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A Decision Support Software Application for the Design of Agrophotovoltaic Systems in Republic of Korea

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Abstract: Agrophotovoltaic (APV) systems produce both solar energy and crops, so they are considered a sustainable alternative to traditional solar power plants, which can potentially destroy farmlands. However, it is challenging to diffuse APV systems because of their high installation and operating costs. Thus, to resolve the issue by maximizing the productivity and profits of an APV system, this study aims to propose a mobile-phone-based decision support system (DSS) for a supply chain network design for APV systems in South Korea using satellite imagery incorporating geographic information system (GIS) data. Particularly, polynomial regression models estimating annual corn (*Zea mays*) yields and the predicted generation of electricity were developed and integrated with the proposed DSS. Field experiment data provided by the APV system at Jeollanamdo Agricultural Research and Extension Services in South Korea were utilized. Two photovoltaic (PV) module types (mono-facial and bi-facial) and three different shading ratios for APV systems (21.3%, 25.6%, and 32.0%) were considered design factors for APV systems. An optimal network structure of 6 candidate APV systems and 15 agricultural markets was devised using the generalized reduced gradient (GRG) method. The profits of the six candidate APV systems are mainly affected by the transportation costs to the markets and the policy of the electricity selling prices. As a result, the proposed supply chain design framework successfully identifies an APV system network with maximum profits from crop production as well as electricity generation.

Keywords: agrophotovoltaic; corn production; photovoltaic; renewable energy; emission reduction; supply chain

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1. Introduction

An agrophotovoltaic (APV) system that produces both crops and solar energy is considered one of the best sustainable alternatives to solar power plants, which potentially destroy existing farmland [1]. Particularly, a country with a land shortage problem such as South Korea faces a trade-off between solar energy production and food security conservation. More specifically, since the Korean government intends to produce 32.2 GW of solar energy by 2030, 425.04 km^2 of land, which is 70% of the land in Seoul, South Korea, needs to be used for solar power plant construction [2]. This implies that approximately 5.16% of rice paddy fields will be converted to solar power plants to produce renewable energy [2].

In fact, the climate change issue is vital to the survival of humanity. Countries around the world signed annual agreements at the United Nations Climate Change Conference and at the Glasgow Climate Pact in Glasgow, England in 2021 [3]. All developed countries have agreed to spend USD 100 billion annually on climate finance to develop renewable energy sources and reduce the use of fossil fuels. In particular, as coal power accelerates global warming, renewable energy has an important role in reducing greenhouse gas (GHG) emissions [3]. As in other countries, the Korean government has made great efforts to use renewable energy and reduce GHG emissions. As mentioned earlier, the Ministry of Trade, Industry, and Energy has announced that by 2030 it will expand the share of renewable energy generation in Korea to 20% [4]. In 2020, 10 APVs were tested in Republic of Korea, and about 67% of people said that the renewable energy expansion policy is important [5]. Therefore, APV systems are a sustainable way of generating renewable energy, especially in densely populated countries [6].

One of the challenges in reviving the use of renewable energy is associated with the economic aspect. For example, for solar energy to be competitive, the selling price, including production costs, should be lower than or similar to the price of existing fossil-fuel-based energy sources. To this end, the Korean government provides a Renewable Energy Certificate (REC) in addition to the system marginal price (SMP). In 2022 in Republic of Korea [7], the production cost of solar energy, coal, natural gas, and nuclear power is USD 148/MWh, USD 123/MWh, USD 186/MWh, and USD 41/MWh, respectively. The global weighted average levelized cost of electricity (LOCE) for utility-scale photovoltaic (PV) projects decreased from 55/MWh in 2020 to 48/MWh in 2021 because of renewable energy policies such as the Solar Investment Tax Credit (ITC) in the U.S. and the Solar Energy Strategy in Europe [8]. Therefore, most ground-mounted solar power plants were installed in Republic of Korea before 2022, but this caused environmental problems such as damage to the natural environment and soil leakage. In addition, given that most farmlands have sufficient solar radiation to produce solar energy, it is true that destroying farmland to build a solar power plant is one of the easiest options [9].

This study aims to make solar energy competitive by reducing the production cost. To this end, an optimal supply chain network of agrophotovoltaic (APV) systems in Republic of Korea is designed using satellite imagery incorporating geographic information system (GIS) data as part of a mobile-phone-based decision support system (DSS). Polynomial regression models estimating corn (*Zea mays*) yields and electricity are integrated into the proposed system, and the models are calibrated against field experiment data collected from an APV system at Jeollanamdo Agricultural Research and Extension Services in Republic of Korea. An optimal network structure of 6 candidate APV systems and 15 agricultural markets is devised using the generalized reduced gradient (GRG) method. The decision variables of the network design problem are two PV module types (mono-facial and bi-facial) and three different shading ratios for APV systems (21.3%, 25.6%, and 32.0%). As a result, the proposed decision support system can help farmers and system engineers efficiently construct APV systems under various conditions (or environmental factors).

2. Background

Supply Chain Network of Agrophotovoltaic Systems

In general, a supply chain network consists of three major actors: suppliers (or farms), storage facilities, and retail markets (or agricultural markets) [10]. Similar to other areas, efficient supply chain management in agriculture is challenging because of its correlation with many factors such as food quality, food safety, shelf life, and different demands in each market [11]. An and Ouyang [12] made a robust grain (corn and soybean) supply chain considering post-harvest loss and harvest timing to maximize potential profits and minimize transportation costs. In particular, a short food supply chain reduces transportation costs and CO_2 emissions, which is helpful for the environment, and this is proven by increasing EU and national legislation [13].

Among the three major actors in the agriculture supply chain, storage facilities are necessary components to ensure the freshness of the raw material (corn) and reduce dry matter losses [14]. However, in a large tower silo (or the storage facility), there is a loss of corn matter between 7.2% and 14.1% in the first month of storage [15]. More specifically, the loss of 28% of dry matter with 72% moisture is 18.05%, and the loss of 45% of dry matter with 55% moisture is 10.47%. Given that each crop has its own cultivation period depending on environmental conditions, storage facilities are essential actors in the agricultural supply chain. Nevertheless, since warehouse facilities are generally located next to farms in

Republic of Korea, only the transportation time between farms and retail markets can be considered a major factor in effective supply chain management. In fact, most corn crops are run by individual farmers with small-scale farms in Republic of Korea, so corn production is stored in a storage facility in the same village, operated by an agricultural cooperative [16].

The supply chain associated with the APV system covers the main characteristics of the existing corn supply chain. This is because the APV system also produces corn under PV modules in addition to generating electricity and delivering it to the power grid [17]. Figure 1a shows the APV system at the Jeollanam-do Agricultural Research and Extension Services in Naju-si (35.0161° N, 126.7108° E), Jeollanam-do, Republic of Korea. As shown in Figure 1b, it has two photovoltaic (PV) module types (mono-facial and bi-facial) and three different shading ratios (21.3%, 25.6%, and 32.0%) [1].

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

Figure 1. Tested agrophotovoltaic system: (**a**) overview; (**b**) APV with different module types (bi- and mono-facial) and shading ratios (21.3%, 25.6%, and 32%).

Moreover, the construction costs of the tested APV system are illustrated in Table 1. In fact, the APV system has high investment costs because of its high ground clearance height for small tractor use [14]. In addition, the total construction cost increases as the shading ratio increases. This is because there exists a positive correlation between the number of modules per unit and the shading ratio. The highest number of PV modules per unit area (m^2) is 0.089 at a shading ratio of 32%.

Table 1. Investment costs of the tested APV system [2].

Data Type	21.3%	25.6%	32%
Solar module cost (USD/m^2)	4.38	4.46	6.30
Structure cost (USD/m^2)	7.24	7.72	10.43
Electric distribution system cost (USD/m^2)	3.45	3.68	4.97
Other costs (USD/m^2) [1]	0.25	0.27	0.36
Total cost (USD/m^2)	15.32	16.34	22.06
Number of PV modules per unit area (units/m^2)	0.062	0.066	0.089

[1] The costs include the building permit fee and the fee for connection to the existing electric distribution system.

To make the APV system competitive, not only energy sales but also crop sales should be considered for APV system management. This implies that an efficient supply chain management system with minimum operational costs should be devised. According to Huang et al. [18], large-scale centralized storage enables the minimization of the total transportation costs of the supply chain of corn in the U.S. because it reduces small-scale transactions between supply chain facilities. However, the study is for biofuel (or ethanol) production. Unlike commercial-scale farms, storage facilities are operated by farmer communities so that farmers can easily consume their harvested crops until the next harvest season [19]. In addition, stored crops can be easily converted into cash when farmers need it [20]. Thus, for the management of non-commercial-scale farms, an appropriate location selection for a farm can be a significant issue. This is not exceptional for supply chain designs for APV systems that are operated by individual farmers.

According to Sharma et al. [21], the geographic information system (GIS) is the most recommended technology for designing an agriculture supply chain under a precision agriculture environment. Because an APV system involves a farm underneath solar panels, this finding can also be applied to an APV system design. Since the GIS provides accurate location information to a user on a map, it is a useful technology for site-planning activities [22]. Multiple factors such as soil quality, terrain properties, drainage, and slope length can be considered under a GIS map [23]. Moreover, Schmedtmann and Campagnolo et al. [24] utilized satellite imagery to develop a common agriculture policy for agricultural subsidy control. They adopted computer-assisted photo interpretation (CAPI) with a support vector machine (SVM) classifier to identify crop types from a satellite image. In this study, we use *K*-Means clustering to identify potential locations for APV systems that produce corn (see Section 3 for more details).

3. Decision Support System for APV System Design

The decision support system (DSS) for designing the APV system consists of three modules, as shown in Figure 2. First, the mobile client module collects and extracts farmland information from the APV system candidate location. Second, the yield estimation module predicts the electricity generation quantities and crop yields of the APV system. The optimal APV system is then designed for each selected candidate site (farmland). Third, the location–allocation module optimizes the supply chain network of APV systems in terms of minimal transport costs.

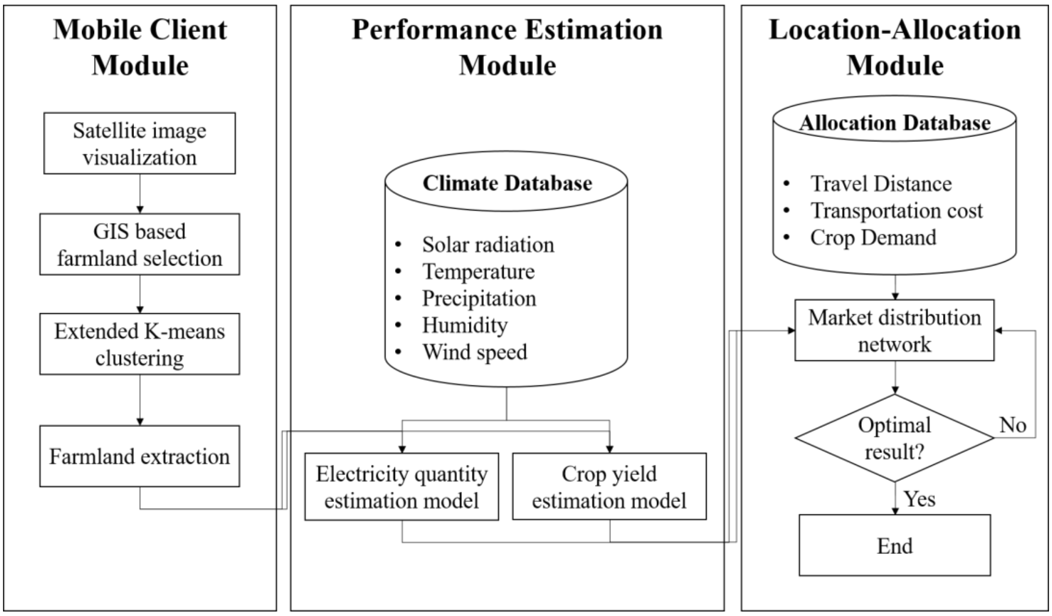


Figure 2. The structure of the decision support system for the APV system.

3.1. Mobile Client Module

The mobile client module helps the DSS user search for farmland for APV construction using the developed smartphone application. The Google Maps Application Programming Interface (API) is used to select a candidate (potential) site. In the mobile application, the potential site of the APV system (farmland) is visualized for the user using a satellite image containing geographic information system (GIS) data. Figure 3 shows an example of a mobile client module for estimating corn yields at a selected location (36.3137° N, 127.0354° E) in Republic of Korea.

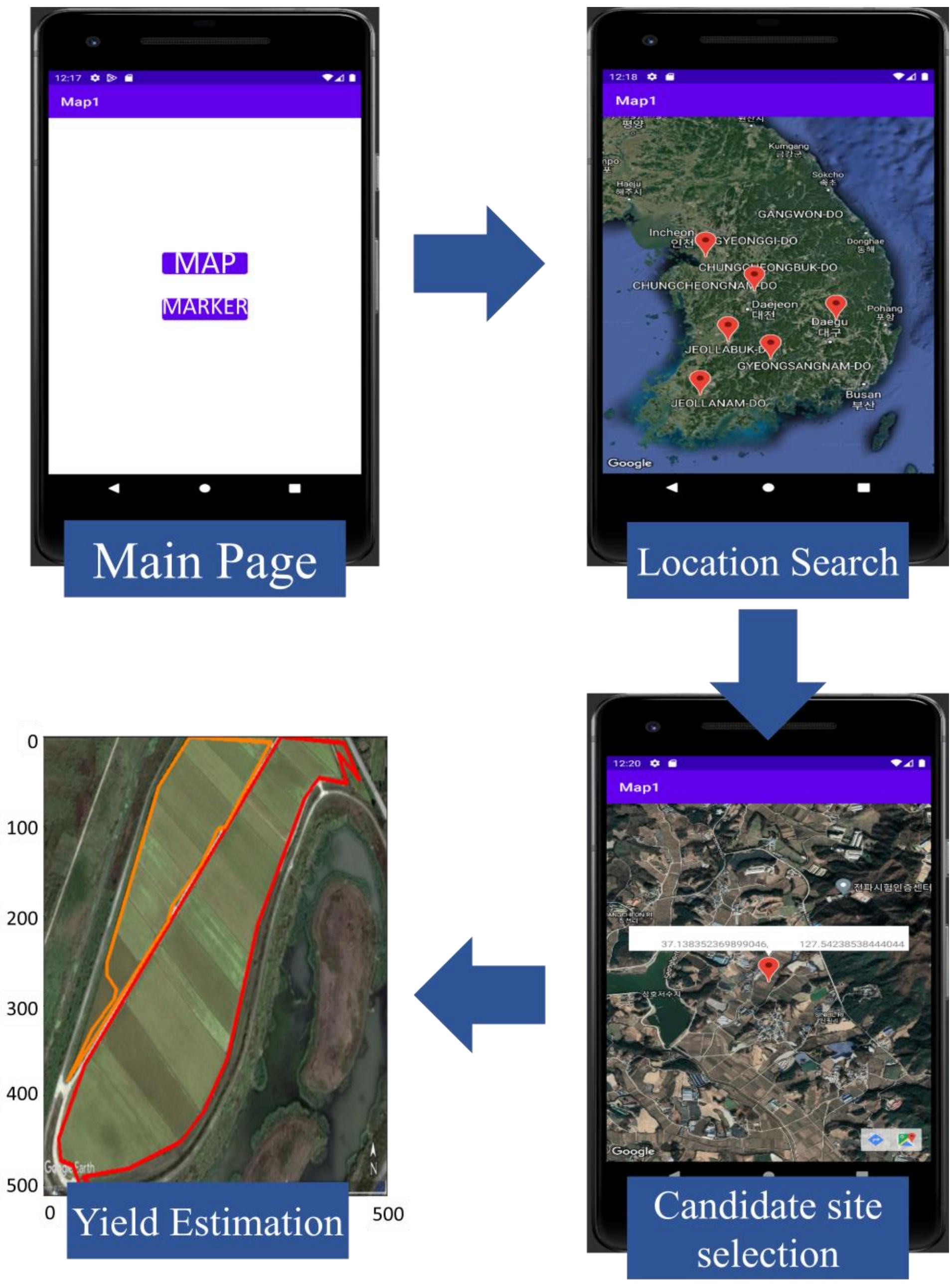


Figure 3. An example of a mobile client module.

Once a user selects a location, the GIS data of the selected farmland is stored in smartphone applications, making it easy for users to obtain the data necessary to analyze the performance of the APV system at the candidate site. This study considers the portable platform because farmers and engineers in the field of agriculture mainly engage in outdoor activities; however, the devised software can be modified for other platforms (desktop or tablet environments). For this purpose, the farmland extraction algorithm detects the farmland from the selected image via *K*-Means clustering with low computational power demand [25]. Specifically, compressed satellite imagery using the Image-Blurring function is clustered through the *K*-Means clustering algorithm [26], and then, the farmland is extracted. Figure 4 reveals the flow chart of farmland detection using satellite imagery.

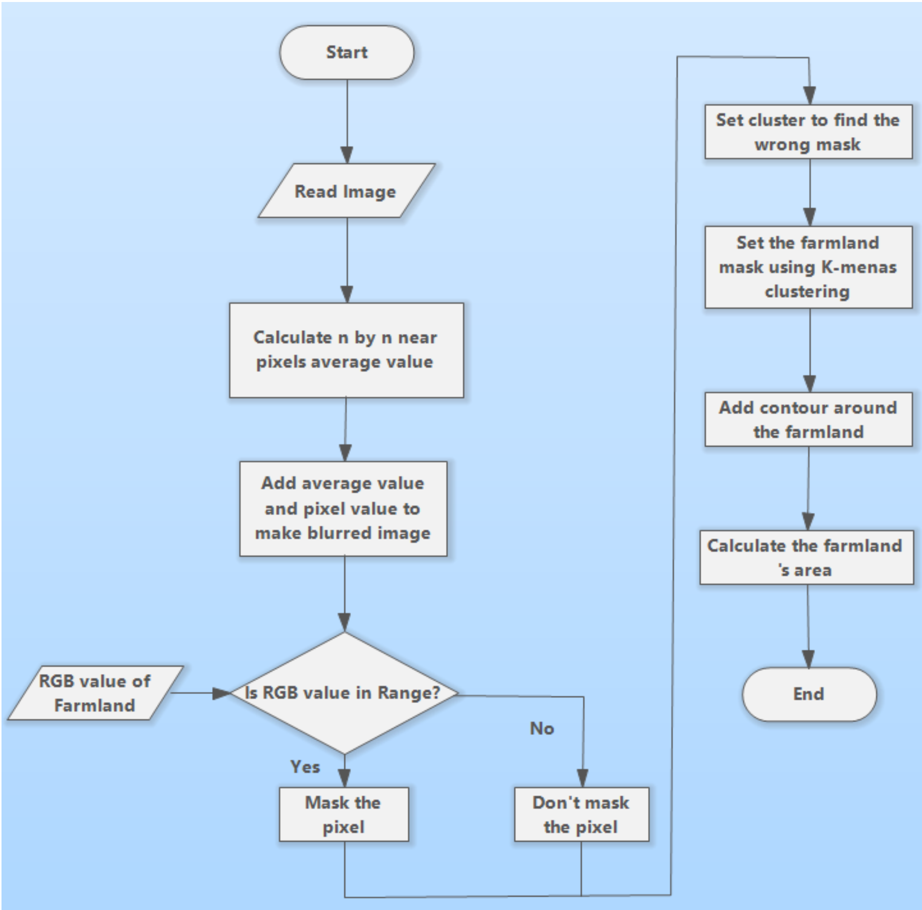


Figure 4. Flow chart of farmland detection using satellite imagery.

Figure 5 shows masked images of the subject farmland. The ranges of red, green, and blue (RGB) values in Figure 5a are 211–241 in red, 224–254 in green, and 158–188 in blue. Although the masking in Figure 5a only presents farmlands, not all farmlands in the subject area are masked. In Figure 5b, the masked area is identical to the whole farmland in the subject area, but some masks with blue color are presented out of the subject area. These noises are created because of the wide range. The ranges of RGB values in Figure 5b are 181–271 in red, 194–284 in green, and 128–218 in blue. To eliminate these noises, *K*-Means clustering is used (see Figure 6).

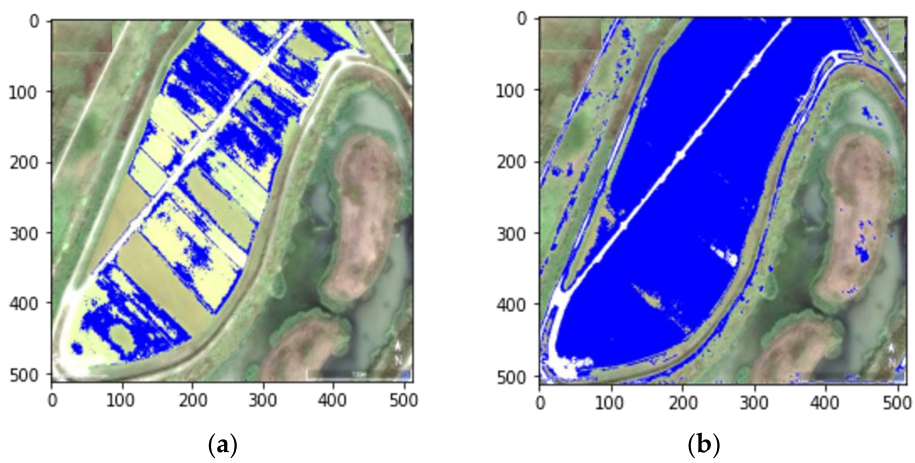


Figure 5. Farmland masked satellite imagery: (**a**) small range; (**b**) large range.

Figure 6. Clustered farmland satellite imagery.

In Figure 6, two large clusters are selected. These clusters involve most of the farmland. The orange cluster's area is 11,840 m^2, and the red cluster's area is 31,587 m^2. The actual farmland area is 44,490 m^2. The selected cluster covers 97.6% of the farmland. The farmland area can be utilized to estimate crop yields from the farm and calculate the capacity of the APV system.

3.2. Performance Estimation Module

The performance estimation module estimates the performance of the APV system at a selected candidate site in terms of the electricity generation amount and the crop yield. The estimated performance of each candidate site is utilized to develop the optimal design of the APV system's supply chain network. To this end, a field experiment with the tested APV system was conducted in the summer period (June–August) [27]. Table 2 describes the data observed in the field study, which used a randomized complete block design (RCBD) with three replicates to plot the graphs. The area of the subplot was 8 $\times$ 10 m (80 m^2), and the plant density was 9 plants/m^2 [1]. The yields of corn at a 0% shading ratio, a 21.3% shading ratio, a 25.6% shading ratio, and 32.0% shading conditions amounted to 8.09 Mg/ha, 8.56 Mg/ha, 6.40 Mg/ha, and 5.63 Mg/ha, respectively [1]. Interestingly, 6% of the corn yield slightly increased under the 21.3% shading ratio. In fact, according to [28], the shadow generated by PV modules in farmland contributes to moisture preservation in the soil so that it can retain organic matter. Thus, this positive impact on soil moisture retention results in an increase in yield. Nevertheless, with shading above 25.6%, the corn yield is significantly reduced because of the low solar radiation affecting the photosynthesis activity of the corn.

Table 2. Observed data (edited from Kim et al. [27]).

Month	Solar Radiation (MJ/m^2)	Ambient Temperature High (°C) [1]	Ambient Temperature Low (°C) [2]	Precipitation (mm)	Humidity (%)	Wind Speed (m/s)	Electricity Generation (kWh/m^2/day)
June	3.70	29.40	19.43	12.72	76.93	2.01	99.83
July	2.77	27.71	20.92	14.80	84.67	1.94	74.95
August	3.62	34.05	24.25	17.83	73.36	2.45	97.81
September	3.03	27.74	16.74	7.17	74.11	1.67	81.73
October	3.27	24.68	8.73	0.30	56.94	1.67	88.37

[1] The highest air temperature; [2] the lowest air temperature.

Both the electricity generation model and the crop yield model are based on polynomial regression (PR), which enables the capture of the non-linear relationship between the variables [27]. Equations (1) and (2) represent the general PR model [1].

$$Y = g(X_1, \ldots, X_n) = \beta_0 + f_1(X_1) + \cdots + f_n(X_n) + \varepsilon,\ \varepsilon \sim N\left(0, \sum_{j=1}^{n} \sigma_j^2\right) \tag{1}$$

$$f_j(X_j) = \beta_{j1}(X_j) + \beta_{j2}\left(X_j^2\right) + \cdots + \beta_{jL}\left(X_j^L\right),\ j = 1\ ,\ 2,\ \ldots,\ n \tag{2}$$

where $f_j(X_j)$ is a polynomial function in X_j, $\beta_0 = \sum_{j=1}^{n} \beta_{j0}\left(X_j^0\right)$, $X_j^0 = 1$, and $\sum_{j=1}^{n} \beta_{j0}\left(X_j^0\right) = \sum_{j=1}^{8} \beta_{j0}$. β_j is a coefficient of X_j, and β_0 is a constant. β_j represents the influence weight of X_j on response variable Y. In this study, six microclimate variables in Table 3 and two decision variables (X_1 is the shading ratio (0.0%, 21.3%, 25.6%, and 32.0%), and X_2 is the solar panel type (1: mono-facial and 2: bi-facial)) are considered. Equation (3) represents the developed electricity generation model in the APV system. The PR is calibrated with microclimate data (see Table 2) and electricity generation data from Jeollanamdo Agricultural Research and Extension Services in Republic of Korea (35.0161° N, 126.7108° E).

$$\begin{aligned} f_R(X_1, X_2) = \ & -812.25 + 184.68A_1 + 9.91A_2 + 6.01A_3 - 0.29{A_3}^2 - 0.65A_4 \\ & + 1.64 \times 10^{-3}{A_4}^2 - 2.10A_5 + 7.14 \times 10^{-5}{A_5}^3 + 0.10A_6 \\ & + 2172.10X_1 + 60.96X_2 \end{aligned} \tag{3}$$

Table 3. Microclimate variables.

Variable Symbol	Variable Name	Unit
A_1	Daily solar radiation	MJ/m^2
A_2	Daily maximum temperature	°C
A_3	Daily minimum temperature	°C
A_4	Daily precipitation	mm
A_5	Daily humidity	%
A_6	Daily wind speed	m/s

In order to verify the electricity generation model, the daily generated electricity data (test set) from 13 June 2020 to 20 October 2020 are compared with the electricity generation values estimated by Equation (3). Pearson's correlation coefficient of determination (R^2) of the electricity generation model is 95.89%. This means that the devised electricity generation model enables the accurate estimation of the electricity generation volume of the tested APV system.

As with the electricity generation model, Equation (4) refers to the crop yield model calibrated with the collected APV data (see Table 2).

$$g_R(X_1) = 8.1208 + 15.488X_1 - 75.119{X_1}^2 \tag{4}$$

To validate Equation (4), the corn yield data (test set) from 13 June 2020 to 20 October 2020 are compared with the corn yield estimated by Equation (7). The R^2 of the corn yield model is 86.03%, so we can conclude that the crop yield model accurately explains the variability present in the field study data.

Moreover, Equations (6) and (7) are used to compute the total profits (Equation (5)) from crop production and electricity generation of the APV system.

$$\text{Total profit } P = f(X_1, X_2) + g(X_1) \tag{5}$$

$$f(X_1, X_2) = \alpha f_R(X_1, X_2) - f_C(X_1, X_2) \tag{6}$$

$$g(X_1) = \beta g_R(X_1) - g_C(X_1) \tag{7}$$

The nomenclature of the total profit model (Equations (5)–(7)) is illustrated in Table 4.

Table 4. Nomenclature of the total profit model.

Symbol	Variable Name	Unit
α	Unit electricity price	USD/kWh
β	Unit crop price	USD/kg
$f_R(\cdot)$	Electricity generation quantity	kWh
$f_C(\cdot)$	Electricity generation cost	USD
$g_R(\cdot)$	Crop yield	kg
$g_C(\cdot)$	Crop production cost	USD

Equation (6) shows the profits from electricity generation, which are calculated by subtracting the solar panel installation costs and the operating costs from the revenue. Equation (7) represents the profit from crop production, which is calculated by subtracting the crop production costs from the revenue from crop production.

3.3. Location-Allocation Module

The location–allocation module evaluates the market distribution network and finds the optimal distribution plan with minimal transportation costs between farms and markets. Equation (8) refers to the optimization model.

$$\text{Min}\, Z = \sum_{i \in \mathrm{F}} \sum_{j \in \mathrm{M}} D_{ij} \times C \times f_{ij}(X_{i1}, X_{i2}) \tag{8}$$

subject to

$$\sum_{j \in \mathrm{M}} f_{ij}(X_{i1}, X_{i2}) \le f_R(X_{i1}, X_{i2}) \text{ for } \forall i \in \mathrm{F} \tag{9}$$

$$\textstyle\sum_{i \in \mathrm{F}} f_{ij}(X_{i1}, X_{i2}) \quad \le \gamma_j \text{for } \forall j \in \mathrm{M} \tag{10}$$

where Z is the total transportation cost (USD) from selected farms to selected markets; F is a set of farms (candidate sites of APV systems); M is a set of markets; X_{i1} is the shading ratio of the farm, $i \in$ F (21.3%, 25.6%, and 32.0%); X_{j1} is a solar panel type, $j \in$ M (1: mono-facial and 2: bi-facial); D_{ij} is the distance (km) between the farm, $i \in$ F, and the market, $j \in$ M; C is the unit transportation cost (USD); $f_{ij}(X_{i1}, X_{i2})$ is the delivery quantities of corn (Kg) between the farm, $i \in$ F, and the market, $j \in$ M; and γ_j is the total market demand, j (Kg). The devised non-linear optimization problem is solved by the generalized reduced gradient (GRG) method [29].

4. Experiments

4.1. Scenario

The proposed DSS system was applied to the corn supply chain network scenario shown in Figure 7. Six candidate APV sites and fifteen agricultural markets in Republic of Korea were considered in the scenario.

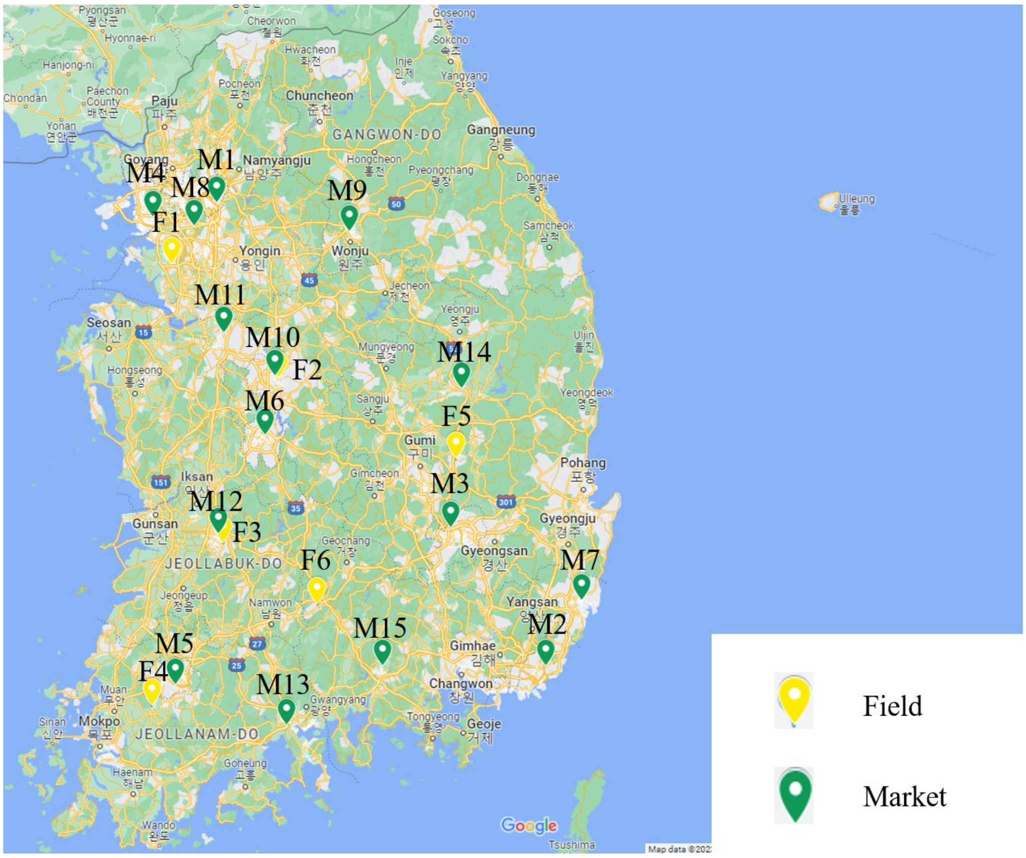


Figure 7. Map image of the corn distribution network in Republic of Korea.

The selected candidate sites in Figure 7 and Table 5 were chosen because APV systems in Republic of Korea are currently operating at these sites [30]. The total capacity of these systems is 536 kW with an area of 9144 m^2. Corn yields were estimated using Equation (4), and corn yields at candidate sites are 0.742 kg/m^2 in F1, 0.742 kg/m^2 in F2, 0.31 kg/m^2 in F3, 0.642 kg/m^2 in F4, 0.467 kg/m^2 in F5, and 0.747 kg/m^2 in F6 [31]. Table 5 summarizes the information about the candidate sites.

Table 5. Information about the selected candidate sites.

Selected APV Candidate Sites	Location	Capacity (kW)	Size (m^2)	Yield (kg)
F1	Hwaseong-si	50	853	633
F2	Cheongju-si	100	1706	1266
F3	Jeonju-si	86	1467	455
F4	Naju-si	100	1706	1095
F5	Gunwi-gun	100	1706	797
F6	Hamyang-gun	100	1706	1274

The summarized information on the fifteen markets is illustrated in Table 6. These markets are major agricultural markets near major cities in Republic of Korea. Jeju-do and Sejong-si are ignored in this study because the population of these places is less than one million. The corn demand ratio in each market is calculated from annual corn consumption data and population data, dividing each market's demand by the total market demand [32,33]. As Gyeonggi-do is the largest population in Republic of Korea, it has the highest corn demand.

Table 6. Information on major agricultural markets.

Markets	Location	Market Name	Corn Demand Ratio (%)
M1	Seoul-si	Garak	18.68
M2	Busan-si	Banyeo	6.56
M3	Daegu-si	Daegu	4.71
M4	Incheon-si	Namchon	5.83
M5	Gwangju-si	Seobu	2.91
M6	Daejeon-si	Ohjung	2.92
M7	Ulsan-si	Ulsan	2.21
M8	Gyeonggi-do	Anyang	26.93
M9	Gangwon-do	Wonju	3.00
M10	Chungcheongbuk-do	Cheongju	3.20
M11	Chungcheongnam-do	Cheonan	4.29
M12	Jeollabuk-do	Jeonju	3.53
M13	Jeollanam-do	Suncheon	3.51
M14	Gyeongsangbuk-do	Andong	5.20
M15	Gyeongsangnam-do	Jinju	6.52

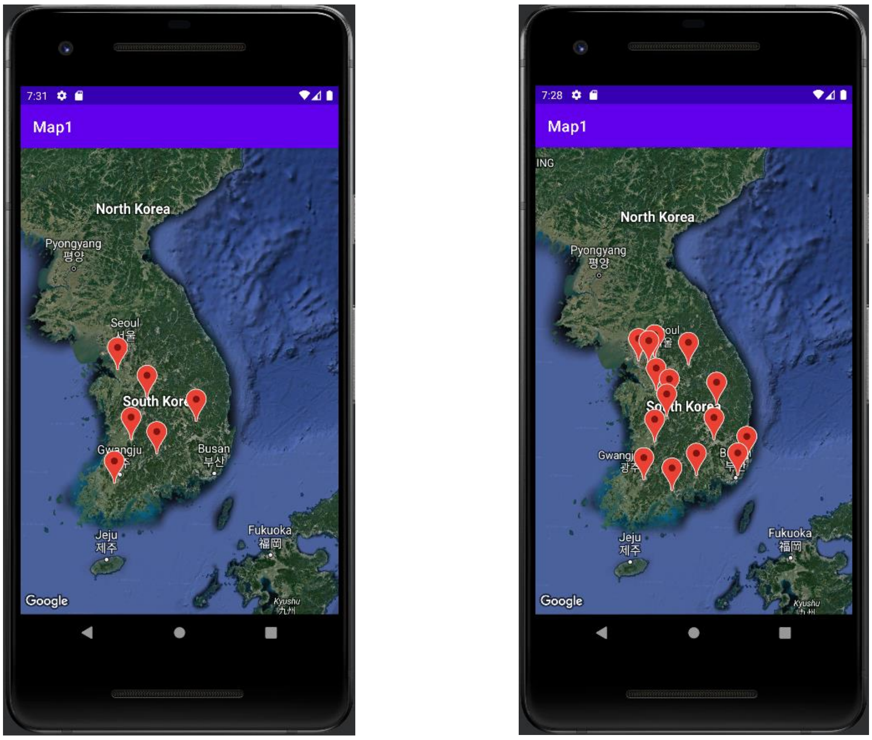
A distance matrix was configured for the candidate locations and markets that were provided. Table 7 describes the distance between the candidate sites (or APV farms) and markets. The distance between Cheongju market (M10) and Cheongju-si (F2) has the shortest distance at 4 km. On the other hand, the distance between Banyeo market (M2) and Hwaseong-si (F1) has the longest distance at 386 km. This is because Hwaseong-si (F1) is located in the northwestern region, and Banyeo market (M2) is located in the southeastern region of Republic of Korea. This implies that the Banyeo market (M2) tends to purchase corn from farms (Gunwi-gun (F5)) near its location to minimize transportation costs.

Table 7. Distance matrix between APV candidate sites and markets.

Markets	APV Candidate Sites (km)					
	F1	F2	F3	F4	F5	F6
M1	51	126	205	308	250	267
M2	386	288	261	302	161	181
M3	271	163	182	229	42	101
M4	33	142	217	335	272	292
M5	289	215	105	24	251	117
M6	143	36	89	192	162	124
M7	364	266	299	336	139	214
M8	35	113	203	306	251	267
M9	122	121	238	341	168	273
M10	119	4	124	228	148	159
M11	66	52	130	233	181	193
M12	185	122	6	122	227	96
M13	311	240	120	111	237	114
M14	234	144	247	322	47	187
M15	320	222	156	190	147	66

4.2. Results

As described in Section 3.2, both PR models are used to determine the PV panel types and shading ratios of the six APV systems to maximize their productivity. Considering the data described in Tables 5–7, the performance of the APV systems at the six candidate sites is computed in terms of the electricity generation amount and crop productivity. Particularly, the proposed DSS selected the bi-facial APV option with a shading ratio of 25.6% as the best alternative for all six candidate sites. Figure 8 shows the APV candidate sites and major markets in Republic of Korea using the mobile DSS developed.



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

Figure 8. Mobile client: (**a**) APV candidate sites; (**b**) major markets in Republic of Korea.

The devised non-linear optimization problem is solved with the generalized reduced gradient (GRG) method addressed in Section 3.3. Table 8 illustrates the result of the optimized transportation quantities between the markets and APV candidate sites shown in Figure 8. Particularly, the quantities of corn transported from the APV candidate sites to markets are described. Since the Gyeonggi-do market (M8) has the highest corn demand in Republic of Korea, its total transportation volume has the highest value at 1486.52 kg. On the other hand, Ulsan-si (M7) received the minimum amount of corn (121.99 kg) and only receives corn from Gunwi-gun (F5). In addition, because all fields have to meet the demand for corn in Republic of Korea, some markets cannot receive corn from the nearest fields. For example, Seoul-si (M1) cannot receive corn from Hwaseong-si (F1) because the two nearest markets (Gyeonggi-do and Incheon-si) consume all corn produced from Hwaseong-si (F1). This means that the productivity gains at the APV candidate site in Hwaseong-si (F1) enable lower transportation costs between Seoul-si (M1) and other APV candidate sites (F2, F4, and F6).

Table 9 illustrates revenue from six bi-facial APV systems with a 25.6% shading ratio. Data on the price of electricity sales in 2020 are used to calculate revenues [34]. The renewable energy credit (REC) is USD 0.11/kWh, and the system marginal price (SMP) is USD 0.07/kWh. In addition, the corn-selling price in 2020 was USD 2.74/kg [1]. In Table 9, the REC case tends to have higher revenue in electricity sales because its unit price includes both the SMP and the REC. For the SMP, approximately 81.11% of total revenues depend on corn production. For the REC, approximately 74.50% of the total revenue depends on corn production. In fact, because of the higher unit selling price of electricity, the impact of selling crops on total revenue is smaller than in the SMP case.

Table 8. Transportation quantities from APV candidate sites to markets.

Markets	APV Candidate Sites (kg)						Total (kg)
	F1	F2	F3	F4	F5	F6	
M1	0.00	89.22	0.00	588.60	0.00	353.30	1031.12
M2	0.00	0.00	0.00	0.00	0.00	362.10	362.10
M3	0.00	0.00	0.00	0.00	222.08	37.90	259.98
M4	321.81	0.00	0.00	0.00	0.00	0.00	321.81
M5	0.00	0.00	0.00	160.63	0.00	0.00	160.63
M6	0.00	0.00	0.00	0.00	0.00	161.18	161.18
M7	0.00	0.00	0.00	0.00	121.99	0.00	121.99
M8	311.12	1000.00	23.12	152.28	0.00	0.00	1486.52
M9	0.00	0.00	0.00	0.00	165.60	0.00	165.60
M10	0.00	176.64	0.00	0.00	0.00	0.00	176.64
M11	0.00	0.00	236.80	0.00	0.00	0.00	236.80
M12	0.00	0.00	194.85	0.00	0.00	0.00	194.85
M13	0.00	0.00	0.00	193.75	0.00	0.00	193.75
M14	0.00	0.00	0.00	0.00	287.03	0.00	287.03
M15	0.00	0.00	0.00	0.00	0.00	359.90	359.90
Total	632.93	1265.86	454.77	1095.26	796.70	1274.38	5519.90

Table 9. Revenue from bi-facial APV systems with a shading ratio of 25.6%.

APV Candidate Sites	Location	SMP Case			REC Case [1]		
		Total Revenue (USD/Month)	Revenue from Electricity Generation (USD/Month)	Revenue from Corn Production (USD/Month)	Total Revenue (USD/Month)	Revenue from Electricity Generation (USD/Month)	Revenue from Corn Production (USD/Month)
F1	Hwaseong-si	680.52	102.45	578.07	739.06	160.99	578.07
F2	Cheongju-si	1361.04	204.90	1156.14	1478.12	321.98	1156.14
F3	Jeonju-si	591.55	176.19	415.36	692.23	276.87	415.36
F4	Naju-si	1205.23	204.90	1000.33	1322.31	321.98	1000.33
F5	Gunwi-gun	932.55	204.90	727.65	1049.63	321.98	727.65
F6	Hamyang-gun	1368.84	204.90	1163.94	1485.92	321.98	1163.94

[1] This includes the renewable energy credit (REC) and the system marginal price (SMP).

The total costs of the six APV candidate sites are illustrated in Table 10. The average electricity production cost of APV systems is 102.87 USD/month; the average corn production cost is 409.76 USD/month; and the average transportation cost is 204.13 USD/month. It should be noted that the unit transportation cost is 1.45 USD/km/ton [25]. Naju-si (F4) has the highest production costs because of its high transportation costs at 362.02 USD/month. In fact, Naju-si (F4) has the greatest average distance to markets (238.6 km) and is 28.76% longer than the average distance (185.31 km) from the candidate sites to the markets (see Table 7). As illustrated in Table 10, the total cost is significantly influenced by the transportation costs.

Figure 9 reveals the total profits of the six APV candidate sites estimated from Tables 9 and 10. In general, the REC case has higher profits than the SMP case because of the higher-unit electricity sales price. The total gain for the REC case is an average of about 34.12% higher than for the SMP case. Cheongju-si (F2) has the highest profits among the candidate sites in terms of size because of its location in Republic of Korea. In fact, it is located in the center of Republic of Korea (see Figure 7), so it can deliver corn to multiple markets with low transportation costs. In both cases, it has higher profits than other candidate sites. On the other hand, Jeonju-si (F3) has negative profits in the SMP case. This is because it has the lowest corn production revenue, and its electricity generation unit price (system marginal price (SMP)) of USD 0.07/kWh is not high enough to make a positive profit. This implies that an appropriate REC policy should be considered in order to maintain a profitable APV system.

Table 10. Total costs of bi-facial APV systems with a shading ratio of 25.6%.

APV Candidate Sites	Location	Electricity Production Cost (USD/Month)	Corn Production Cost (USD/Month)	Transportation Cost (USD/Month)	Total Cost (USD/Month)
F1	Hwaseong-si	57.58	228.39	32.87	318.83
F2	Cheongju-si	115.16	458.91	117.45	691.52
F3	Jeonju-si	99.02	394.62	163.85	657.50
F4	Naju-si	115.16	458.91	362.02	936.09
F5	Gunwi-gun	115.16	458.91	191.40	765.47
F6	Hamyang-gun	115.16	458.91	357.18	931.25

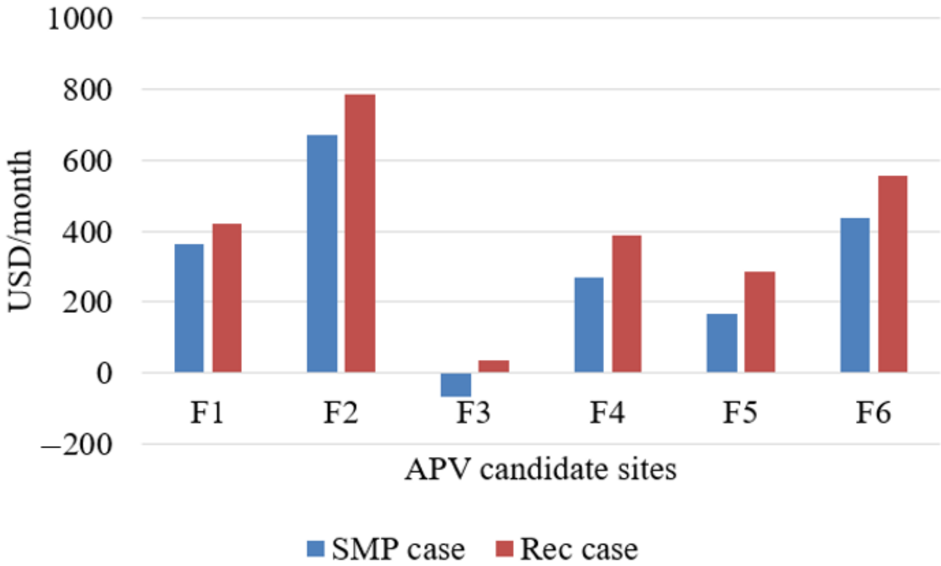


Figure 9. Total profits of bi-facial APV systems with a 25.6% shading ratio.

4.3. Discussion

The proposed system was utilized to develop a supply chain network for APV systems regarding their profits. Two photovoltaic (PV) module types (mono-facial and bi-facial) and three different shading ratios for APV systems (21.3%, 25.6%, and 32.0%) were considered design factors for APV systems. The experiment results showed that the bi-facial APV option with a shading ratio of 25.6% is the best alternative for all six candidate sites. This is because the electricity generation productivity of a bi-facial PV module is higher than that of a mono-facial PV module. Moreover, although there exists a positive correlation between electricity generation quantities and shading ratios, crop growth decreases as the shading ratio increases. This trend was also observed by other studies [35–37]. Particularly, Touil et al. [35] mentioned that a low shading ratio equal to or lower than 25% is recommended for crop harvesting because there is significant harvesting yield reduction with a shading ratio greater than 25%. Thus, those studies supported the experiment result wherein a bi-facial APV option with a shading ratio of 25.6% can produce electricity without significantly sacrificing the crop harvesting yield. Note that this study only considered three different shading ratios for APV systems (21.3%, 25.6%, and 32.0%).

Under the selected best design for an APV system, a supply chain network was developed. Although the candidate site of F6 had the highest yield, it was not selected as the best candidate site in terms of the total profits. Unlike the electricity sales profits, which were heavily dependent on a renewable energy pricing policy (SMP and REC), the crop sales profits were significantly dependent on the transportation cost between the APV systems and the agricultural markets. Regarding the distance to markets and the market demand for corn, the candidate site of F2 had the highest profit from corn sales under both the SMP and REC policies. In addition, the REC policy had a higher electricity sales price than that of the SMP policy [38,39]. Therefore, the F2 candidate site enabled the highest profits under the REC policy.

5. Conclusions

This study proposes a smartphone-based decision support system (DSS) to identify an optimal supply chain network for APV systems in terms of total operating costs. The major advantage of the proposed system is its practicality. Once the location of the APV system is determined, polynomial models integrated into the system estimate its corn (*Zea mays*) yield as well as the electricity generation amount. The proposed models are calibrated based on data collected from the APV system at Jeollanam-do Agricultural Research and Extension Services in Republic of Korea. The R^2 values of the electricity estimation model and corn yield estimation models are 95.89% and 85.03%. This means that the proposed models make it possible to accurately capture variability in the collected data. In the experiments, a supply chain network consisting of 6 candidate APV systems and 15 agricultural markets is considered, and its optimal design in terms of total operating costs is identified using the generalized reduced gradient (GRG) method. The optimization includes decision variables such as two photovoltaic (PV) module types (mono-facial and bi-facial) and three different shading ratios for APV systems (21.3%, 25.6%, and 32.0%). The experiment shows that Cheongju-si (F2) in Republic of Korea is the best location with a profit of USD 786.6/m^2/month under the REC policy. In fact, it is located in the center of Republic of Korea (see Figure 7), so it can deliver corn to multiple markets with a low transportation cost of USD 117.45/m^2/month. The total profits of the six candidate APV systems are mainly influenced by the transportation cost to markets and the electricity pricing policies (SMP and REC). This implies that a proper decision should be made to make a profitable APV system. As a result, the proposed decision support system can help farmers and system engineers efficiently construct APV systems taking into account their financial benefits by minimizing the total operating cost of the supply chain network.

In future research, the proposed system will be applied to the supply chain design of APV systems with multiple crop types in a climate change environment. Particularly, an APV system with major crop types (rice, bean, barley) should be considered in order to accurately estimate the impact of APV systems on the existing agricultural supply chain network.

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