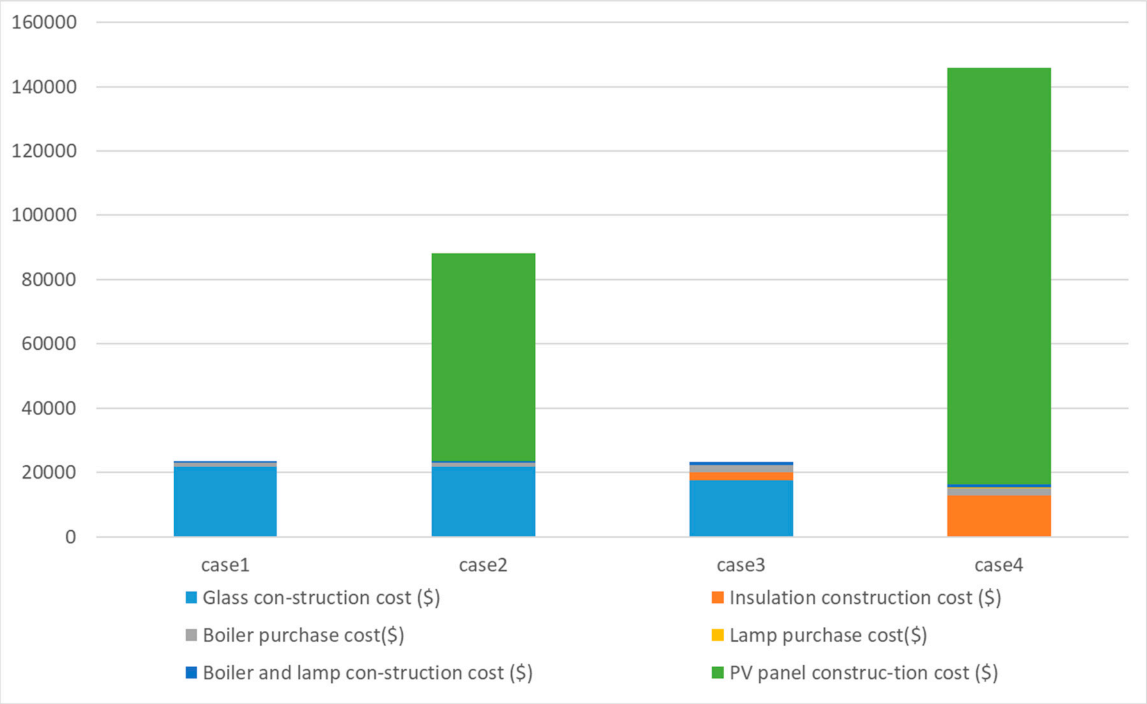
3. Results

3.1. Case-Wise Plant Factory Construction Costs

Table 4 summarizes the glass/adiabatic envelope area, lighting quantity, and PV panel installation area. The glass envelope area decreases with the adiabatic envelope area. Owing to the assumption that plant cultivation was performed under natural light (except in Case 3), the number of lights was set to satisfy the light saturation point. Under these conditions, the construction costs for each case were calculated, by referring to data in a price information magazine [17], as shown in Figure 3. The costs included USD 24/m^2 per glass area for glass installation, USD 14/m^2 for insulation installation, USD 1120 for two oil boilers, USD 2243 for two electric boilers, USD 4.2/unit for 15 W LED lighting, and USD 250/m^2 for PV panel installation. The material and installation costs were included in all construction costs.

Table 4. Area per envelope, heating capacity, and lighting quantity.

Category	Glass Envelope Area (m^2)	Adiabatic Envelope Area (m^2)	Heating Capacity (W)	Number of 15 W LED	PV Panel Installation Area (m^2)
Case 1	920	0	66,854	0	0
Case 2	920	0	66,854	0	259
Case 3	736	184	66,854	0	0
Case 4	0	920	66,854	43	518



Category	Glass Construction Cost (USD)	Insulation Construction Cost (USD)	Boiler Purchase Cost (USD)	Lamp Purchase Cost (USD)	Boiler and Lamp Construction Cost (USD)	PV Panel Construction Cost (USD)	Total
Case 1	21,913	0	1,120	0	495	0	23,201
Case 2	21,913	0	1,120	0	495	64,750	87,951
Case 3	17,540	2577	2,243	0	992	0	22,697
Case 4	0	12,880	2,243	181	1,073	129,500	145,168

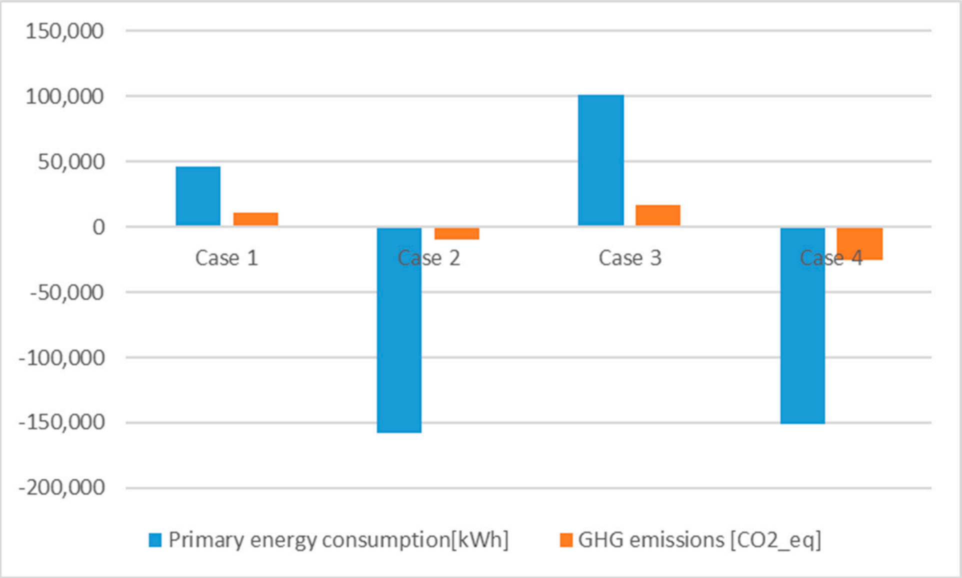
Figure 3. Case-wise construction costs.

In comparison to the installation costs of other structures, PV systems appear to have a larger impact on each case. The construction cost was the highest in Case 4, followed by Cases 2, 1, and 3, in reverse order for energy consumption. The construction cost in Case 4 was approximately 6.2 times higher than that in Case 1, which is the simplest glass greenhouse. This appears to be because the cost of PV installation is the highest among the construction items.

3.2. Case-Wise Energy Consumption and GHG Emissions

The annual primary energy consumption and GHG emissions based on usage of electricity (A1) and petroleum (B) and electricity production through PV power generation (A2) were obtained for each case, as shown in Figure 4. In Korea, the primary energy conversion factors are 2.75 for electricity and 1.1 for fuel [18]. The applied GHG emission factors were 0.259 for heating oil and 0.4691 for electricity, according to the 2019 National GHG Inventory Report [19].

In the case of renewable energy production, the amount of energy obtained by subtracting the electricity production (A2) from the electricity consumption in the plant factory (A1) was expressed as the net electricity consumption. In addition, the total consumption was obtained by converting the electricity and petroleum energy sources into the primary energy requirement.



Category	Annual Energy Consumption (kWh)					Primary Energy Consumption (kWh_{pe}*)	GHG Emissions (ktCO2eq)
	Electricity Consumption (A1)	Electricity Production (A2)	Net Electricity Consumption (A = A1 − A2)	Petroleum (B)	Total (A + B)		
Case 1	1,585.5	0	1,586	38,477.81	40,063	46,686	10,710
Case 2	1,585.5	43,650	−42,064	38,477.81	−3587	−158,002	−9766
Case 3	36,861.26	0	36,861	0	36,861	101,368	17,291
Case 4	32,288.05	87,299.84	−55,012	0	−55,012	−151,283	−25,806

* Note: pe = primary energy.

Figure 4. Case-wise annual energy consumption and GHG emissions.

As shown in the results of the total (A + B) in Figure 4, the basic glass greenhouse exhibited the largest annual petroleum and electricity consumption, owing to the operation of oil boilers. In Case 3, where partial insulation was applied without PV electricity production, the second highest energy consumption occurred. In Cases 2 and 4 (with PV panels), the energy production was found to be higher than consumption. Particularly, in Case 4, the primary energy consumption was the lowest, despite the additional energy consumption for lighting. In comparison to Case 1, a 438% reduction in primary energy consumption and a 191% reduction in GHG emissions were observed in Case 2, where electric boilers and PV panels were installed. Case 3, where partial insulation was applied, showed a 117% increase in the primary energy requirement and a 61% increase in GHG emissions. Case 4, where insulation was applied on all sides and PV and artificial light were used, exhibited a 424% reduction in the primary energy requirement and a 340% reduction in GHG emissions. In Case 3, the GHG emissions and primary energy requirement were higher than those in Case 1, despite the application of insulation. This is because the conversion factor of electricity was more than twice as high among the conversion factors for each energy source; thus, the primary energy consumption and GHG emissions were significantly affected when the units were unified. Therefore, it is evident that Case 2 represents the highest fossil fuel savings based on primary energy consumption, and Case 4 represents the minimum GHG emissions.

3.3. Economic Analysis

Table 5 presents the annual calculated energy cost for each case, by applying the unit cost of each energy source in Korea. The electricity consumption was calculated based on the electricity cost for agriculture [20], and the oil heating value was calculated based on the heating value conversion and carbon emission factors for each energy source provided by the Korea Energy Agency [21]. The electricity cost was calculated using the SMP (system marginal price) electricity unit cost (as of March 2022) [22].

Table 5. Case-wise annual costs for each energy source.

<table>
<tr><th colspan="5">Electricity Cost</th><th>Oil Cost</th></tr>
<tr><th colspan="3">Cost Classification (A*)</th><th rowspan="2">VAT (A * %)</th><th rowspan="2">Industrial Foundation Fund (A * %)</th><th rowspan="2">Unit Price (USD/L)</th></tr>
<tr><th>Basic Rate (USD/kW)</th><th>Energy Charge (USD/kW)</th><th>Green Rates (USD/kW)</th></tr>
<tr><td>1.15</td><td>0.039</td><td>0.007</td><td>10%</td><td>3.7%</td><td>0.9</td></tr>
<tr><th colspan="3">Electricity Cost</th><th colspan="3">Oil Cost</th></tr>
<tr><th>Category</th><th>Contract Demand (kW)</th><th>Electricity Cost (USD)</th><th>Oil Heating Value (MJ/L)</th><th>Unit Price (USD/L)</th><th>Oil Price (USD)</th></tr>
<tr><td>case 1</td><td>3</td><td>40.1</td><td>34.2</td><td>0.91</td><td>3664.7</td></tr>
<tr><td>case 2</td><td>3</td><td>−3.6</td><td>34.2</td><td>0.91</td><td>3581.2</td></tr>
<tr><td>case 3</td><td>5</td><td>36.9</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>case 4</td><td>5</td><td>55.0</td><td>-</td><td>-</td><td>-</td></tr>
</table>

A* = each energy price. A * = Basic rate, Energy charge Green rates.

Based on the previously analyzed case-by-case installation and energy costs, the discounted payback period was used to perform the analysis. The discounted payback period calculates a period to recover the initial investment cost based on the present value of cash flow in a period, which overcomes most shortcoming of the existing payback period, which did not consider the time value. In this study, the recovery period of the initial investment cost was calculated by reflecting the time value by means of applying the social discount rate to the cash flow of the profits obtained through the energy production sales produced via PVs.

The PV installation cost of installed cost can be covered by the government subsidy called “New and Renewable Energy Finance Support Project” [23]. For example, up to 90% of installation costs can be subsidized for an individual business, which is reflected in this study. This project supports 90% of the total installation cost, and the principal is repaid with an installment for 10 years after paying only 1.75% of interest for the first five years. For the energy cost, changes in electricity tariffs and kerosene prices in the last 10 years from 2012 to 2021 (7.4.1 Consumer Price Index (2015 = 100) (National) were used. Electricity, gas, and other fuels in the Economic statistics system of Bank of Korea, provided by the Economic statistics system of the Bank of Korea [24], and for the discount rate, the social discount rate provided by the Ordinance of the Ministry of Strategy and Finance of the Republic of Korea “General guidelines for conducting preliminary feasibility studies” [25] were employed. To calculate the fixing and replacement cost of input facilities, it was assumed that new and renewable facilities and boilers were replaced, with the increased facility cost being according to the inflation rate with a period of 25 and 10 years, respectively. For the insurance premium, the cost of crop accident insurance for fruit crops was used. The insurance premium is subsidized by 50% by the central government and 40% by the local government on average [26]. Thus, 10% of the premium was used. Table 6 presents the indexes and values used in the analysis.

Table 6. Inflation rate index.

Item	Index
Electricity tariff increase rate (average increase rate for the last 10 years from 2012 to 2021)	−0.70%
SMP unit price increase rate (average increase rate for the last 10 years from 2012 to 2021)	0.30%
Kerosene price increase rate (average increase rate for the last 10 years from 2012 to 2021)	−2.50%
Inflation rate (average increase rate for the last 10 years from 2011 to 2020)	1.48%
Discount rate	4.50%

In Table 7, the recovery period was calculated through the cash flow of the additional installation cost for each case based on the installation cost of Case 1. Case 2 refers to the installation of PV on 50% of the rooftop area, with the same conditions as Case 1, and its initial investment cost increased by USD 6475 compared to that of Case 1. However, because the energy production exceeded the energy consumption, the cash flow became positive (+) in the second year through the sales profit in the analysis. In the analysis, the positive cash flow was maintained due to the income from energy, even in the sixth year when the principal repayment started through the “New and Renewable Energy Finance Support Project”, and a profit could be obtained, exceeding the principal of the PV installation cost subsidized by the government in the ninth year.

Table 7. Case-wise construction cost recovery period with energy savings.

	Additional Initial Installation Cost (USD)	The Recovery Period of the Initial Installation Cost (yr)	Return Period, Including the Government Subsidy Principal (yr)
Case 1 = Baseline	0	-	-
Case 2	6475	2 years	9 years
Case 3	−505	-	-
Case 4	5417	1 year	7 year

Case 3 refers to 80% of glass and 20% of insulated walls in the greenhouse and the use of an electric boiler. Its initial installation cost was reduced by USD 505, because the material cost of the insulation was relatively inexpensive compared to that of a glass greenhouse. The energy cost of Case 3 was calculated at a level of 57% of Case 1 on average, because the kerosene price and average reduction rate used in the oil boiler were larger than that of electricity.

Case 4 refers to the use of an electric boiler and LED lighting with 100% insulated walls and 100% PV in the rooftop area. Its initial installation cost increased by USD 5417 compared to that of Case 1 in the analysis, but the cash flow became positive (+) from the first year through the energy sales profit produced through the PV. The profit also exceeded the principal of the PV installation cost subsidized by the government in the seventh year in the analysis.

4. Conclusions

In this study, an economic analysis was conducted on fossil fuel energy savings compared to the additional installation cost by applying architectural energy-saving technology and renewable energy systems (PV systems) to plant factories in rural areas.

Four plant factory case studies were conducted based on the installation of insulation, artificial light, and PV systems, along with a typical glass greenhouse for comparison purposes. In each case, the growth conditions of the cultivated crop (strawberries), such as the cultivation period, proper daylight illuminance and light saturation point, and suitable lighting and heating conditions, were ensured.

First, the unit cost was based on one plant factory, and the construction unit cost was set based on glass, insulation, LED lighting, PV panel installation costs, and boiler type. Second, for case-wise annual energy consumption, all energy sources were converted into primary energy consumption. In Cases 2 (−158,002 kWh_{ep}) and 4 (−151,283 kWh), where PV panels were installed, the energy consumption reduction effect was significant, owing to the energy production. Specifically, the lowest primary energy consumption and largest greenhouse gas (GHG) emission reduction effect (25,806 $CO2_{eq}$) were observed in Case 4, despite the additional energy consumption for lighting. Third, after the economic analysis, using Case 1 as the basis, the recovery period was calculated using the cash flow of the added installation cost for each case. Since a government subsidy is provided for new and renewable energy sources, Cases 2 and 4 needed two years and one year for recovery of the initial installation cost, and Cases 2 and 4 required nine and seven years, considering a recovery period including the principal of the government subsidy. Case 4 exhibited the best results from an environmental perspective, considering the primary energy consumption, GHG emissions, and recovery period.

This study was limited to winter strawberries; however, it is necessary to use varying types of cultivated crop or conduct research on prolific plant factories. It is also important to conduct research on methods that reduce the primary energy consumption or GHG emissions using electric heat pumps instead of general electric heaters. In the case of electric heat pumps, the coefficient of performance varies depending on the outdoor temperature distribution. Therefore, further research regarding this factor is required.

In addition, because the issue of fruit production quality according to the architectural energy-saving measures is also important, it would be desirable to conduct a study on the correlation between energy-savings and fruit quality.

Author Contributions: Conceptualization, data curation, and analysis: Y.K. Data curation: H.-R.S. Investigation: S.-h.O. Review and Editing: K.-H.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the KICT Research Program (project no.20220202-001, Design and Construction Optimization for ZEB Implementation of Existing Buildings) funded by the Ministry of Science and ICT.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: This research was supported by the Major Project of the Korea Institute of Civil Engineering and Building Technology (KICT) (grant number 20210294-001).

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

References

1. Guterres, A. *Carbon Neutrality by 2050: The World's Most Urgent Mission*; United Nations Secretary—General: Paris, France, 2020. Available online: https://www.un.org/sg/en/content/sg/articles/2020-12-11/carbon-neutrality-2050-the-world%E2%80%99s-most-urgent-mission (accessed on 9 August 2021).
2. Kwon, J.-G. Evolution from energy consumption to production. In *Energy Independence Declaration of Agriculture*; RDA Interrobang: Seoul, Korea, 2012; pp. 10–11.
3. Environmental Management—Life Cycle Assessment—Principles and Framework. 2006. Available online: https://link.springer.com/content/pdf/10.1065/lca2006.02.002.pdf (accessed on 25 March 2022).
4. Gazboura, N.; Razongles, G.; Monniera, E.; Joannya, M.; Charbuillet, C.; Burguna, F.; Schaeffera, C. A path to reduce variability of the environmental footprint results of photovoltaic systems. *J. Clean. Prod.* **2018**, *197*, 1607–1618. [CrossRef]
5. Tong, Y.; Kozai, T.; Nishioka, N.; Ohyama, K. Reductions in Energy Consumption and CO2 Emissions for Greenhouses Heated with Heat Pumps. *Appl. Eng. Agric.* **2012**, *28*, 401–406. [CrossRef]
6. Li, L.; Li, X.; Chong, C.; Wang, C.-H.; Wang, X. A decision support framework for the design and operation of sustainable urban farming systems. *J. Clean. Prod.* **2020**, *268*, 121928. [CrossRef]
7. Graamans, L.; Baeza, E.; van den Dobbelsteen, A.; Tsafaras, I.; Stanghellini, C. Plant factories versus greenhouses: Comparison of resource use efficiency. *Agric. Syst.* **2018**, *160*, 31–43. [CrossRef]

8. Benis, K.; Reinhart, C.; Ferrão, P. Building-Integrated Agriculture (BIA) In Urban Contexts: Testing A Simulation-Based Decision Support Workflow. In Proceedings of the 15th IBPSA Conference, San Fransisco, CA, USA, 7–9 August 2017.
9. Weidner, T.; Yang, A.; Hamm, M.W. Energy optimisation of plant factories and greenhouses for different climatic conditions. *Energy Convers. Manag.* **2021**, *243*, 114336. [CrossRef]
10. Graamans, L.; Tenpierik, M.; van den Dobbelsteen, A.; Stanghellini, C. Plant factories: Reducing energy demand at high internal heat loads through façade design. *Appl. Energy* **2020**, *262*, 114544. [CrossRef]
11. Jiang, J.A.; Su, Y.L.; Shieh, J.C.; Kuo, K.C.; Lin, T.S.; Lin, T.T.; Fang, W.; Chou, J.; Wang, J. On the application of a new hybrid maximum power point tracking (MPPT) based photovoltaic system to a closed plant factory. *Appl. Energy* **2014**, *124*, 309–324. [CrossRef]
12. Yorifuji, R.; Obara, S.Y. Economic design of artificial light plant factories based on the energy conversion efficiency of biomass. *Appl. Energy* **2022**, *305*, 117850. [CrossRef]
13. Despommier, D. *The Vertical Farm: Feeding the World in the 21st Century*; St. Martin's Publishing Group: New York, NY, USA, 2010; 305p.
14. Rural Development Administration, Service of Guidelines for Optimal Environment Setting of Smart Farms. Available online: https://smartfarm.rda.go.kr/mntr/inTP/acsrtpchstb.do (accessed on 18 March 2022).
15. Nongsaro. Available online: https://www.nongsaro.go.kr/portal/contentsFileView.do?ep=TxQcDle8jqMTbs55ixHbYqF1juab8B2M@r/xMBcjs5BtyvGH/qhCuqmdMsUch4d/ (accessed on 18 March 2022).
16. Architectural Standards and Performance of Eco-Friendly Houses, Ministry of Land, Infrastructure and Transport Notice, No. 2009-1014. Available online: https://www.law.go.kr/admRulSc.do?menuId=5&subMenuId=41&tabMenuId=183&query=%EC%B9%9C%ED%99%98%EA%B2%BD%EC%A3%BC%ED%83%9D#liBgcolor0 (accessed on 5 May 2022).
17. Price Information Magazine of Korea. Available online: http://www.kpi.or.kr/www/ (accessed on 18 March 2022).
18. Operating Regulations for Building Energy Efficiency Rating Certification and Zero-Energy Building Certification System, Annexed Table 3. Notice No. 0529200215 of the Korea Energy Agency. Available online: https://www.law.go.kr/admRulSc.do?menuId=5&subMenuId=41&tabMenuId=183&query=%EC%B9%9C%ED%99%98%EA%B2%BD%EC%A3%BC%ED%83%9D#liBgcolor0 (accessed on 25 March 2022).
19. 2019 National GHG Inventory Report. Available online: https://www.gir.go.kr/home/board/read.do?menuId=36&boardId=49&boardMasterId=2 (accessed on 5 May 2022).
20. Korea Electric Power Corporation. Available online: http://cyber.kepco.co.kr/ckepco/front/jsp/CY/E/E/CYEEHP00105.jsp (accessed on 18 March 2022).
21. Park, C.-K. *A Study on Development of Standards for Heating Value Conversion and Carbon Emission Factors for Each Energy Source*; Korea Energy Agency: Yongin, Korea, 2013; pp. 58–61.
22. Elceric Power Statistic Information System (As of March 2022 MP Electricity Unit Cost). Available online: http://epsis.kpx.or.kr/epsisnew/ (accessed on 4 May 2022).
23. Ministry of Trade, Industry and Energy Notification No. 2022-190, Notification of Support for New and Renewable Energy Finance Support Project in 2022. Available online: https://www.knrec.or.kr/biz/main/main.do (accessed on 5 May 2022).
24. Economic Statistics System of Bank of Korea. Available online: http://ecos.bok.or.kr/ (accessed on 4 May 2022).
25. Ordinance of the Ministry of Strategy and Finance of the Republic of Korea "General Guidelines for Conducting Preliminary Feasibility Studies". Available online: https://www.law.go.kr/LSW/admRulLsInfoP.do?admRulSeq=2100000177914 (accessed on 4 May 2022).
26. Ministry of Agriculture, Food and Rural Affairs Website. Available online: https://www.mafra.go.kr/mafra/1336/subview.do (accessed on 4 May 2022).