Field Study and Sensitive Analysis of PV System by Multiple regression method

Qingrong Liu*, 1 Yuji Ryu2, Weijun Gao3 and Yingjun Ruan4

1 Ph.D candidates, Faculty of Environment Engineering, The University of Kitakyushu, Japan
2 Professor, Faculty of Environment Engineering, The University of Kitakyushu, Japan
3 Associate Professor, Faculty of Environment Engineering, The University of Kitakyushu, Japan
4 Ph.D candidates, Faculty of Environment Engineering, The University of Kitakyushu, Japan

Abstract
In this paper, the PV system in Kitakyushu Science and Research Park (KSRP) in Japan has been introduced. By analyzing the recorded data in 2002, the power generation result has been evaluated. On the basis of this, comprehensive module conversion efficiency for two different photovoltaic cells, single-crystal and multi-crystal, has been discussed. Furthermore, the factors influencing power generation amount and module conversion efficiency have been analyzed by using the single regression and the multiple regression method. And the environment contribution also has been evaluated.

The results can be summarized as follows: 1) Although the PV system has been responsibility for little part of power consumption at KSRP, it has high reliability and stable running situation. 2) The average hourly module conversion efficiency is 10.6%, about 74.1% of comprehensive conversion efficiency with 14.3%. 3) Irradiance is the most important influence factor on power output of PV system and almost in direct proportion with power generation amount. The influence from air temperature is important than the one from wind velocity on power output, but the influence from them are both very small. 4) PV system has contributed to reduce environmental load greatly.

Keywords: comprehensive module conversion efficient; multiple regression method; irradiance; air temperature; wind velocity

1. Introduction
In 21st century, sustaining economical development and global environmental protection are the important themes of human being. In order to prevent from globe greenhouse, the important measure is to reduce the greenhouse gas emissions. Therefore, the searching for a substitute for fossil energy sources has increased the interest in photovoltaic system as a long-term, inexhaustible, environmentally friendly and reliable energy technology. The main advantages of PV system include: reasonable conversion efficiencies (6-18%), efficiently integrated in buildings, high reliability and long lifetime, low maintenance cost and low environmental load. PV system is proving to be an effective option in helping countries to meet their CO₂ reduction and renewable energy generation targets. On these backgrounds, in the last five years, the production of photovoltaic cells has increased steadily by an average of 30% per year. In 2002, the total PV production capacity in the world has reached 520.15MW, among of which Japan shared of 274MW, more than 52%. In Japan, the commitment under the Kyoto Protocol to reduce its greenhouse gas emissions by 6% at the end of 2010, compared to the 1990 level, is an argument for the accelerated development and research of PV system.

In this paper, the PV system at Kitakyushu Science and Research Park (KSPR) in Japan has been introduced. By analyzing the recorded data in 2002, field study and sensitive analysis of PV system by multiple regression method have been carried out. And the environment contribution also has been evaluated.

2. The research system
Fig.1 is the flow of the power supply system at KSRP. In this system, the fuel cell (200kW), gas engine (160kW) and PV system have been installed to generate electricity servicing the consumer at KSRP, and the insufficiency electricity for demand is purchased from electric power company [1]. Table 1 is the performance of this PV system. Fig.2 is the photograph of PV array. The PV system has been installed with 156 double-sides glass single-crystal silicon solar modules in the eaves of building and 912 multi-crystal silicone solar modules on the tilting table of the roof. The total capacity of this PV system is 153kW, including 21kW from single-crystal and 132kW from multi-crystal silicon solar cell. As Table 1 shown, the module conversion efficiencies (Rated conversion efficiency is measured at 25°C) for the single-crystal and multi-crystals silicon solar cell are 7.2% and 13.3%, respectively. In this case, because the
ineffective module area being made from the light-passed glass is about 50% of the total module area, single-crystal has smaller module conversion efficiency than multi-crystal. The module's effective areas generating power are 1.008 m² for single-crystal and 1.006 m² for multi-crystal, and so the actual module conversion efficiency for crystal silicon solar cell can be described as the following expression:

\[
\text{Module Conversion Efficiency} = \frac{\text{Module Maximum Output}}{\text{Effective Area Generating Power}}
\]  

(1)

According to the above expression and the effective areas generating power for single-crystal and multi-crystal module, their actual module conversion efficiencies are 13.4% and 14.4%, respectively.

3. The research method

Firstly, power generation amount and comprehensive module conversion efficiency of PV system have been discussed by using the running data recorded by the energy center at KSRP during 2002. In this paper, respectively, comprehensive module conversion efficiency is described as the overall evaluation index for the single-crystal silicon solar cell and multi-crystal silicon solar cell. It was defined by the following expression:

\[
\eta' = \frac{\eta_1 \times F_1 + \eta_2 \times F_2}{F_1 + F_2}
\]

(2)

Where,
- \( F_1 \): area of the single-crystal silicon solar cells m²;
- \( F_2 \): area of the multi-crystal silicon solar cells m²;
- \( \eta_1 \): comprehensive module conversion efficiency %;
- \( \eta_1 \): module conversion efficiency of single-crystal silicon solar cell %;
- \( \eta_2 \): module conversion efficiency of multi-crystal silicon solar cell %;

The running module conversion efficiency of this system can be calculated by using the following expression and the measured data:

\[
\eta = \frac{W \times 100}{I_1 \times F_1 + I_2 \times F_2}
\]

(3)

Where,
- \( \eta \): module conversion efficiency %;
- \( I_1 \): horizontal irradiance kW/m²;
- \( I_2 \): slope irradiance kW/m²;
- \( W \): power generation amount kW;

Basing on the measured data, the influence degrees on the system power output from irradiance, air temperature, and wind velocity have been studied by
using the single regression and multiple regression method.

As for the environment contribution of PV system, the CO₂ emissions of this PV system have been evaluated. According to the Central Research Institute of Electric Power Industry of Japan report, the Original units of CO₂ emissions for various power plant systems are shown in Table 2[4]. The value of this table, is gained with expected lifetimes of power plant system is 30 years.

4. Running results and conversion efficiency analysis

4.1 Running results

In this system, field data was recorded by all kinds of meters every one hour. The running results of this PV system have been summarized as following described.

The monthly power generation amount and the received irradiance of PV system were shown in Fig.3. As Fig.3 shown, the power generation amount and the irradiance are almost fluctuating synchronism. Because June had the largest irradiance, correspondingly, it generated largest monthly amount of power generation with 17.1GWh, about 11% of the total power generation amount of PV system in 2002. The smallest amount of power generation occurred in December with about 6.2GWh, accounting for about 4% of total annual power generation.

The total power generation amount in 2002 was 152.91GWh, and the total of summer (June, July, and Aug.) reached 47.4GWh, about 31% of the annual power generation, followed by spring (Mar., Apr., and May) with 42.8GWh (about 28%), autumn (Sep., Oct., Nov.) with 38.2GWh (about 25%) and winter (Dec., Jan., Feb.) with 24.5GWh (about 16%).

Figure.4 displayed the hourly power generation amount of the day, which had the largest daily power generation amount in every month. As Fig.4 shown, the amount of power generation from 11:00 o’clock to 14:00 o’clock at any day shared about 50~70% of total daily power generation amount. Every day the maximum hourly power generation amount almost occurs around 12:00 o’clock. Among these days, the amount of power generation at 12:00 on August 21st was largest with 114kW and the value at 12:00 on December 1st was smallest with 81kW, and their difference was 33kW. However, in 2002, the maximum value of hourly power generation amount emerged at 11:00 o’clock on April 25th and was recorded as 125kW, about 81.7% of PV system capacity with 153kW.

Percentage of various power supplies for KSRP from PV system, fuel cell, gas engine, and utility electricity in 2002 were shown in Fig.5. From this figure, it can be found that the most important power supply resource was utility electricity with 49.4% of annual power consumption, followed by gas engine with 34.1%, fuel cell with 13.2% and PV system with 3.3%.

4.2 Analysis of module conversion efficiency

According to expression (3), hourly module conversion efficiency can be calculated. The accumulation curve of the hourly module conversion efficiency of this PV system was shown in Fig.6. From the data, it was 2303 hours that the hourly module conversion efficiency was larger than 10% throughout the year, accounting for 79.7% of overall power generation hours. Considered the hours which conversion efficiency exceeded 10%, it was the most with 633 hours in summer, followed by 593 hours in autumn, 579 hours in spring, and 298 hours in winter. The average of hourly module conversion efficiency in 2002 was 10.6%, about 74.1% of comprehensive conversion efficiency with 14.3%, which was calculated by using the expression (2) and the module conversion efficiency value of single-crystal (13.4%) and multi-
crystal (14.4%) silicon solar cell calculated by expression (1). The comprehensive conversion efficiency was displayed as the straight line in Fig.7. And the daily average module conversion efficiency calculated by expression (3) also was illustrated as curved line shown in Fig.7. The maximum value of the daily average conversion efficiency was 13.2% and the minimum value was 5.2%. The average value of daily conversion efficiency for 2002 was 10.9%. From this figure, it can be concluded that the changing range of daily average conversion efficiency was very large.

5. Regression analysis
As the foregoing paragraph described, the changing range of daily average module conversion efficiency was very large, the reason is that it being influenced with irradiance intensity, angle of incidence, air temperature, wind velocity, rain, etc. Generally, irradiance intensity is the most important influence factor among these factors. On the other hand, the output of solar cell declines with the rise of cell temperature. The cell temperature is generally considered as an inevitable factor when discussing the characteristics of relationship between power output of solar cell and external influence factors [3]. However, since cell temperature was not recorded, the influences of irradiance intensity, air temperature and wind velocity were analyzed in this paper.

5.1 Single regression analysis
In this paper, single regression method was used to analyze the relation between power generation amount and irradiance. The results are shown in Fig.8. From the results, it can be concluded that:

1) Considered difference seasons, it is obvious that the irradiance was larger in summer than that other seasons. The hourly average irradiance for summer is 526.9kW and 300.9kW for winter. And it is almost the same in spring and autumn, about 470kW. It is about 380 hours that the hourly irradiance is larger than 500kW in summer and the value is the half of summer with about 176 hours in winter.

2) The amount of power generation is almost directly proportion to irradiance. However, the inclinations of regression line for various seasons are somehow difference. In the same irradiance amount, spring generated more power than other seasons. For example, in the condition of 1000 kW irradiance, the amounts of power generation in spring is 115kW, followed by winter (112kW), autumn (107kW) and summer (104kW). The reason may be that the angle of incidence is smaller and the intensity of sunlight is more larger in spring than other seasons and also the calculated cell temperature is more close to 25˚C which is the
measurement condition when the rated performance of solar module is measured. The cell temperature was calculated by the equation put forward in the reference [2]. Moreover, the difference of the inclination is caused by some environmental factors, such as air temperature, wind velocity and the angle of incidence, and so on.

5.2 Multiple regression analysis
In this paper, June 21st was selected as the representative day to analyze the characteristics of timely change of power generation amount, irradiance, air temperature, and wind velocity. And it is shown in Fig. 9. From this figure, the power generation amount is very closely associated with irradiance; but the influence degree from air temperature and wind velocity seems very little and not very clearly. Therefore, the multiple regression method was selected to analyze the relation between irradiance, air temperature and wind velocity with power generation amount.

During analysis, irradiance, air temperature, and wind velocity was considered as independent variables and power generation amount was considered as dependent variable.

The results are shown in Table 3. From this table, the results can be concluded as follows:
1) In any season, the standard partial regression coefficient of irradiance is larger than 0.99. Therefore, Irradiance is considered as the most important influence factor to the amount of power generation.

2) It is proved that the relation between air temperature and the amount of power generation serves as negative correlation. That is to say, the air temperature rise leads to the rise of cell temperature, therefore, module conversion efficiency decrease. On the other hand, it is found that the standard partial regression coefficient of air temperature in summer is largest.

![Fig. 9. The fluctuation of irradiance, air temperature, wind velocity and power generation amount of June 21st](Image)

Table 3. The result of multiple regression analysis

|                | Explanation variants | Partial regression coefficient | Standard partial regression coefficient | Judgment mark | Standard error | partial correlation coefficient | Single correlation coefficient |
|----------------|----------------------|-------------------------------|----------------------------------------|---------------|---------------|---------------------------------|-------------------------------|
| Winter         | Irradiance           | 0.1140                        | 0.9968                                 | [**]          | 0.0004        | 0.9967                          | 0.9967                        |
|                | Air temperature      | -0.0165                       | -0.0019                                | [ ]           | 0.0284        | -0.0222                         | 0.0727                        |
|                | Wind velocity        | 0.0356                        | 0.0028                                 | [ ]           | 0.0413        | 0.0327                          | 0.0383                        |
|                | Constant             | -1.1295                       |                                        |               | 0.3447        |                                 |                               |
| Spring         | Irradiance           | 0.1027                        | 0.9728                                 | [**]          | 0.0011        | 0.9618                          | 0.9563                        |
|                | Air temperature      | -0.0565                       | -0.1125                                | [**]          | 0.0778        | -0.3772                         | 0.0382                        |
|                | Wind velocity        | 0.1349                        | 0.0078                                 | [ ]           | 0.1762        | 0.0283                          | 0.1568                        |
|                | Constant             | 16.3710                       |                                        |               | 1.5230        |                                 |                               |
| Summer         | Irradiance           | 0.1009                        | 0.9986                                 | [**]          | 0.0006        | 0.9886                          | 0.9882                        |
|                | Air temperature      | -0.3965                       | -0.0419                                | [**]          | 0.0534        | -0.2654                         | 0.1925                        |
|                | Wind velocity        | -0.1101                       | -0.0063                                | [ ]           | 0.0965        | -0.0422                         | 0.0785                        |
|                | Constant             | 13.7090                       |                                        |               | 1.4535        |                                 |                               |
| Autumn         | Irradiance           | 0.1973                        | 0.9983                                 | [**]          | 0.0006        | 0.9889                          | 0.9900                        |
|                | Air temperature      | -0.1210                       | -0.0242                                | [**]          | 0.0283        | -0.1580                         | 0.3349                        |
|                | Wind velocity        | 0.1222                        | 0.0072                                 | [ ]           | 0.0896        | 0.0509                          | 0.0756                        |
|                | Constant             | 1.9835                        |                                        |               | 0.6198        |                                 |                               |
| Year           | Irradiance           | 0.1056                        | 0.9945                                 | [**]          | 0.0004        | 0.9806                          | 0.9818                        |
|                | Air temperature      | -0.1550                       | -0.0383                                | [**]          | 0.0151        | -0.1876                         | 0.2937                        |
|                | Wind velocity        | 0.0266                        | 0.0016                                 | [ ]           | 0.0577        | 0.0086                          | 0.0624                        |
|                | Constant             | 3.4312                        |                                        |               | 0.3535        |                                 |                               |

Note: [**] The independent variables is an important explanation variable to the dependent variable;
[*] The independent variables is an relative important explanation variable to the dependent variable;
[ ] The independent variables is not suitable as an explanation variable to the dependent variable.
with only -0.04, which shows the air temperature influence on the amount of power generation is comparatively small.

3) Generally, the cell temperature is influenced by wind velocity, and the influence of wind velocity has been included in the expression of relations of the cell temperature and output characteristic of solar cell in other research documents. However, in this paper, it is found that the effect of wind velocity on the amount of power generation is very small from the multiple regression analysis.

In sum, the most important factor of power generation is irradiance, followed air temperature and wind velocity with very small effect.

6. Environment analysis

CO₂ emission in power generation is mainly release by two paths: one is fuel burning and the other occurs in the progress of the equipment manufacture and employment. Compared with oil fired power plant, coal fired power plant, LNG fired power Plant and LNG combined fired power plant, the CO₂ emission of PV system only comes from the manufacture and disposal of equipment and employment progress. In addition, CO₂ emissions for other four power plant systems mainly come from fuel burning about 75%~95% of all emissions. According to the original unit of CO₂ displayed in table 2, the CO₂ emissions of other normal generation plant system and PV system at the power generation amount of PV system in 2002 at KSRP can be calculated and were shown in Fig.10. Compared with oil Fired Power Plant, coal fired power plant, LNG fired power plant, and LNG combine fired power plant, the CO₂ emission discharge curtailment of PV system were 140.98Ton, 105.35Ton, 84.86Ton, and 71.25Ton, respectively. Therefore, it can be concluded that PV systems can contribute significantly to the mitigation of CO₂ emissions.

7. Conclusion

In this paper, the PV system at Kitakyushu Science and Research Park (KSRP) in Japan has been introduced. By analyzing the recorded data of the system in 2002, the power generation amount has been gained. On the basis of this, comprehensive module conversion efficiency has been discussed. Furthermore, the comprehensive factors influencing power generation amount and module conversion efficiency were analyzed. The following conclusions were acquired.

1) The total power generation amount in summer was larger than other seasons, and the maximum month power generation (June) was about 3 times the minimum month power generation (December).

2) The average hourly module conversion efficiency was 10.6%, about 74.1% of comprehensive conversion efficiency.

3) Irradiance is the most important influence factor of the power generation amount and almost in direct proportion with power generation amount. The influence from air temperature is important than the one from wind velocity on power generation, but the influence from them are both very small.

4) Compared with other power plant systems, the CO₂ emissions of PV system are remarkably small. Therefore, PV system has contributed to reduce environmental load greatly.

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