Shape Study on a Green Roof Integrated Photovoltaic System for Bi-objective Optimization of Investment Value and CO₂ Emission

Jieli Sui*¹ and Junzo Munemoto²

¹ Doctor, Graduate School of Engineering, Kyoto University, Japan
² Professor, Graduate School of Engineering, Kyoto University, Japan

Abstract

A simulation methodology has been proposed for evaluating the performance of CO₂ Emission (CE) and Investment Value (IV) of the shape of the Green Roof Integrated Photovoltaic System (GRIPVS) of a Wooden Detached House (WDH) using Genetic Algorithm (GA). CE and IV, acting as evaluation indices were studied in this paper. It is an analytical comparative study of searching for an efficient GRIPVS by maximizing IV and minimizing CE simultaneously. Considering the influence of the climate condition on the amount of electric power generation of PVS, three typical locations in Japan are taken into account: Sapporo, Tokyo and Naha. The GRIPVS was treated as a bi-objective problem of combinational optimization. Through numerical GRIPVS’ representation evaluated by GA, the optimal Pareto curve of each location is found. Feasible solutions illustrated that: GRIPVSs with a larger southern roof area and fully covered with PVS perform the best concerning IV than others, and the pitches of GRIPVSs in the given locations should be less than their local optimal solar absorption pitches. To minimize CE, GRIPVSs with larger roof pitches for enlarging the PVS installation area to generate more electric power and larger greening area to absorb more CO₂ are needed.

Keywords: roof shape; CO₂ emission; investment value; green roof integrated photovoltaic system; genetic algorithm

1. Background

Energy saving and mitigation of global warming are the main concern of all industries today. Mass production and mass consumption, as well as the emission of large amounts of harmful gases such as CO₂ into the atmosphere, are the main reasons for the lack of energy and the speedup of global warming. Compared with the criterion year, CO₂ emission (CE) in Japan increased by 7.6% in 2002; actually it has increased by 8% (Satoko Ido 2003) since 1990. From the perspective of energy conservation, solar energy, with its features of non-pollution and sustainability, has been greatly promoted (Fig.1.). By the end of 2005, the total installation of PVS in Japan had reached 1,420,000kW, accounting for 44% of the world market. The goal for solar PVS in Japan is that the total installed capacity reaches 4,800,000kW by 2010². To mitigate CE, the Japanese government has made a succession of proposals and laws concerning environmental protection since the 1990s, such as Action Projects for Preventing Global Warming (1990), Basic Law of the Environment (1999), and Basic Projects of the Environment (1994). Recently the Japanese Government has decided to increase the greening area to achieve 3.9% CE reduction of the targeted total of 6%. Therefore, it is obvious that enlarging the greening area is significant for Japan to realize the goal of decreasing CE.

The architectural industry is near the top concerning energy consumption and waste discharge. As is shown by statistics, energy consumption during construction accounts for 30% to 50% of the total¹. Meanwhile

*Contact Author: Jieli Sui, Doctoral Candidate, Graduate School of Engineering, Kyoto University
Katsura, Nishikyo-ku, Kyoto-City, Kyoto 615-8540 Japan
Tel: +81-75-383-2917 Fax: +81-75-383-2916
E-mail: lljlp2005@yahoo.co.jp
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the proportion of environmental pollution related to the architectural industry is about 34% of the total. In recent years, owing to mass construction, energy consumption has been increasing while the area for greening tends to decrease gradually. In order to save energy during construction, to reduce CE, to enlarge the greening area in the city and to protect the environment, many researchers in this field have been exploring the feasibility of energy-saving and sustainable development from various perspectives.

Compared to other parts, the roof is the main component of building shape. Nowadays, the roof serves as a multi-function component of buildings, and can be designed to fulfill a series of functions simultaneously, such as isolation, electric power generation, as well as green roof planting. These roof functions have great advantages in dealing with problems in the fields of CE reduction and electricity generation, etc. The roof has become an important component of buildings.

The surface area of a roof and surface area distributed in four directions, incline, roof direction, and the ratio area of the installed photovoltaic system, or green roof planted area, are all shape variables of a roof or roof system, the IV and gross CE of roof or roof system will change along with them. This means that efficient roof shape design is necessary from the point of view of CE reduction and low-investment value of users.

In Sui (2005, 2006), the authors carried out studies of the green roof shape and photovoltaic integrated roof shape respectively and the bi-objective optimization of IV and CE is thus proposed.

In this paper, considering that planting of the rooftop and installation of solar panels are adopted as an integrated component to be applied to the same roof for energy-saving, enlarging the greening area and mitigating the heat island phenomenon, the planting of the rooftop and the solar panels perform differently taking society's benefits and the individual's benefits into consideration. To save energy, the installation area of the photovoltaic system should be as large as possible; however, a larger area of installation will also result in increased investment. To reduce Life Cycle CE, the greening area on the roof should be enlarged thus reducing investment, however, electricity investment will increase. This dilemma serves as the inspiration of this study, i.e. how to balance private and social interests in order to fulfill the principle of mutual benefit in integrated roof shape design.

2. Purpose
This paper aims at exploring the bi-objective optimization of IV and CE on green photovoltaic integrated roof shape in cases where conditions are the same as well as the optimal proportions of aspects and areas between PVS and the green lawn in the model. Regarding the influence of sunlight and the climate on the study, three specific regions in Japan are chosen as site locations: Naha (N26.12; E127.21), Tokyo (N35.41; E139.41) and Sapporo (N43.03; E141.21).

3. Past Studies
The following researchers carried out studies on the rooftop lawn and PVS: R. Kumar, etc. (2004). Their paper describes a mathematical model for evaluating the cooling potential of green roof and solar thermal shading in buildings. The following studies are concerned with CO₂ emission reduction by installing a photovoltaic system on existing buildings: Sakai et al. (2003) presented a simple prediction method of photovoltaic system output using a yearly performance ratio by surveying 333 grids connected to a residential photovoltaic system in the western part of Japan. They pointed out that the photovoltaic system installed on a 30 degree roof slope is the best solution. The genetic algorithm method used to study the performance of PVS on buildings is: Yamori et al. (2004) who created optimal arrangement forms of PVS modules united with louvers installed on the building wall using multi-objective Genetic Algorithm. By studying simulation cases, they got understand the clear seasonal factors influencing PVS installation. So far, the author's laboratory has studied a wooden detached house model and found optimum combinations of materials and construction method, which could reduce Life Cycle CO₂, Life Cycle Cost and Life Cycle Waste (Munemoto et al., 2002). In Sui, et al. (2005), the authors proposed a simulation methodology for evaluating the performance of LCCO₂ emission of the roof shape of a wooden detached house using Genetic Algorithm. Annual LCCO₂ emission, acting as an evaluation index was studied in this paper. It was found that a roof with a larger surface area and fully covered with green lawn performs better regarding LCCO₂ emission than a tiled roof under the same conditions. In Sui, et al. (2006), the authors consider the roof integrated photovoltaic system in three locations. Through numerical roof shape representation evaluated by GA, the optimal Pareto curve of each location is found. Little research has been carried out to incorporate PVS with the greening of the roof until recently. Aiming at protecting the environment, an architectural design was made by Oberlin College in northeastern Ohio in the U.S. Half of the energy the building needs is provided by the PVS power-generating equipment on the curved roof with the obliquity of the panel tracing the sun automatically; the other part of the roof is covered by green lawn. This kind of roof acts in absorbing solar power quickly and ameliorating microclimate. The roof of the energy-saving model building of the Chinese Science and Technology Ministry incorporates the green lawn with a solar photovoltaic power-generating and solar water heating system, which provides about 5% to 6% of the energy the whole building needs.
4. Method

4.1 Outline of the Model

In this paper, the authors assume that the green photovoltaic integrated roof is designed for a 128 sq.m. wooden detached house, whose attributes are shown in Table 1. This research is only devoted to finding the optimal shape of the gable roof including the special single slope roof, on which a green lawn is laid and PVS installed, that is, the Green Roof Integrated Photovoltaic System (GRIPVS) (Fig.2.). It is assumed that the direction, materials and thickness are fixed and that the surface area of the roof equals the sum of the greening area and area of PVS. PVS can be installed on the southern roof as well as on the northern roof with the specific installation position being selected by the evaluation system. The specification of the selected SANYO PV panel and the information of the sedums green lawn are shown in Sui. et al. (2006) and Sui. et al. (2005). Based on the conditions assumed above, the performance of the gable roof shape on $CE$ and $IV$ will be influenced by the following three factors: 1) surface area of the roof; 2) area of PVS installed on the roof; 3) area of the green lawn on the roof. The above three factors will change with different gable roof shapes.

4.2 Methods for Obtaining the Changeable Roof Shape

The shape of the gable roof is mainly determined by the following factors, which will be the three variables to be studied in this paper: 1) Ratio of aspect ($Rs0$) 2) Position of the roof ridge ($X_\gamma$) 3) Pitch of the roof slope ($A_r$). The installation position and area ratio of PVS on the roof are selected at random while GRIPVS must meet the following requirements: a) the total output of PVS is no less than the yearly average electricity consumption of a 4-person family, i.e. 4500kWh/y; b) the sum of PVS and greening area equals the roof surface area; c) the total $CE$ of the roof and the $IV$ are in the optimal stage. By modifying the area ratio of PVS and greening and the three variables mentioned above, changeable roof shape will be achieved.

4.3 Evaluation

To find the optimal gable roof shape with minimization of $CE$ and maximization of $IV$ is a bi-objective problem relating to the optimal combination of roof shape and the position and area ratio of the green lawn to the PV panel. GA, as an efficient technique to deal with multi-objective optimization problems will be utilized in this paper. Two parameter parts are involved in the study: one part for recording the variation of roof shape: $Rs0$, $X_\gamma$ and $A_r$, and the other for recording the variation of the area ratio of PVS to the southern and northern roof: $Rs_p$ and $Rn_p$. The area ratio of greening to the southern and northern roof is then $(1- Rs_p)$ and $(1- Rn_p)$ respectively. All variables are encoded as genes to be applied with GA (Table 2.).

5. Evaluation Functions

In this paper, $IV$ and $CE$ acting as two indices are calculated as follows:

$$f_1 = IV(Rs0, X_\gamma, A_r, Rs_p, Rn_p) \rightarrow \text{Max} \quad (\times10^3 \text{yen}) \quad (1)$$

$$f_2 = CE(Rs0, X_\gamma, A_r, Rs_p, Rn_p) \rightarrow \text{Min} \quad (\text{kg-C/m}^2\text{y}) \quad (2)$$

$Rs0$: Ratio of floor aspect ($Rs0=\frac{Ls}{Le}$, $Ls$: Length of the southern side of house floor, $Le$: Length of the eastern side of house floor).

$X_\gamma$: Ratio of $m$ (Horizontal projection distance of roof ridge in $X$-direction)to $Le$.

$A_r$: Pitch of the roof southern slope (degree).

$Rs_p$: Ratio of area percentage of PVS installed on the southern roof slope to the southern roof.

$Rn_p$: Ratio of area percentage of PVS installed on the northern roof slope to the northern roof.

5.1 $CE$ Calculation

$CE$ is the value of total $CO_2$ emission from the green photovoltaic integrated roof. Its value is combined by three parts: one part of $CE$ from materials ($CE_m$) and the rest saved from the PVS output ($CE_p$) as well as green lawn ($CE_g$). The calculation method and formulas are shown as follows:

$$CE = ((CE_m - CE_p)/S) - CE_g \quad (\text{kg-C/m}^2\text{y}) \quad (3)$$

Where,

$$CE_m = CE_i + CE_j + CE_z \quad (\text{kg-C/y}) \quad (4)$$

$$CE_i = \sum_i (\sum_j (N_{Uj} \times U_{ij})) \quad (\text{kg-C/y}) \quad (5)$$

$$CE_j = \sum_j (\sum_i (N_{Uj} \times U_{ij})) \quad (\text{kg-C/y}) \quad (6)$$

$$CE_z = \sum_i (N_{Uz} \times U_{iz}) \quad (\text{kg-C/y}) \quad (7)$$

$$CE_p = (U_{e} - U_{p}) \times E \quad (\text{kg-C/y}) \quad (8)$$

$$CE_g = V_{e} \times S_{e} \times h \quad (9)$$

| Information                                      | Genes | Range    | Levels | Bits |
|--------------------------------------------------|-------|----------|--------|------|
| Ratio of aspect                                  | $Rs0$| 0.25~4.0 | 16     | 4    |
| Ratio of $m$ to $Le$                             | $X_\gamma$| 0.0~1.0 | 16     | 4    |
| Pitch of the southern roof (degree)              | $A_r$| 5~80     | 16     | 4    |
| Area ratio of PVS installed on the southern roof slope | $Rs_p$| 0.0~1.0 | 16     | 4    |
| Area ratio of PVS installed on the northern roof slope | $Rn_p$| 0.0~1.0 | 16     | 4    |
Where,

$CE_g$: Total CO$_2$ absorption by the green lawn (kg-C /m$^2$.y)

$V_g$: Velocity of photosynthesis

$S_g$: Active area of green roof (m$^2$)

$h$: Irradiation time (Fig.3.)

$CE_m$: CO$_2$ emission from building materials (kg-C /y)

$CE_p$: CO$_2$ saved by PVS output (kg-C /y)

$CE_g$: CO$_2$ absorptions by green lawn

$S$: Building floor area (m$^2$)

$CE$: CO$_2$ emission from building (kg-C /y)

$CE_m$: CO$_2$ emission from producing materials (kg-C /y)

$CE_f$: CO$_2$ emission from producing framework (kg-C /y)

$i$: Kinds of material

$j$: Kinds of part

$N_i$: Amount of materials used (kg)

$N_C$: Amount of machineries used (kW.h)

$U_{i0}$: CO$_2$ units of materials (kg-C /kW.h)

$U_{iP}$: CO$_2$ units of parts (kg-C /kW.h)

$U_C$: CO$_2$ units of machineries (kg-C /kW.h)

$U_P$: CO$_2$ unit of PVS production (kg-C /kW.h)

$U_o$: 0.02 kg-C /kW.h

$E$: Yearly output of PVS (kW.h/y)

The details of $CE_m$ can be found in Yada (1999).

As shown in Fig.4., if Solar Zenith Angle ($h_s$) is no less than $A_n$, the solar photovoltaic panel can be installed on the northern roof and the green lawn at the same side can also have photosynthesis. Otherwise, being in a poor light, the northern roof is not suitable for PVS installation of the solar photovoltaic panels. The data utilized to calculate solar radiation falling on different pitches of roof in three locations are shown in Figs.5. ~ 6. Velocity of photosynthesis is 4.5 mgCO$_2$/dm$^2$.h.

5.2 IV Calculation

To calculate IV, the following sub-values are considered:

(i) Cost by PVS Installation ($CI$)

(ii) Cost by Greenlawn ($CG$)

(iii) Cost Saving by PVS Output ($CSO$)

(iv) Cost Saving by National Subsidy ($CSN$)

(v) Cost by Roof Materials used ($CRM$)

The value of IV can be calculated by the following formulas:

$$IV = CSO + CSN - CI - CRM - CG \ (\times 10^4 \ yen) \quad (10)$$
Where,

\[ CI = E_p \times C_0 \quad (\times 10^4 \text{ yen}) \]  \hspace{1cm} (11)

\[ CSO = \sum_{k=1}^{24} C_p \quad (\times 10^4 \text{ yen}) \]  \hspace{1cm} (12)

\[ C_p = E_p \times P_e \quad (\times 10^4 \text{ yen}) \]  \hspace{1cm} (13)

\[ E_y = E_d \times S_{pys} \times D_s \quad (\text{kWh}) \]  \hspace{1cm} (14)

\[ E_d = E_y \times r \quad (\text{kWh/m}^2) \]  \hspace{1cm} (15)

\[ CSN = E_y \times N_i \quad (\times 10^4 \text{ yen}) \]  \hspace{1cm} (16)

\[ CRM = \sum_{i=1}^{n} S_{mi} \times Cm_i \quad (\times 10^4 \text{ yen}) \]  \hspace{1cm} (17)

\[ CG = C_s \times S_g \quad (\times 10^4 \text{ yen}) \]  \hspace{1cm} (18)

\[ \text{Each basic cost can be found in Sui, J. L (2006).} \]

6. Simulation

To solve this bi-objective problem and find its preferred solution, the single optimization set in each location can be determined in the first stage.

6.1 Single Objective in Three Locations

6.1.1 Optimal Solutions of \( IV \)

The initial conditions of GA operations are: Total Trials = 10,000; Population Size = 200; Crossover Rate = 0.6; Mutation Rate = 0.001. The method of crossover utilized in this paper is the same as that proposed in Genesis Version 5.0 (John, 1990).

Table 3. shows the optimal solutions of \( IV \) in Sapporo, Tokyo and Naha after \( 1 \times 10^4 \) trails by applying GA. A, B and C are optimal solutions of \( IV \) in each location respectively. The reason lies in that the cost of PVS is much more expensive than that of tiles or sedum turf. Therefore, with respect to \( IV \), minimization can be gained when the installation area of PVS is as small as possible, while its power generation is as large as possible. Based on the above analysis, the following results can be gained in terms of roof pitch and the installation area of PVS: 1) The pitch of the southern roof in each location is close to the local optimal angle of PVS power generation. Meanwhile, at this angle, roof shape must satisfy the requirement of the power generated by PVS. That is, the need of the yearly electricity consumption of a 4-person family. 2) As soon as the proposed installation area on the southern roof satisfies yearly electricity generation for a 4-people family, the other part of the roof should become northern roof slope, in order to allow the roof to have the smallest roof area and volume to reduce Life Cycle CO\(_2\) emission and \( IV \). 3) The installation area of PVS on the northern slope equals 0, \( R_p = 1 \), \( R_n = 0 \). As the author has assumed that the total roof area equals gross area of green roof area and the installed photovoltaic system area, \( R_p = 1 \) and \( R_n = 0 \), the area with the solar PV panels installed on the northern roof slope is 0, and the planted green.

Fig.5. Annual Average Amount of Irradiation in Four Directions of Three Locations

*Source: Solar Architecture Design Guider Book (p. 123, p. 125, p. 129)
roof surface area of the southern roof is 0. The reason lies in the fact that: to reduce investment in materials and air-conditioning, the pitch of the slope should be as small as possible to achieve minimization of the surface area and volume of the roof, as roof pitch can minimize the materials used as well as the indoor and outdoor thermal exchange, while volume can decrease the ventilation times of the air-conditioning. As soon as PVS installed on the southern roof meets the need of the yearly electricity consumption of a 4-person family, the northern roof should be utilized so as to reduce the materials used for the roof and to decrease the investment.

It will take about 29.5 years to reclaim the investment in PVS on the southern roof when the pitch is optimal. As to the northern roofs in three locations, since the generation efficiency of solar PVS on the northern roof is lower than that of the southern roof, it will be much more uneconomical for the residents to install PVS on the northern roof taking the profits they can gain from subsidy and their investment into consideration. Therefore, although northern roofs can also absorb sunlight at certain times of the day (when $h_s > A_n$), none of them in the three locations is chosen for PVS installation.

### 6.1.2 Optimal Solutions of CE

The optimal solutions of CE in three locations are worked out after $1 \times 10^4$ trails by applying GA. As is shown in Table 5., D, E and F are the optimal solutions in each location respectively, which show: 1) The maximum height (6m) is chosen as much as possible for all roofs, as this allows the largest installation of the PVS system. 2) The coverage of PVS installed on the southern roof is confined to the exact area within which the power generation of PVS can meet the need of the yearly average electricity consumption of a 4-person family. The rest of the surface area is used for laying green lawn on the roof.

Although the photovoltaic system can generate electrical power, its producing process and the materials used can still emit CO$_2$ as well. However, sedum can absorb CO$_2$ through photosynthesis. Therefore, to minimize the life cycle of CO$_2$ emission of the roof, the area of the green roof photovoltaic system should be as large as possible. However, to meet the need of the electricity consumption, the photovoltaic system must be installed on the roof and the installation angle should be adjusted to or be close to the local ideal angle of photovoltaic system power-generation so that it can minimize the installment area of PVS (Tokyo: 32.7 degrees; Naha: 17.9 degrees; Sapporo: 35.3 degrees). A trade-off between pitch area of PVS installation and maximization of the sedum area, and the roof pitch of the optimal solutions in three locations is the result of balancing the above two factors. Moreover, this angle is smaller than the Solar Zenith Angle in three locations (Fig.6.), which means that the northern roof of the optimal solution is in the sunlight, and can provide the condition for photosynthesis.

### 6.2 Bi-objective Optimization of IV and CE

The optimization of IV and CE is calculated in section 6.1. It is easy to observe that, to optimize CE and IV of a GRIPVS simultaneously, there exist a set of trade-off solutions called Pareto-optimal solutions. After applying GA with the initial and termination...
conditions as: Total trails =10,000, Population Size =200, Crossover Rate =0.5, Mutation Rate =0.05. The outcomes represented by using graphical representation of the Pareto-optimal curves are shown in Figs.7. ~ 9. All cases on the optimal curve are feasible solutions.

7. Results and Discussions
The shape of GRIPVS is restricted by the shape coefficient, information of greening and performance of PVS. It is a product of the optimal grouping of the three factors mentioned above, whether in the exploration of single objective optimization or bi-objective optimization. To IV, its value is mainly decided by two items: area of PVS installation and amount of its electric power generation. The two items have a tradeoff on IV value: to minimize IV, the area of PVS should be as small as possible, but to generate enough electric power, a larger PVS installed area is needed. At the same time other tradeoffs lie in A_r, X_ and Ls values selection. The solutions found in Tables 3. and 5. are inevitable results when various aspects are suitable for CE. Concerning CE, both a larger area of PVS installation and green lawn planted area are efficient in reducing CE from a building. Comparing the performance of PVS and green lawn, the green lawn itself not only does not emit CO_2, but also absorbs CO_2 by photosynthesis. It is more efficient in cutting the amount of CE than PVS. Regarding integrated roof shape, the PVS installed area is made larger in order to generate enough power while reducing CO_2. Since the performance of green lawn is better than PVS, apart from the area of PVS, the rest of the roof surface area is completely covered with green. For bi-objective optimization, feasible solutions regarding the Pareto curve are suitable for minimizing CE and IV values simultaneously.

8. Conclusions
In this chapter, the authors made clear the optimal shape of a green roof integrated photovoltaic system. When IV minimization only is taken into consideration, roof shape fulfills the goal of maximizing solar power generation and the pitch of the southern roof is close to the local optimal pitch for photovoltaic system power-generation in each location: A_r (T) =15 degrees; A_r (S) =5 degrees; A_r (N) =25 degrees; when the southern roof is totally covered by PVS, PVS installation on the northern roof is 0. While in case

| Indices | Locations | Sapporo | Tokyo | Naha |
|---|---|---|---|---|
| Solution Label | D | E | F |
| Roof Shape | | | |
| CE | 3.75 | 3.75 | 3.75 |
| Rsθ | 55 | 55 | 55 |
| A_r | 0.51 | 0.6 | 0.54 |
| X_ | 0.9 | 0.9 | 0.9 |
| Rn_p | 0 | 0 | 0 |
| Yearly Energy Power Generation (kWh) | 4522 | 5601 | 4713 |
| CE (kg-C/m²·y) | -90.25 | -103.41 | -112.7 |

Table 5. Details of CE Optimal Solution in Three Locations

Fig.6. Solar Altitude in Three Locations
of CE minimization, the roof shape must satisfy the requirement of maximizing the area of sedum laid on the roof and that of receiving sunshine so as to absorb as much CO$_2$ as possible through photosynthesis. All slopes of the roof on the northern side are fully covered with green.

The author found that all of the Pareto-optimal solutions in each location, on each Pareto-optimal curve are efficient in optimizing Life Cycle CO$_2$ emission as well as IV of a green roof integrated photovoltaic system.

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