Dissertation for the Doctor of Philosophy

A study on the Analysis of Solar Irradiation and Floating Photovoltaic Power Generation on the Dam Surface

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February 2022

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A Dissertation submitted to the graduate school of Pukyong National University in partial fulfillment of the requirements for the degree of Doctor of Philosophy

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February 2022

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이 논문을 장용해의 공학박사 학위논문으로 인준함

2022년 2월 25일

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List of Abbreviations

EPP	:	Electric power production
PV	:	Photovoltaics
SAM	:	System Advisor Model
HD0	:	Irradiance data measured per hour
HD1	:	Hourly irradiation data converted from monthly cumulative irradiation data using the sunshine time mean method
HD2	:	Hourly irradiance data converted from monthly cumulative irradiance data using SOLPOS algorithm
HD3	:	Hourly irradiance data converted from monthly cumulative irradiance data using Duffie and Beckman algorithm
R0	:	Monthly power output measurement from PV systems using HD0 (TMY data)
R1	:	Estimated monthly power output from PV systems using HD1 (Sunshine hour mean)
R2	:	Estimated monthly power output from PV systems using HD2 (SOLPIS)
R3	:	Estimated monthly power output from PV systems using HD3 (Duffie and Beckman)
RMSE	:	Root mean square error
MBE	:	Mean bias error
MAPE	:	Mean absolute percentage error

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Abstract

A Study on the Analysis of Solar Radiation and Water Solar Power Generation in Dam Water Surface

The hourly irradiance value from the sun is essential data for reasonable estimation of power generation (EPP) in PV systems. Generally, data extracted from weather satellites are available to collect monthly radiation data, but hourly radiation data is not available efficiently in developing countries or rural areas that require PV systems. To provide such hourly radiation data, this work utilizes three methods (Academic Mean Method, SOLPOS Algorithm Method, and Duffie and Beckman Algorithm Method) to transform monthly irradiance data into hourly irradiance data. The monthly cumulative irradiance data used in this study utilized field data acquired by the National Renewable Energy Institute.

The hourly irradiance data derived from the above three methods were compared and analyzed with the actual solar irradiance values measured from the local solar radiation sensors. In addition, hourly irradiance data is inputted into the System Advisor Model program to estimate the EPP values produced in PV systems and compare and analyze the actual generation yield values. This paper shows that water solar power can be predicted closest to real value by transforming solar radiation values using SOLPOS algorithmic method.

Ⅰ. Introduction

Recently, the government has been pushing for energy conversion through renewable energy expansion. The renewable energy 3020 plan, which aims to make the share of renewable energy generation 20% by 2030, is planning to switch to safe and clean renewable energy through the nuclear-free policy. According to the plan, more than 95% of the newly installed new power generation facilities will supply clean energy such as solar power and wind power.

Since 70% of Korea's land consists of mountainous land, it is not easy to build solar power plants using flat land. In addition, if a solar power plant is built using mountainous land, the terrain may be transformed and the natural environment may be damaged. For these reasons, water photovoltaic power generation using dam water surface space has been actively underway recently, and this type of power plant is expected to greatly resolve the geographical disadvantage of developing renewable energy in Korea.

Previously, there was no solar radiation data at the surface of the dam, so it was difficult to accurately predict water solar power generation due to indirect use of solar radiation on land. In this paper, we will analyze the amount of solar radiation at the surface of 16 emergency water source dams in Korea and study the potential for water solar power generation based on the results. Through this, it is intended to predict the potential for power generation due to the construction of water solar power plants using dam water surface and to enable efficient and economical development of renewable energy.

After analyzing the annual solar radiation in 16 emergency water dams in Korea, the accumulated solar radiation values in the emergency water dam area managed by the Korea Meteorological Resource Center are converted to Sunshine hours, the SOLPOS algorithm, the Duffie and Beckman algorithm. By applying the time unit solar radiation value converted from accumulated monthly solar radiation and actual time unit solar radiation value to the System Advisor Model program, water solar power generation is predicted and compared to actual power generation.

This paper can be summarized as follows.

Chapter 1 summarizes PV system prediction models, solar radiation observations, and EPP prediction methods.

Chapter 2 summarizes solar radiation measurement and analysis methods.

Chapter 3 studies solar radiation transformation and error analysis.

Chapter 4 studies the amount of PV system generation in water photovoltaic power generation in Korea.

Chapter 5 summarizes the results obtained in this paper.

Ⅱ. PV System Prediction Model

1. PV System Prediction Model

In order to reasonably predict electricity generation(EPP) using PV systems on land or water, data on solar radiation per hour in the region is essential. Solar radiation data in Korea can be used for monthly average solar radiation data provided by weather observation satellites or the National Institute of Meteorological Science Meteorological Resources Center.

In general, solar radiation measurement sensors can be operated in the area where PV systems will be installed to estimate solar power near the most actual value, but this is generally difficult to realize due to the time limitations of solar power projects.

Many researchers have previously developed models and software that can be utilized to predict EPPs from PV systems [1 - 9]. It is divided into two categories, depending on the type of solar radiation data entered into the programs and models that predict these EPPs. The first is to predict the EPP using time-unit solar radiation and the other type is to predict the EPP using monthly solar radiation averages. PV-SOL [10], Polysun [11], INSEL [12] and RETScreen[13] simulates EPP using solar radiation mean value data every month.

The System Advisor Model (SAM) [14], PVWats [15], and PVsyst[16] use hourly solar radiation data. Using solar radiation data per hour is preferred to estimate PV system-based EPP.

This is because EPP results extracted from time-unit data are more accurate and reliable than monthly average data when both monthly solar radiation average and hourly solar radiation values are available.

In addition, the use of solar radiation data in time units allows us to consider both the prediction of EPPs per hour during the day in PV systems and the system load, which makes the economic evaluation process for PV projects easier.

2. Solar radiation

The EnergyPlus website[17] operated by the National Renewable Energy Institute (NREL) provides weather observation data, including solar radiation data per hour, to major locations around the world. Based on these hourly data, SAM, PVWats, and PVsyst software mentioned previously can predict the hourly EPP produced by PV systems. Since most of EnergyPlus' solar solar radiation observation sites are distributed in the United States, China, and European countries, it is difficult to obtain abundant data in developing countries such as Africa, South America, and Southeast Asia.

NASA provides long-term observation data on solar radiation per month by analyzing numerous satellite images, including world meteorological information[18]. Therefore, countries such as developing countries which do not have solar radiation stations can obtain monthly average (or cumulative) solar radiation data to predict the EPP of PV systems.

In Korea, solar radiation data per hour is only available in several major metropolitan cities equipped with an observation system, and in other regions, solar energy resource maps provided by the National Institute of Meteorological Science can provide data on average solar radiation per month.

If monthly solar radiation data can be converted to solar radiation data per hour within an appropriate confidence range, appropriate software can be selected to accurately predict EPPs per hour or total monthly EPPs. It will also help to assess the feasibility of PV projects in developing countries, such as those without solar radiation observation systems.

Earlier, various researchers have studied solar energy estimation and utilizable solar energy prediction methods per hour. Goh and Tan studied probabilistic modeling for estimating solar radiation per hour[19], and Perez studied how to predict solar radiation using either the Global Horizontal Irradiance or Diffuse Horizontal Irradiance(DHI) values[20–22]. Aguiar analyzed the relationship between the daily clarity index(CI) and the hourly CI and analyzed the statistical hourly solar radiation[23].

Santamouris analyzed the solar radiation measurement model through cloud data analysis[24], and Zhang and Huang studied solar radiation estimation methods considering geopolitical information including temperature, humidity, wind speed, and cloud volume[25]. Most previous works have focused on developing simple models for estimating hourly solar radiation from previously observed solar radiation data and have not paid attention to the possibility of applying these models to universally diverse regions.

Although studies have been conducted to predict EPPs in PV systems by dividing monthly or annual solar radiation data by average values[26-28], these methods do not accurately measure solar radiation, which makes it impossible to predict the EPPs required by PV projects. Furthermore, no studies have been conducted on the correlation between estimated solar radiation data by time, actually observed solar radiation data, and the actual amount of power produced from PV systems.

3. Measurement target and solar irradiance meter

In this study, the annual amount of solar radiation on the surface of the water was measured in 16 emergency water dams in Korea as shown in [Table 2-1].

[Table 2-1] Solar radiation measurement site

Site	Address	Latitude	Longitude
Soyang Dam	Wolgok-ri, Dong-myeon, Chuncheon-si, Gangwon-do	37.9	127.8
Chungju Dam	Jongmin-dong, Chungju-si, Chungbuk	37	128.1
Yimha Dam	Imha-ri, Andong-si, Gyeongsangbuk-do	36.5	128.8
Hapcheon Dam	Sangcheon-ri, Daebyeong-myeon, Hapcheon-gun, Gyeongsangnam-do	35.5	128
Daecheong Dam	Miho-dong, Daedeok-gu, Daejeon	36.3	127.5
Yongdam Dam	Wolgye-ri, Yongdam-myeon, Jinan-gun, Jeollabuk-do	35.8	127.5
Seomjin-gang Dam	Yongsu-ri, Gangjin-myeon, Imsil-gun, Jeollabuk-do	35.5	127.1
Boryeong Dam	Yongsu-ri, Misan-myeon, Boryeong-si, Chungcheongnam-do	36.3	126.6
Bohyeon-san Dam	Hwabuk-myeon, Yeongcheon-si, Gyeongsangbuk-do	36	129
Daeam Dam	Gusu-ri, Eonyang-eup, Ulju-gun, Ulsan	35.5	129.1
Seonam Dam	Seonam-dong, Nam-gu, Ulsan	35.5	129.3
Gucheon Dam	Guchon-ri, Dongbu-myeon, Geoje-si, Gyeongsangnam-do	34.8	128.6
Su-eo Dam	Seomgeo-ri, Jinsang-myeon, Gwangyang-si, Jeollanam-do	35	127.7
Gunwi Dam	Hakseong-ri, Goro-myeon, Gunwi-gun, Gyeongsangbuk-do	36.1	128.8
Seongdeok Dam	Seongjae-ri, Andeok-myeon, Cheongsong-gun, Gyeongsangbuk-do,	36.2	128.9
Gimcheon Buhang Dam	Yuchon-ri, Buhang-myeon, Gimcheon-si, Gyeongsangbuk-do	35.9	127.9

The solar meter used to measure solar radiation uses secondary standard class equipment in accordance with ISO 9060. Photographs and major specifications of solar irradiance meters used in this study are as shown in [Figure 2-1] and [Table 2-2].

[Figure 2-1] Solar irradiance model

[Table 2-2] Solar radiance meter major specifications

Classification	Specifications
1. Output	mV
2. ISO 9060 classification	Secondary Standard Class
3. Response time 95% (sec)	< 0.5
4. Zero offset - Thermal radiation (200W/m^2)	< 1 W/m^2
5. Zero offset - Temperature change (5K/hr)	+/- 1 W/m^2
6. Non-stability (change/5 years)	+/- 0.5 %
7. Non-linearity (at 1000W/m^2)	+/- 0.2 %
8. Directional response (at 1000W/m^2)	< 10 W/m^2
9. Spectral selectivity (0.35-1.5μm)	+/- 3 %
10. Temp. response (for 70°C band)	< 1 %
11. Tilt response (at 1000W/m^2)	+/- 0.2 %
12. Sensitivity (μV/W/m^2)	Approx. 10
13. Impedance (Ω)	Approx. 45kΩ
14. Operating temperature range (°C)	- 40 to +80
15. Irradiance range (W/m^2)	0 - 4000
16. Cable length	10m
17. Wavelength range in nm	285 to 3000
18. Ingress protection	IP 67

The definitions of major terms used in solar radiation meter standards are as follows:

A. **Response time**: In general, the thermal equilibrium process of a horizontal solar system is described by several time constants, and the setting behavior is determined by the time it takes the device to reach 95% of its final value. The figure from In the World Meteorological Organization is 99% close to the final value, but the uncertainty caused by offsets increases and is more affected by wind speeds. However, it is also considered to take the time it takes to reach 99.5% of the figure to accurately measure the solar radiation of rapidly changing radiant sources.

B. **Zero off-set**: The zero offset effect can mainly be thought of in the two most frequent cases. It does not include rapid changes in the main body temperature, such as when there is a cold shower, and in the case of wind at the level of the fan, it meets the given upper limit and can be used.

C. **non-stability**: In general, the reactivity of a horizontal solar system is known to be within ± 0.5%. The low stability of the horizontal solar system reactivity can be corrected by performing recalibration more frequently depending on the acceptable uncertainty level.

D. Non-linearity: Non-linearity is defined for the full range of effective solar radiation (approximately 100 to 1000 W/m2).

E. Direct response (for direct solar radiation)

- To ensure that the limit is met, the reactivity to the angles of incidence 30˚, 40˚, 50˚, 60˚, 70˚ and 80˚ at the 12-degree angle — 0˚, 30˚, 60˚... 330˚ — must be determined. (Azimuth ψ=0° indicates the direction of the cable outlet of the horizontal solar system.)
- The directionality of the horizontal pyrheliometer is expressed as a function of the response to direct radiation and the direction of the horizontal pyrheliometer. For an ideal horizontal pyrheliometer, it is defined as the ratio of the signal to the solar radiation, with the reactivity constant depending on the direction. The actual change in direction of the horizontal pyrheliometer causes measurement error. This occurs when changes in reactivity or angular distribution of irradiation are unknown or ignored.

Directionality is defined as absolute error(W/m2), which is caused by ignoring the change in reactivity or the use of appropriate figures when the measured normal incident irradiation is 1000 W/m2. This "directional error of 1000W/m2" is expressed mathematically as follows.

$$\varDelta_{1000}(\Theta,\psi) = \left[\frac{R(\theta,\psi)}{R(\theta=0)}-1\right]$$

$\varDelta 1000(\Theta,\psi)$: Directional error of 1000 W/m^2

Θ : Incident angle(Θ=0 means normal incidence), ψ : Azimuth

$R(\Theta,\psi)$: reactivity to irradiation at defined Θ, ψ

$R(\Theta=0)$: reactivity to normal incident irradiation

Another definition of the directionality of the horizontal pyrheliometer is the cosine error or $\delta_{cos}(\Theta,\psi)$, which is defined as the ratio of the error of the reactivity from the normal incident figure.

$$\varDelta_{1000}(\Theta,\psi) = 100\left[\frac{R(\theta,\psi)}{R(\theta=0)}-1\right]$$

The cosine error is related to the 1000 W/m^2 directional error as follows.

$$\delta_{cos}(\Theta,\psi) = \frac{\varDelta_{1000}(\theta,\psi)}{10\cos\theta}$$

The 1000 W/m^2 directional error and cosine error is calculated as follows.

$$\varDelta_{1000}(\Theta,\psi) = 1000\left[\frac{S(\theta,\psi)}{S(\theta=0)}-\cos\theta\right] \text{ or}$$

$$\delta_{cos}(\Theta,\psi) = 100\left[\frac{S(\theta,\psi)}{S(\theta=0)\cos\theta}-1\right]$$

$S(\Theta,\psi)$is the signal, and $\varDelta 1000$ is selected according to the horizontal pyrheliometer because of the following advantages.

a) This function is a directional function with fewer values of change.

b) It can be measured with the same precision($\approx$ 3 W/m^2) in all direction of incidence.

c) For every level of horizontal pyrheliometer, only one figure is required to define performance for all directions(e.g., 10 W/m^2, 20W/m^2, 30W/m^2).

Furthermore, since direct sunlight is no larger than 1000 W/m^2, ⊿1000 provides approximate maximum limit values for errors that can occur due to the directionality of the horizontal pyrheliometer response in outdoor use.

4. EPP Prediction Process

Using solar radiation data obtained from 16 emergency water dams in Korea, electric power production(EPP) is predicted that can be produced through PV system. By utilizing data on solar radiation per hour from emergency water dams, solar power production is predicted, analyzed, and compared to the actual amount of electricity produced from solar power systems through three methods. The research processes performed in this paper are shown in [Figure 2-2].

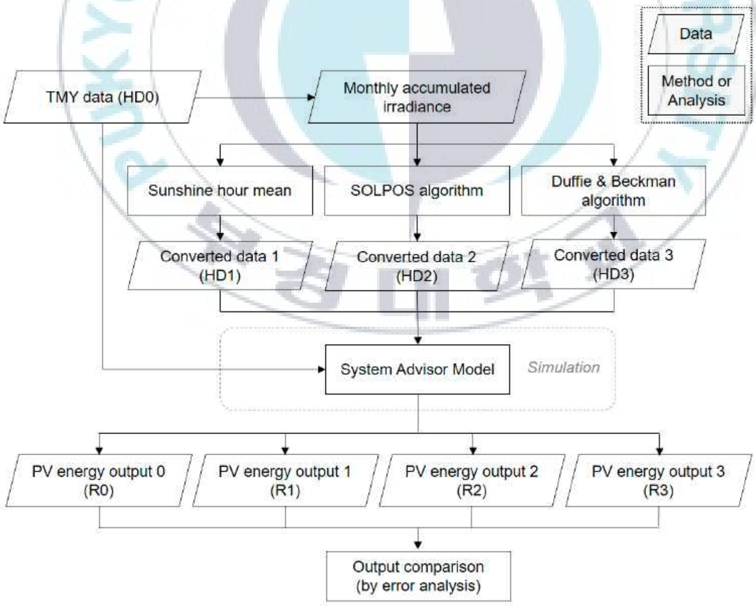
A. EPP is predicted (R0) by entering observed solar radiation data (HD0) into the simulation program.

B. After converting observed hourly solar radiation data(HD0) to monthly accumulated solar radiation data, EPP is predicted(R1) by converting it back to daily average hourly solar radiation data(HD1). The capacity of PV systems here is designed by selecting appropriate models such as inverters and PV modules.

C. EPP is predicted(R2) by converting observed hourly solar radiation data(HD0) to monthly accumulated solar radiation data and then to solar radiation data with the SOLPS algorithm(HD2). The capacity of the PV system is designed by selecting appropriate models such as inverters and PV modules.

D. EPP is predicted(R2) by converting observed hourly solar radiation data(HD0) to monthly accumulated solar radiation data and then to solar radiation data with the Duffie&Beckman algorithm(HD3). The capacity of the PV system is designed by selecting appropriate models such as inverters and PV modules.

E. The EPP predictive values calculated above — R0, R1, R2, R3 — and the actual amount of photovoltaic power produced during the observation period are compared and analyzed.



[Figure 2-2] Conversion of Solar Data and Process of Solar Power Prediction

Ⅲ. Solar Radiation Measurement and Conversion Methods

1. Monthly accumulated irradiation of domestic dams

The monthly accumulated solar radiation data at the surface of 16 emergency water dams in Korea used in this paper is from weather data managed by the National Institute of Meteorological Sciences[29]. The data from the National Institute of Meteorological Sciences is converted from the measurement units [MJ/m2] to [kW/m2], as shown in [Table 3-1], [Table 3-2], [Figure 3-1], and [Figure 3-2] according to the formula below.

$$1[W] = 1[J/s] \tag{3.1}$$

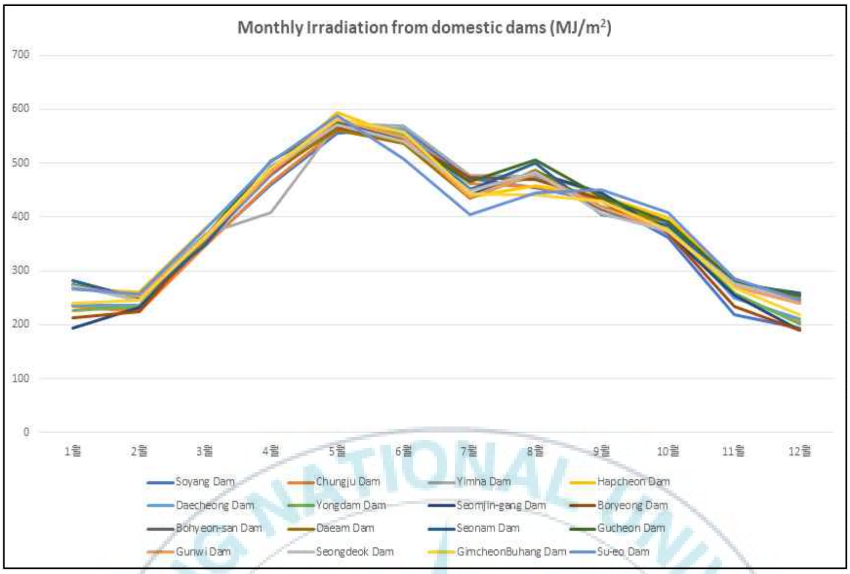
$$1[kW] = 1{,}000[J/s] = 860[kcal/h] \tag{3.2}$$

[Table 3-1] Monthly irradiation from domestic dams (unit: MJ/m^2)

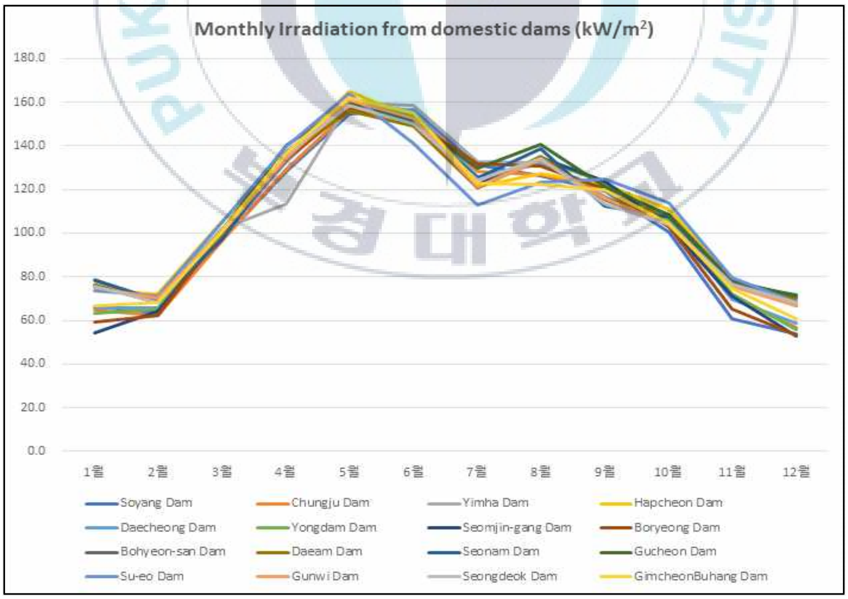
Site	Monthly irradiation											
	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Soyang Dam	237.8	228.9	348.6	460.9	555.8	563.5	471.7	454.2	428.5	361.5	219.2	193.5
Chungju Dam	233.8	224.7	346.6	464.5	561.8	559.5	461.8	456.2	432.3	379.4	254.5	205.2
Yimha Dam	270.3	254.8	367.5	407.8	573.3	570	477	475	419.7	376.2	277.8	240.2
Hapcheon Dam	265.8	260.2	379.8	486.9	593.2	548.2	437.2	458.1	439.6	398.5	283.5	243.9
Daecheong Dam	236	236.4	354.3	476.9	574.4	562	452.3	473.9	430.9	381.6	250.2	210.9
Yongdam Dam	226.7	234	365.5	486	579.8	552.5	434.8	481.8	443.7	380.1	259.7	201.6
Seomjin-gang	194.6	231.4	355.5	488.2	573.5	541.1	440.4	483.8	445.5	369.9	255.7	190.9
Boryeong Dam	213.5	223.9	362	481.7	565.3	543.1	473.6	469.7	432.6	371	234.6	191
Bohyeon-san	274.6	246.3	359.4	485.4	576.2	540.8	436.4	482.5	414.6	373.2	277.1	247
Daeam Dam	281.1	249.7	354	487.4	562	536	434.8	486.3	417.4	390.6	277.8	252.6
Seonam Dam	282.8	248.3	348.1	493.1	571.4	545.8	450.7	499.4	405	385.7	277	258.7
Gucheon Dam	274.5	245.9	364	503.9	573.2	542.2	466.2	505.2	437.3	390.3	280.5	255.6
Su-eo Dam	265.9	256.7	378.2	502	589.1	507	405.4	444.1	449.7	409.1	285.8	246
Gunwi Dam	270.1	252.7	360.6	483.4	579.8	548.8	436.9	481.1	417.5	373.2	271.4	239.3
Seongdeok	271.6	246.3	363.3	490.1	570.3	540.7	447.9	482.6	407	374.8	275.6	245.1
Gimcheon Buhang Dam	240.3	244.9	363.4	491.3	582.5	557.5	442.2	440.4	430.3	374.9	268.6	219.3

[Table 3-2] Monthly irradiation from domestic dams (unit: kW/m^2)

Site	Monthly irradiation											
	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Soyang Dam	66.1	63.6	96.9	128.1	154.5	156.6	131.1	126.2	119.1	100.5	60.9	53.8
Chungju Dam	65.0	62.4	96.3	129.1	156.1	155.5	128.3	126.8	120.1	105.4	70.7	57.0
Yimha Dam	75.1	70.8	102.1	113.3	159.3	158.4	132.6	132.0	116.6	104.6	77.2	66.8
Hapcheon Dam	73.9	72.3	105.6	135.3	164.9	152.4	121.5	127.3	122.2	110.7	78.8	67.8
Daecheong Dam	65.6	65.7	98.5	132.5	159.6	156.2	125.7	131.7	119.8	106.1	69.5	58.6
Yongdam Dam	63.0	65.0	101.6	135.1	161.1	153.5	120.8	133.9	123.3	105.6	72.2	56.0
Seomjin-gang	54.1	64.3	98.8	135.7	159.4	150.4	122.4	134.5	123.8	102.8	71.1	53.1
Boryeong Dam	59.3	62.2	100.6	133.9	157.1	150.9	131.6	130.5	120.2	103.1	65.2	53.1
Bohyeon-san	76.3	68.5	99.9	134.9	160.1	150.3	121.3	134.1	115.2	103.7	77.0	68.6
Daeam Dam	78.1	69.4	98.4	135.5	156.2	149.0	120.8	135.1	116.0	108.6	77.2	70.2
Seonam Dam	78.6	69.0	96.7	137.0	158.8	151.7	125.3	138.8	112.6	107.2	77.0	71.9
Gucheon Dam	76.3	68.3	101.2	140.0	159.3	150.7	129.6	140.4	121.5	108.5	78.0	71.0
Su-eo Dam	73.9	71.3	105.1	139.5	163.7	140.9	112.7	123.4	125.0	113.7	79.4	68.4
Gunwi Dam	75.1	70.2	100.2	134.3	161.1	152.5	121.4	133.7	116.0	103.7	75.4	66.5
Seongdeok	75.5	68.5	101.0	136.2	158.5	150.3	124.5	134.1	113.1	104.2	76.6	68.1
Gimcheon Buhang Dam	66.8	68.1	101.0	136.5	161.9	154.9	122.9	122.4	119.6	104.2	74.6	60.9



[Figure 3-1] Monthly irradiation from domestic dams (unit: MJ/m^2)



[Figure 3-2] Monthly irradiation from domestic dams (unit: kW/m^2)

2. Conversion of irradiation in time units

As mentioned earlier, this study used three methods (Arithmetic Mean Method, SOLPOS Algorithm Method, and Duffie and Beckman Algorithm Method) to transform solar radiation data accumulated monthly on 16 domestic dam surfaces. These three methods generally follow the following equations, where m means number of months, and t time.

$$GHI_C(m,h) = A(m) \times F(m,h) \tag{3.3}$$

$$DNI_C(m,h) = A'(m) \times F'(m,h) \tag{3.4}$$

GHI_C is the converted global horizontal irradiance (GHI, unit W/m2), DNI_C is the converted direct irradiance (DNI, unit W/m2) for a specific month.

$A(m)$ represents a function for the monthly mean value, and $F(m,h)$ a function for a particular month and time. Therefore, the values of $A(m)$ and $F(m,h)$ depend on the function utilized in the conversion method.

To calculate GHI_C and DNI_C, the monthly cumulative solar radiation values shown in [Table 3-2] were converted by applying each of the above three methods, which were compared to the actual measured solar radiation values.

3. Arithmetic Mean Method

Arithmetic Mean Method means arithmetic calculation of the average solar radiation value by time using the accumulated solar radiation per month as shown below.

$$A(m) = \sum GHI(m) / \sum ST(m) \tag{3.5}$$

$$F(m,h) = 1 \text{ or } 0 \tag{3.6}$$

$$A'(m) = \sum DNI(m) / \sum ST(m) \tag{3.7}$$

$$F'(m,h) = 1 \text{ or } 0 \tag{3.8}$$

Here, sunshine duration is defined as the time of day from the time the sun rises to the time it sets, and $\sum ST(m)$ means the total time of sunshine in a particular month. $F(m,h)$ and $F'(m,h)$ are represented by 1 if there exists a solar radiation value, and 0 if there is no solar radiation value. $\sum ST(m)$ is smaller than $\sum T(m)$, and $A(m)$ is larger than the simple formulaic average. Solar radiation values converted by time can only be applied in the solar radiation time range, not in time range with a solar radiation value of zero. As the converted solar radiation per hour(GHI_C or DNI_C) has a constant value in all solar time ranges, a slight change in solar radiation cannot be considered.

Arithmetic Mean Method can be applied to EPP software using PV by simply converting accumulated solar radiation per month because it only takes into account the total time during sunlight hours.

4. SOLPOS Algorithm Method

The SOLPOS algorithm calculates the position of the Sun and solar radiation of a particular day based on clear weather conditions and estimates the solar radiation per hour, $GHI_s(m,h)$ and $DNI_s(m,h)$. The algorithm is calculated by considering solar radiation outside the Earth, radius of the Earth[30], and angle of refracted ceiling[31].

The values of solar radiation per hour converted by the SOLPOS algorithm can be obtained from the formula below.

The formula below is used to obtain GHI.

$$A(m) = \sum GHI(m) / \sum GHI_s(m,h) \tag{3.9}$$

$$F(m,h) = GHI_s(m,h) \tag{3.10}$$

The formula below is used to obtain DNI.

$$A'(m) = \sum DNI(m) / \sum DNI_s(m,h) \tag{3.11}$$

$$F'(m,h) = DNI_s(m,h) \tag{3.12}$$

$GHI_s(m,h)$ and $DNI_s(m,h)$ represent GHI and DNI for a specific month and time zone, respectively.

5. Duffie and Beckman Algorithm Method

The Duffie and Beckman algorithm is commonly used in RETScreen software programs for analyzing renewable energy generation, and in the case of photovoltaic power generation, the of data is usually processed as a cumulative monthly solar radiation value.

This algorithm uses a method to calculate solar radiation per hour on a horizontal plane that has the same figure as the average monthly-daily solar radiation value[32]. In addition, the method utilizes the Collares-Pereira and Rabl models[33] and the solar azimuthal data of the time when the sun sets on a clear day to calculate the solar irradiance per hour, $GHI_{DB}(m,h)$v and $GNI_{DB}(m,h)$, by segmenting monthly average solar irradiance.

The values of solar radiation per hour converted by the Duffie and Beckman algorithm can be obtained from the formula below.

The formula below is used to obtain GHI.

$$A(m) = \sum GHI(m) / \sum GHI_{DB}(m,h) \tag{3.13}$$

$$F(m,h) = GHI_{DB}(m,h) \tag{3.14}$$

The formula below is used to obtain DNI.

$$A'(m) = \sum DNI(m) / \sum DNI_{DB}(m,h) \tag{3.15}$$

$$F'(m,h) = DNI_{DB}(m,h) \tag{3.16}$$

$GHI_s(m,h)$ and $DNI_s(m,h)$ represent GHI and DNI for a specific month and time zone, respectively, which are calculated using Duffie and Beckman.

Equations (3.13) and (3.15) have constant results, but the function $F(m,h)$ will have different values of solar radiation per hour depending on the specific month and time.

Ⅳ. Solar Radiation Conversion and Error Analysis

1. Solar radiation conversion

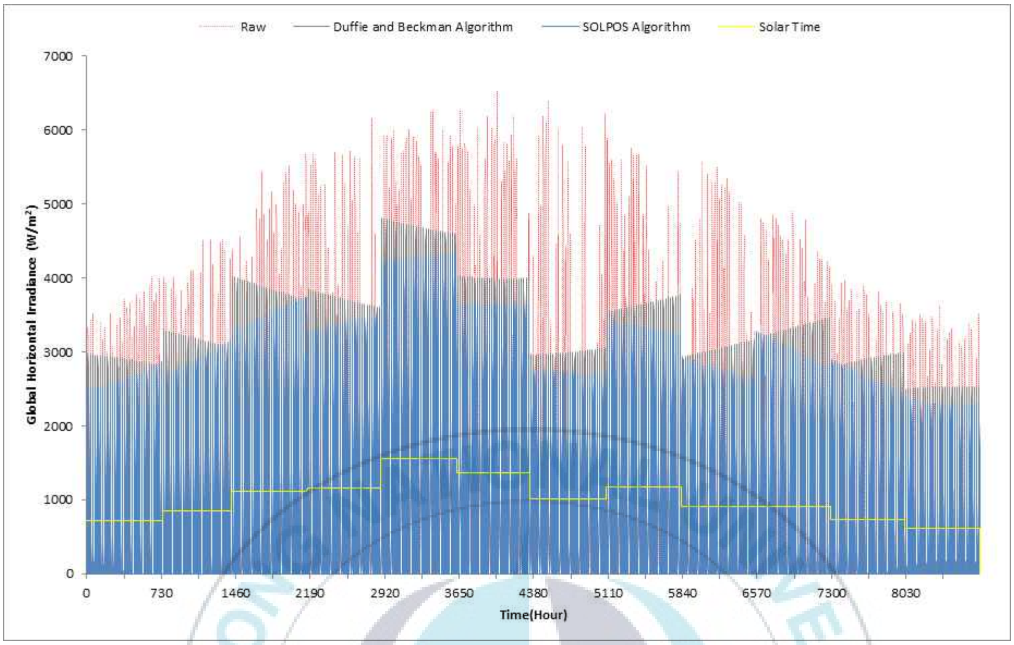
According to [Table 3.1] which shows the irradiation data measured on the surface of 16 dams for emergency use in Korea by the National Institute of Meteorological Sciences, accumulated monthly solar radiation is the highest in May and June, while the sunshine hours of the year highest in July and August. This is mainly due to a decrease in average daily solar radiation in summer, when monsoon and typhoons are generally concentrated.

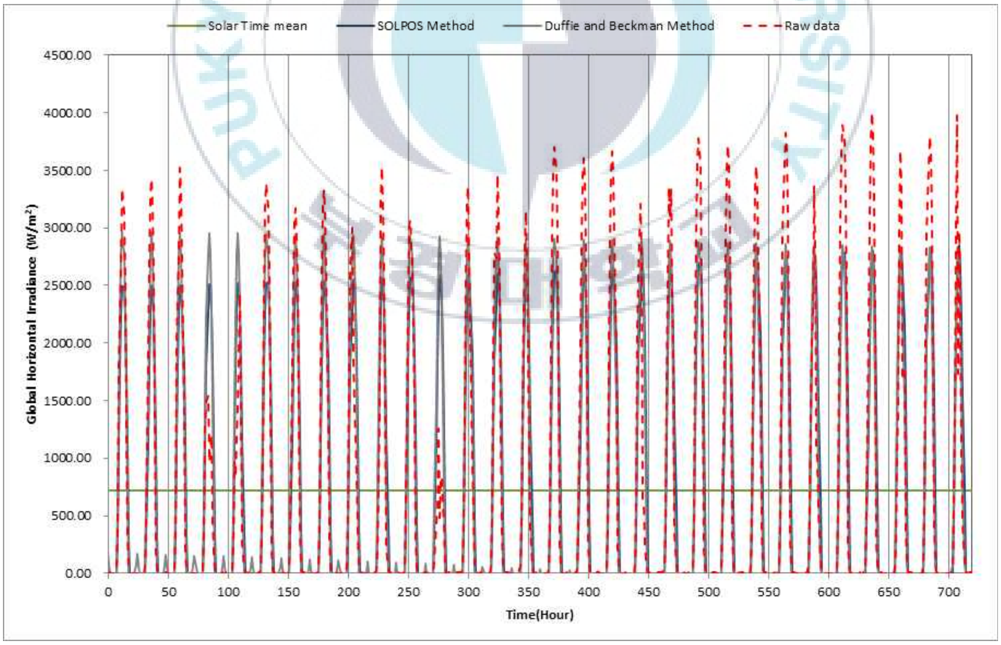
The results of converting accumulated solar radiation from 16 dams to solar radiation in time using the aforementioned three methods (Arithmetic Mean Method, SOLPOS Algorithm Method, and Duffie and Beckman Algorithm Method) are shown below.

The sum of solar radiation by time zone according to arithmetic mean method and SOLPOS algorithm method is equal to the sum of solar radiation by time zone obtained from solar radiation sensors, but the data values of solar radiation per hour per year are different. This is because the change in solar radiation measured per hour is irregular and the range of fluctuations is large.

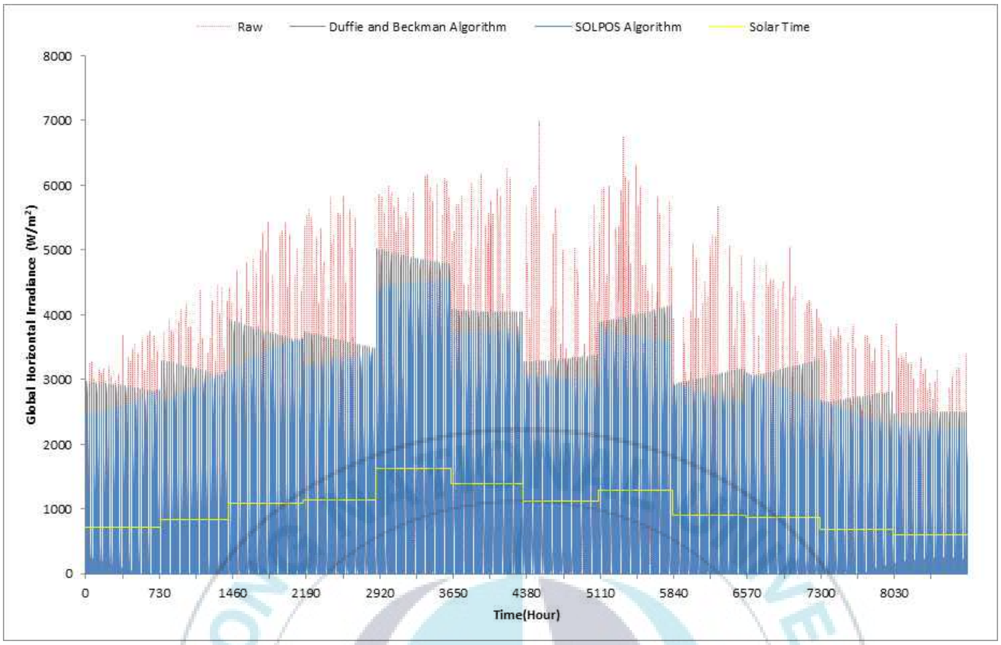
Solar radiation converted by time zone shows the same tendency for most of the time except when data is temporarily not received due to communication failure.

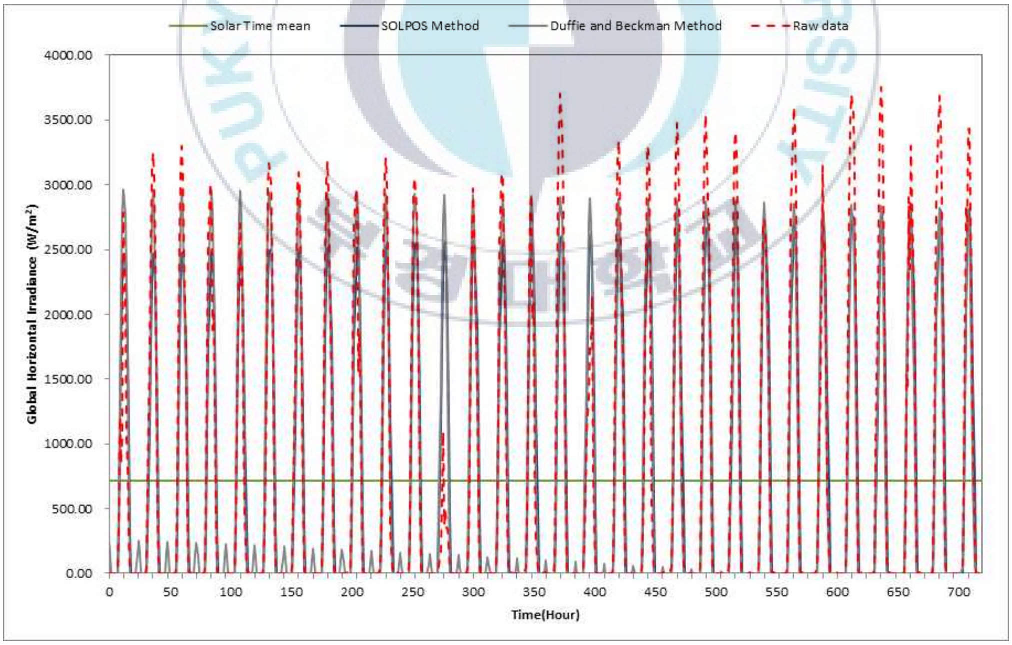
The results of converting accumulated solar radiation from 16 dams to solar radiation in time using those three methods are shown in [Figure 4-1] ~ [Figure 4-16] below.



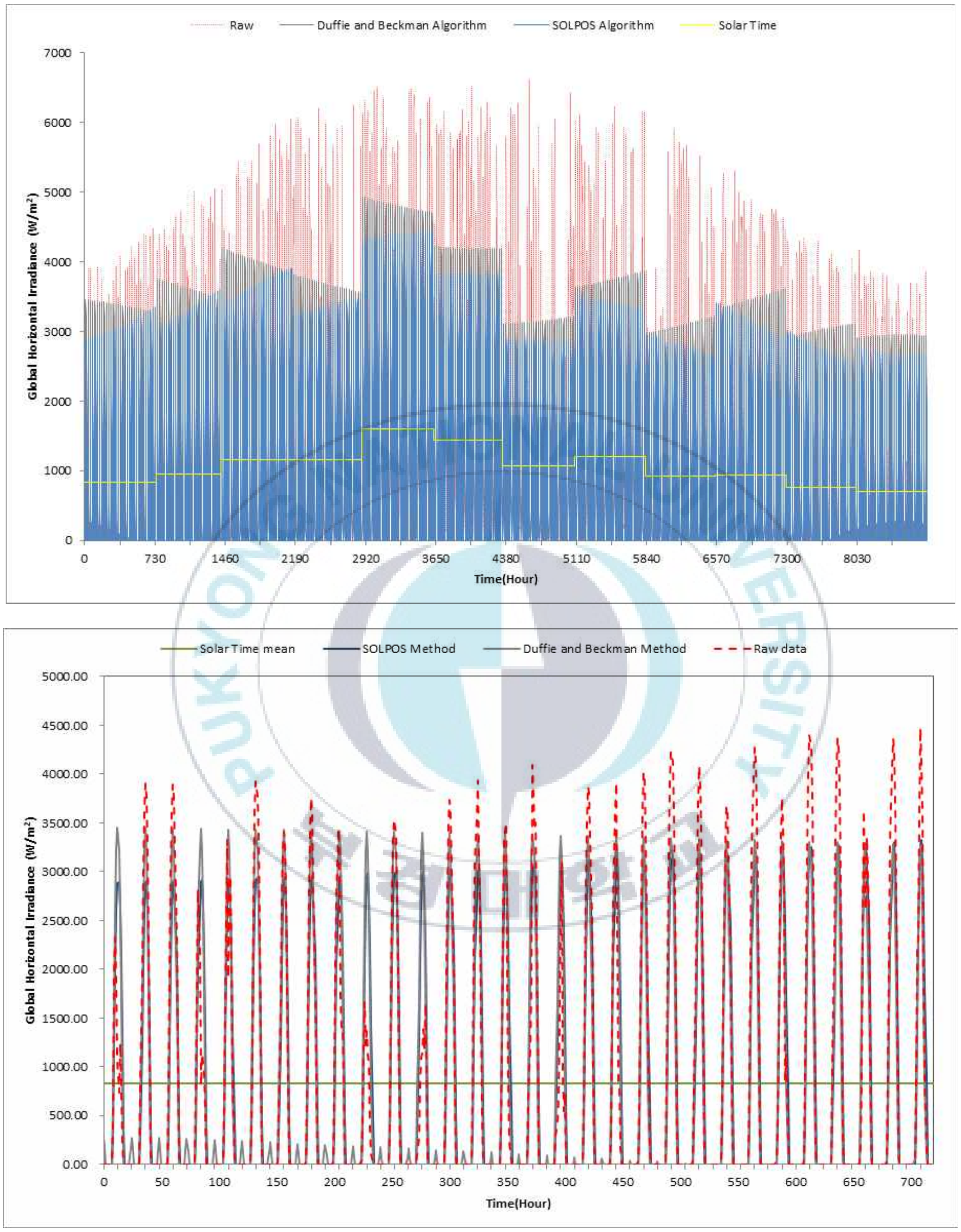


[Figure 4-1] Hourly irradiation at Gucheon Dam (unit: W/m^2)

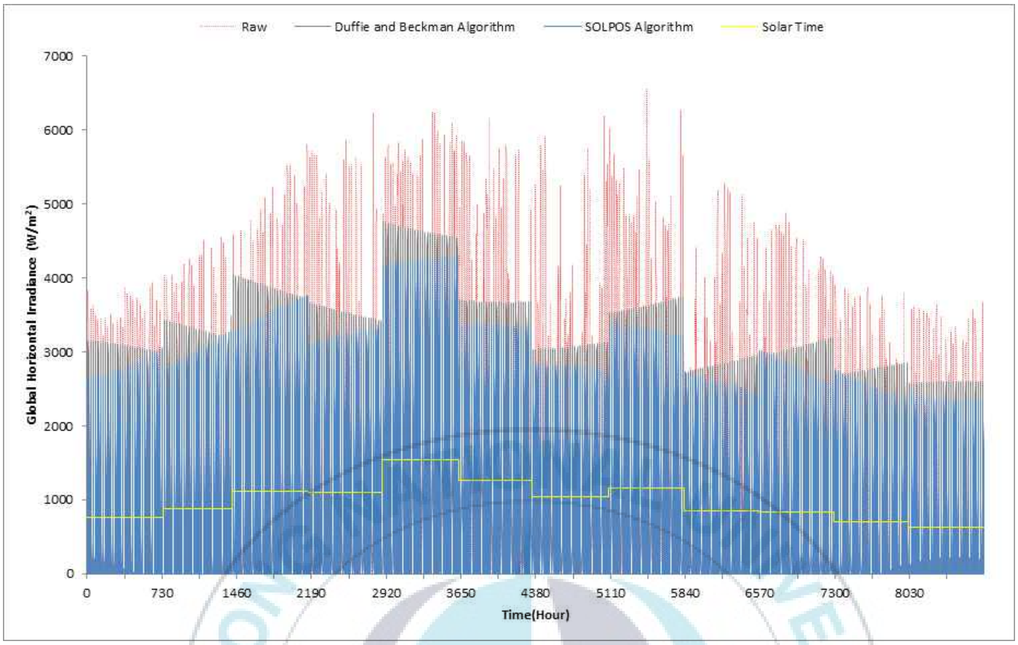


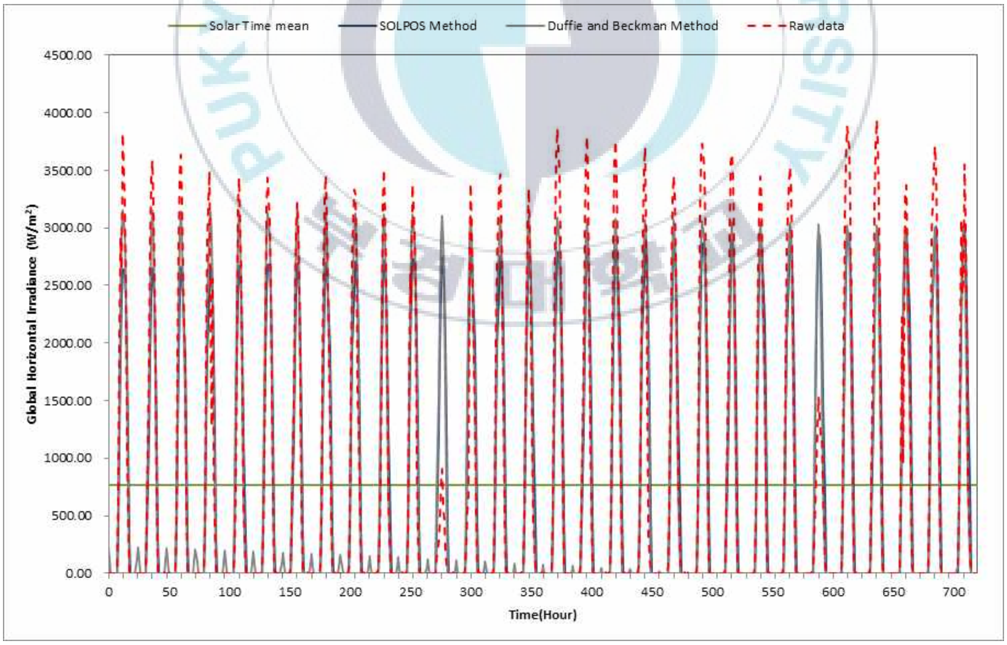


[Figure 4-2] Hourly irradiation at Gunwi Dam (unit: W/m^2)

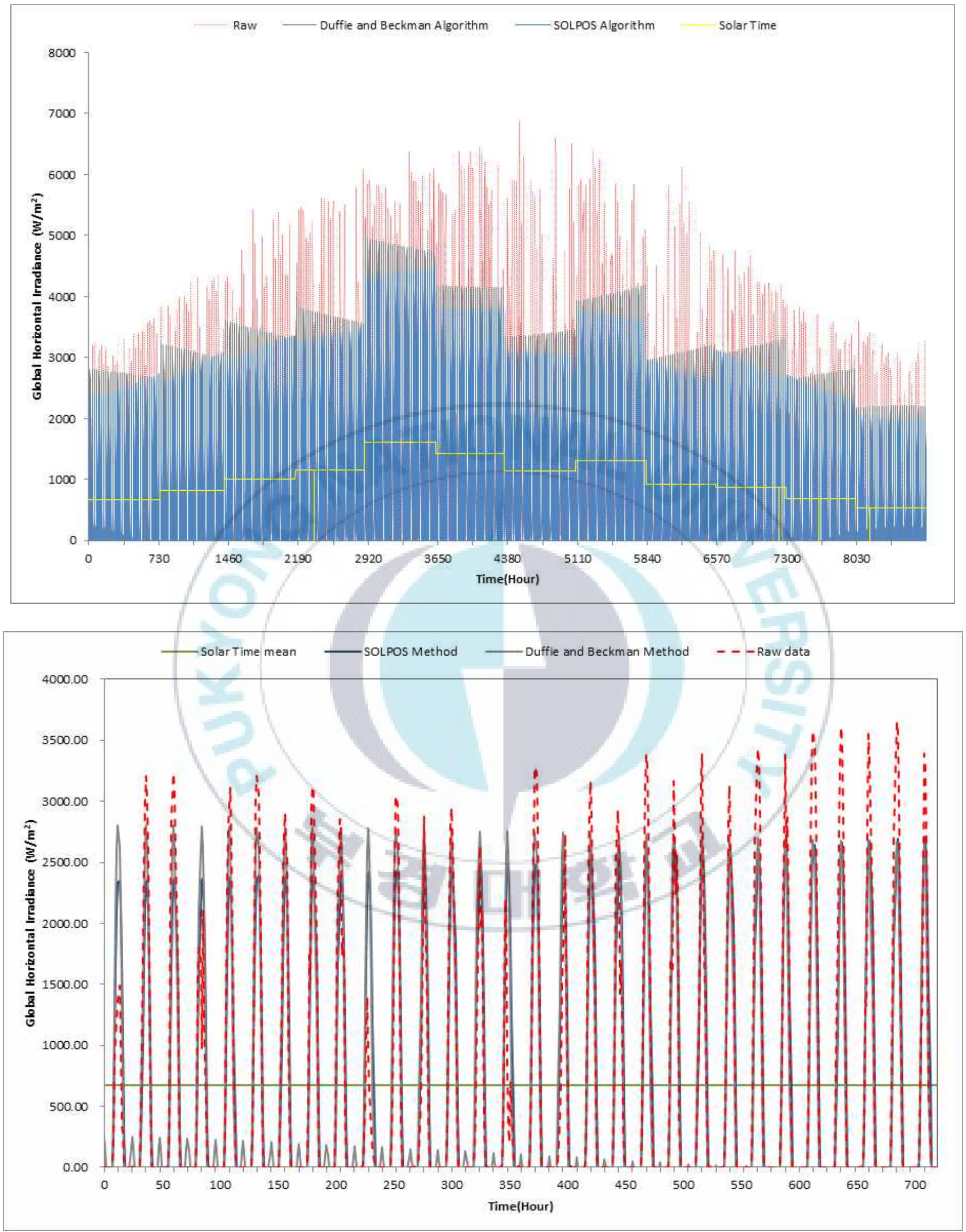


[Figure 4-3] Hourly irradiation at Gimcheon Buhang Dam (unit: W/m^2)

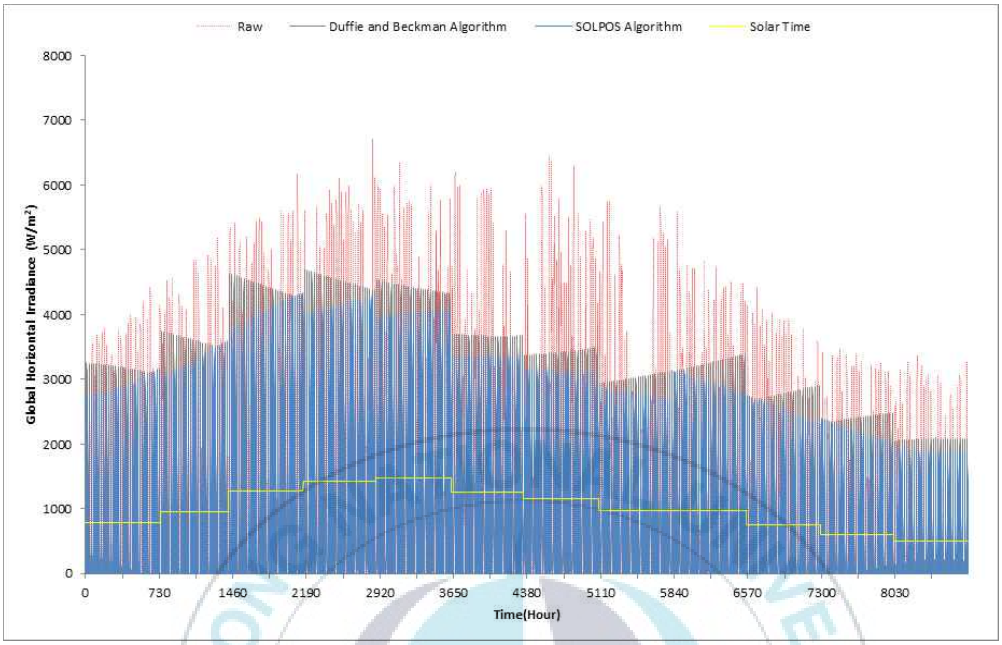


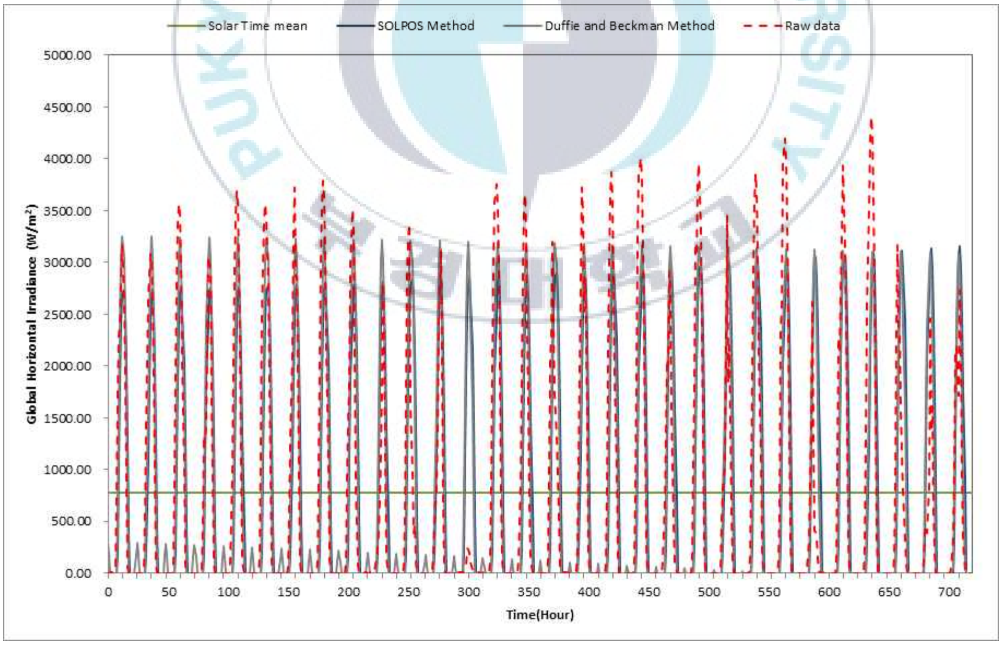


[Figure 4-4] Hourly irradiation at Daeam Dam (unit: W/m^2)

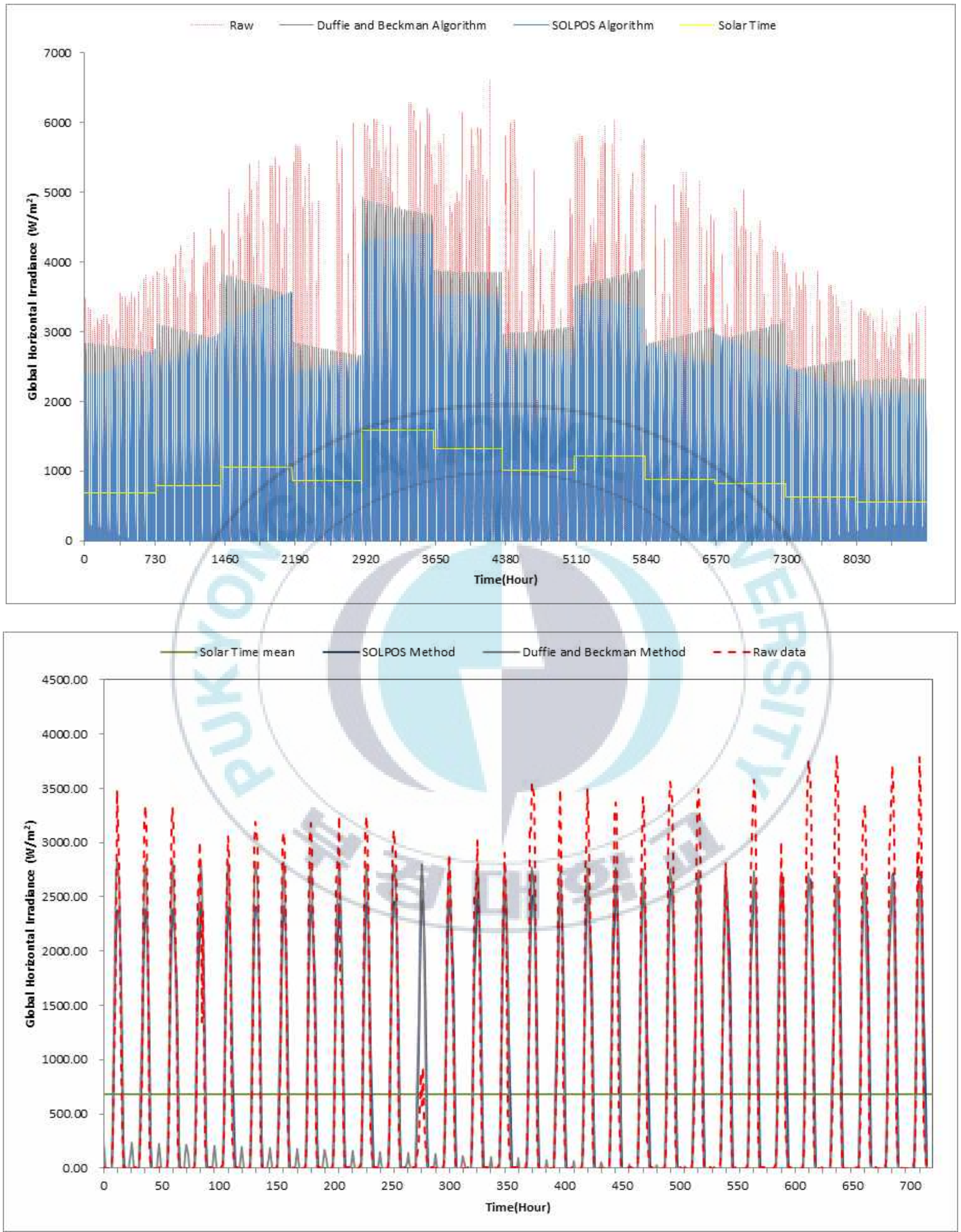


[Figure 4-5] Hourly irradiation at Daecheong Dam (unit: W/m^2)

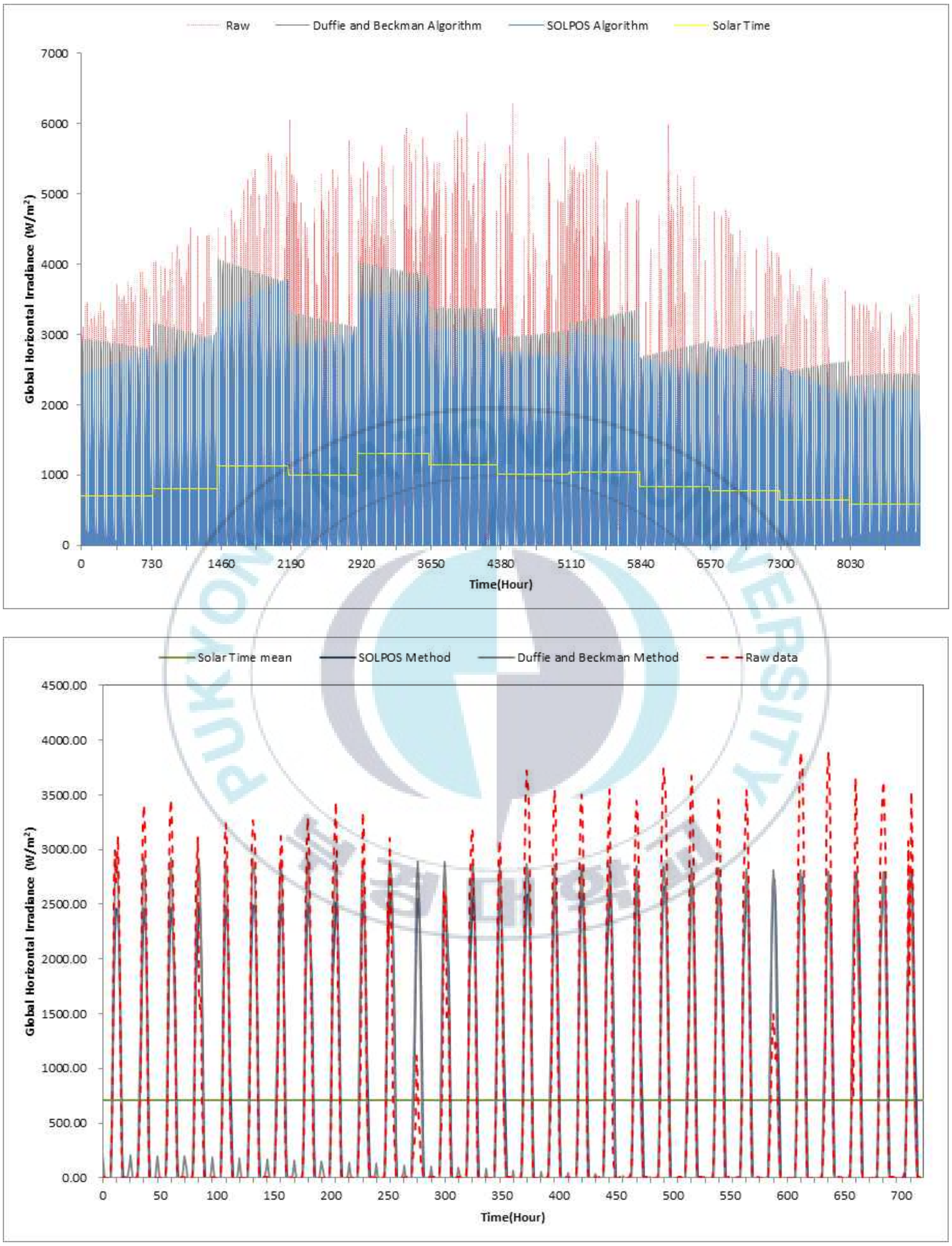




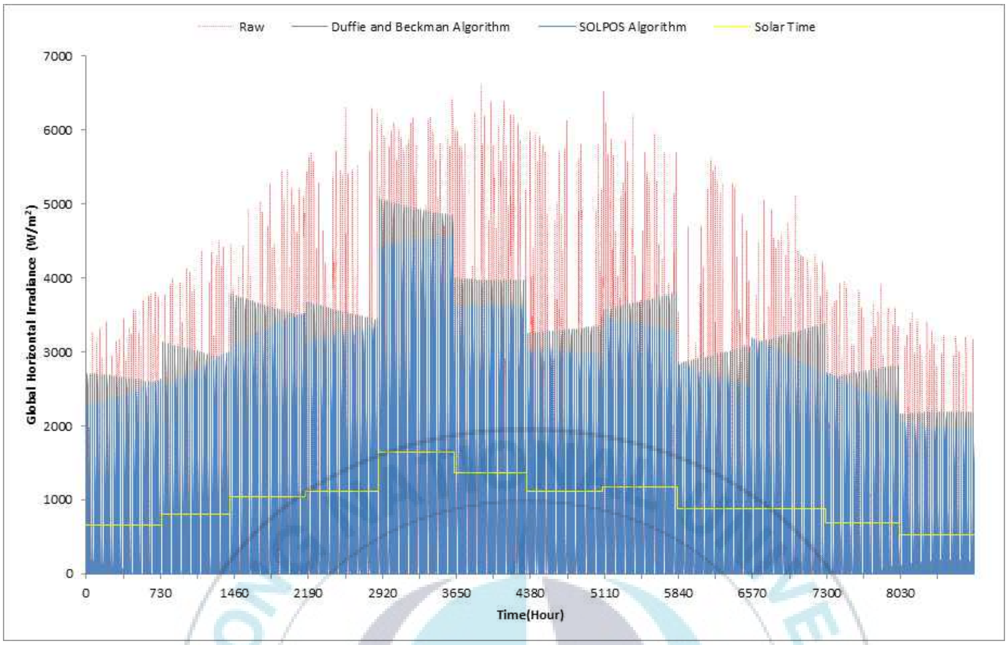
[Figure 4-6] Hourly irradiation at Boryeong Dam (unit: W/m^2)

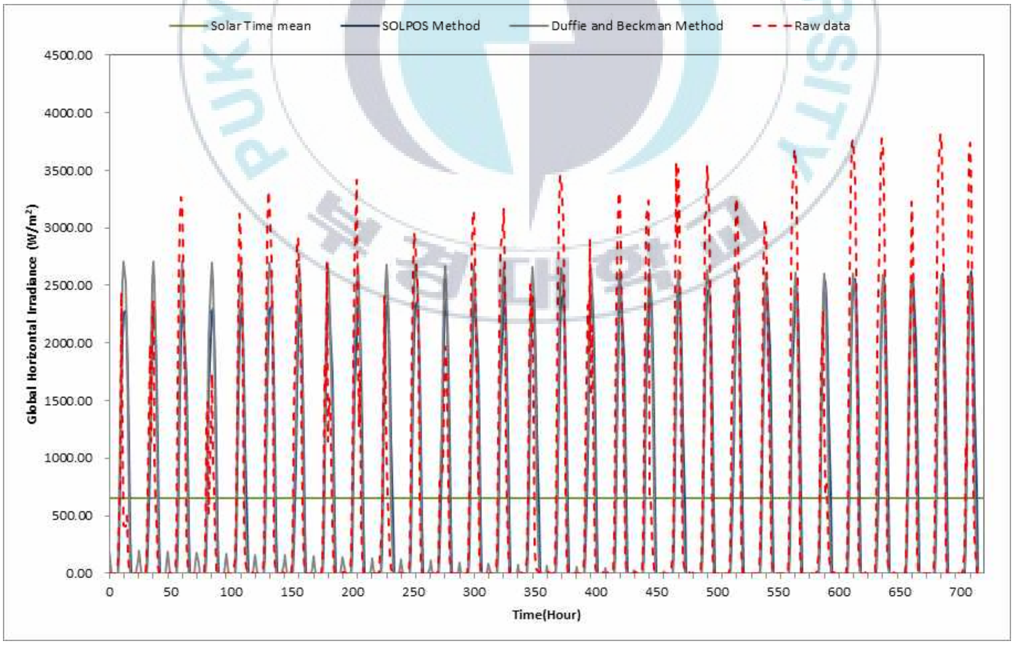


[Figure 4-7] Hourly irradiation at Bohyeon-san Dam (unit: W/m^2)

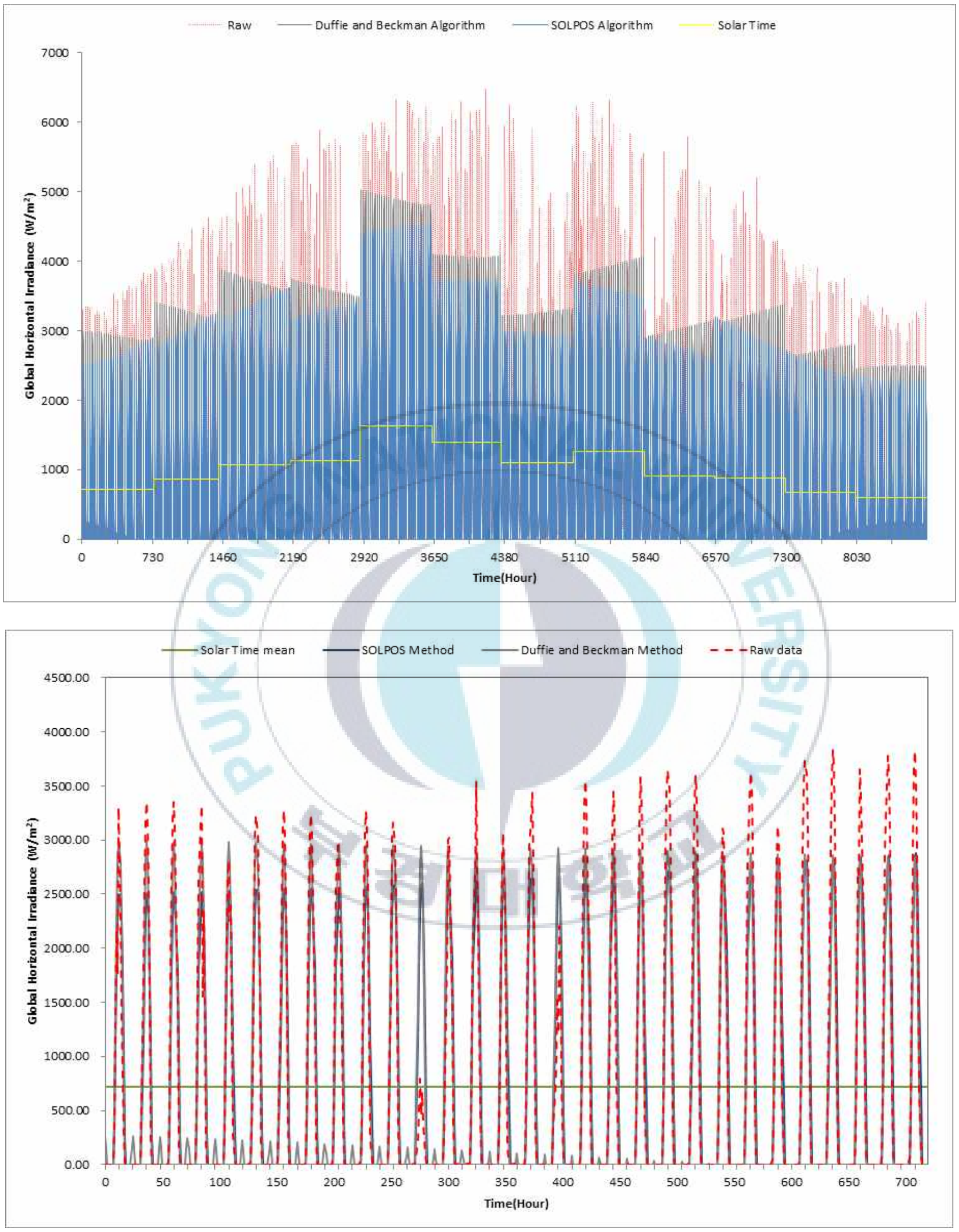


[Figure 4-8] Hourly irradiation at Seonam Dam (unit: W/m^2)

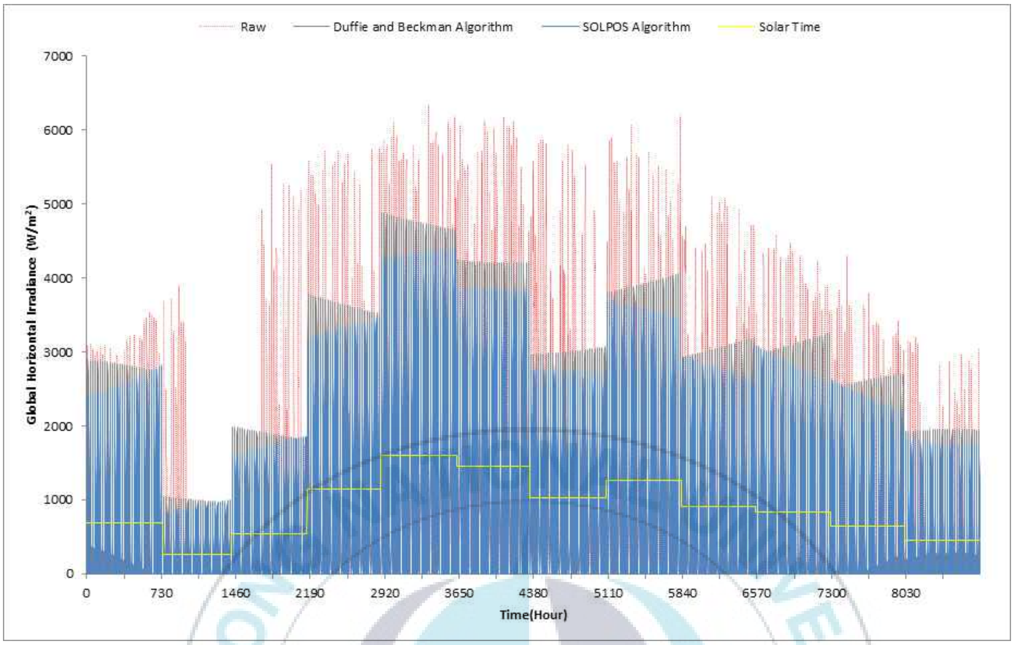


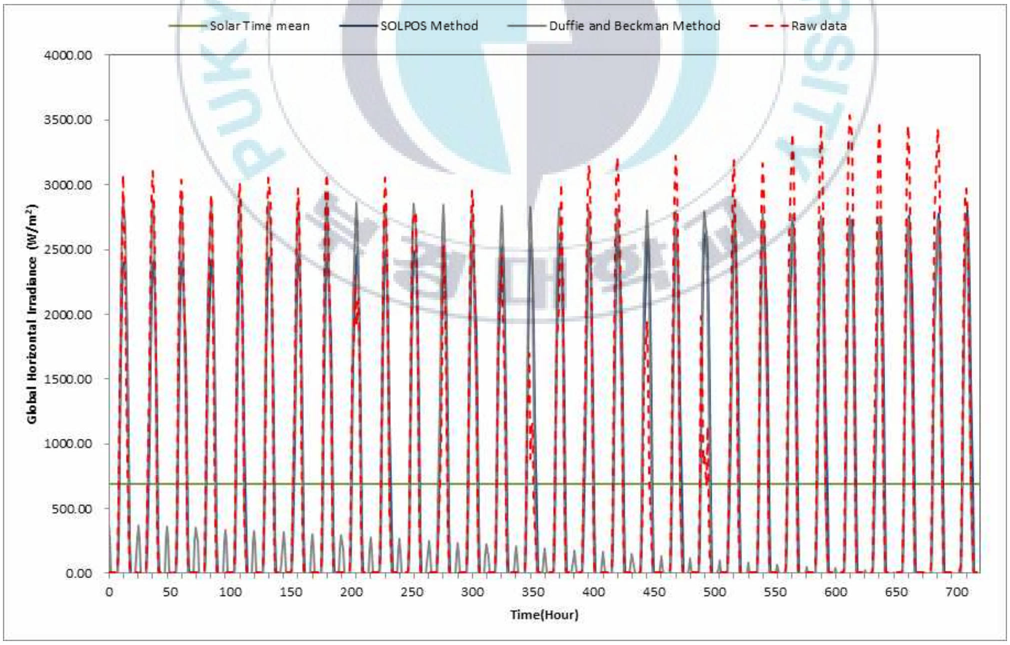


[Figure 4-9] Hourly irradiation at Seomjin-gang Dam (unit: W/m^2)

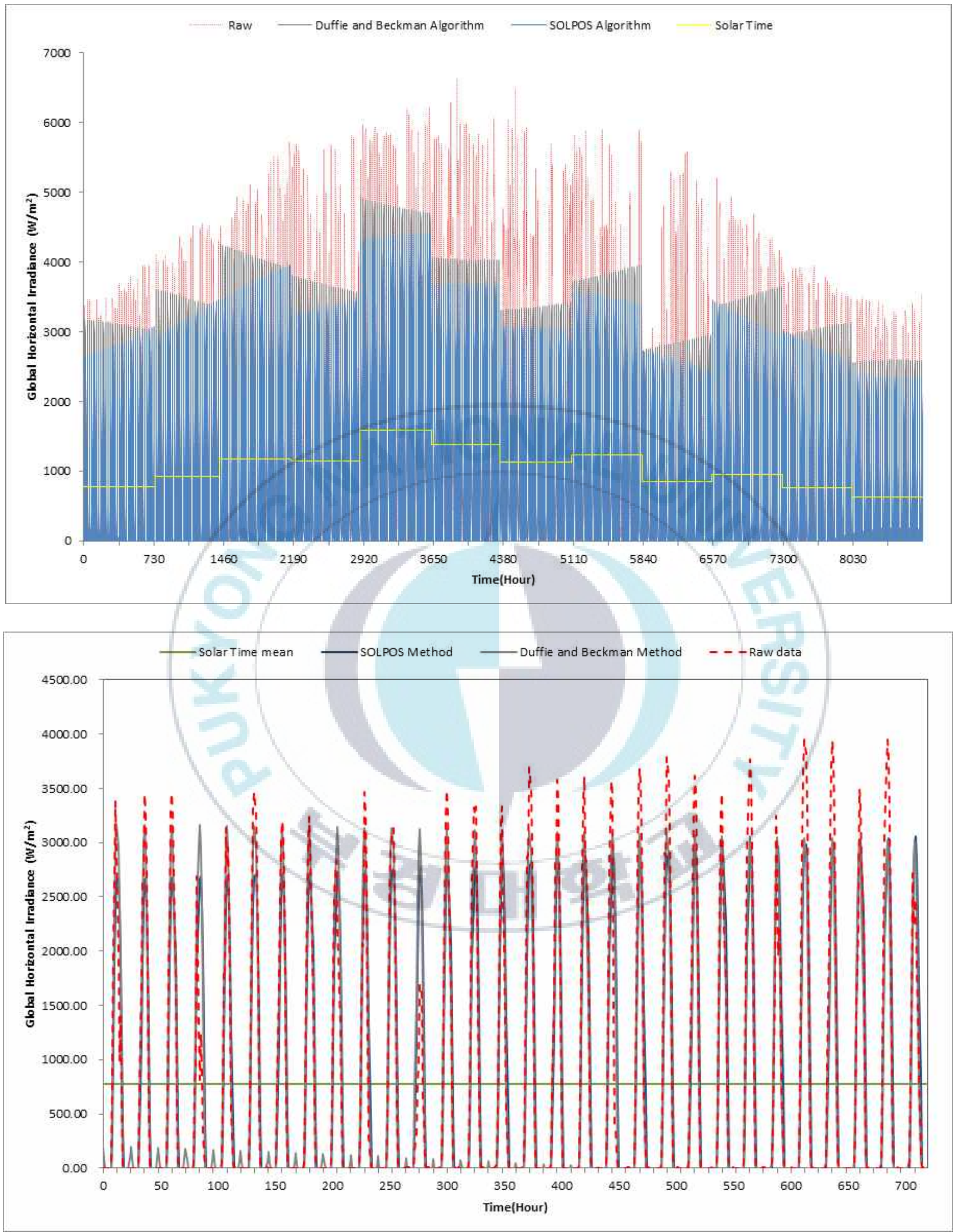


[Figure 4-10] Hourly irradiation at Seongdeok Dam (unit: W/m^2)

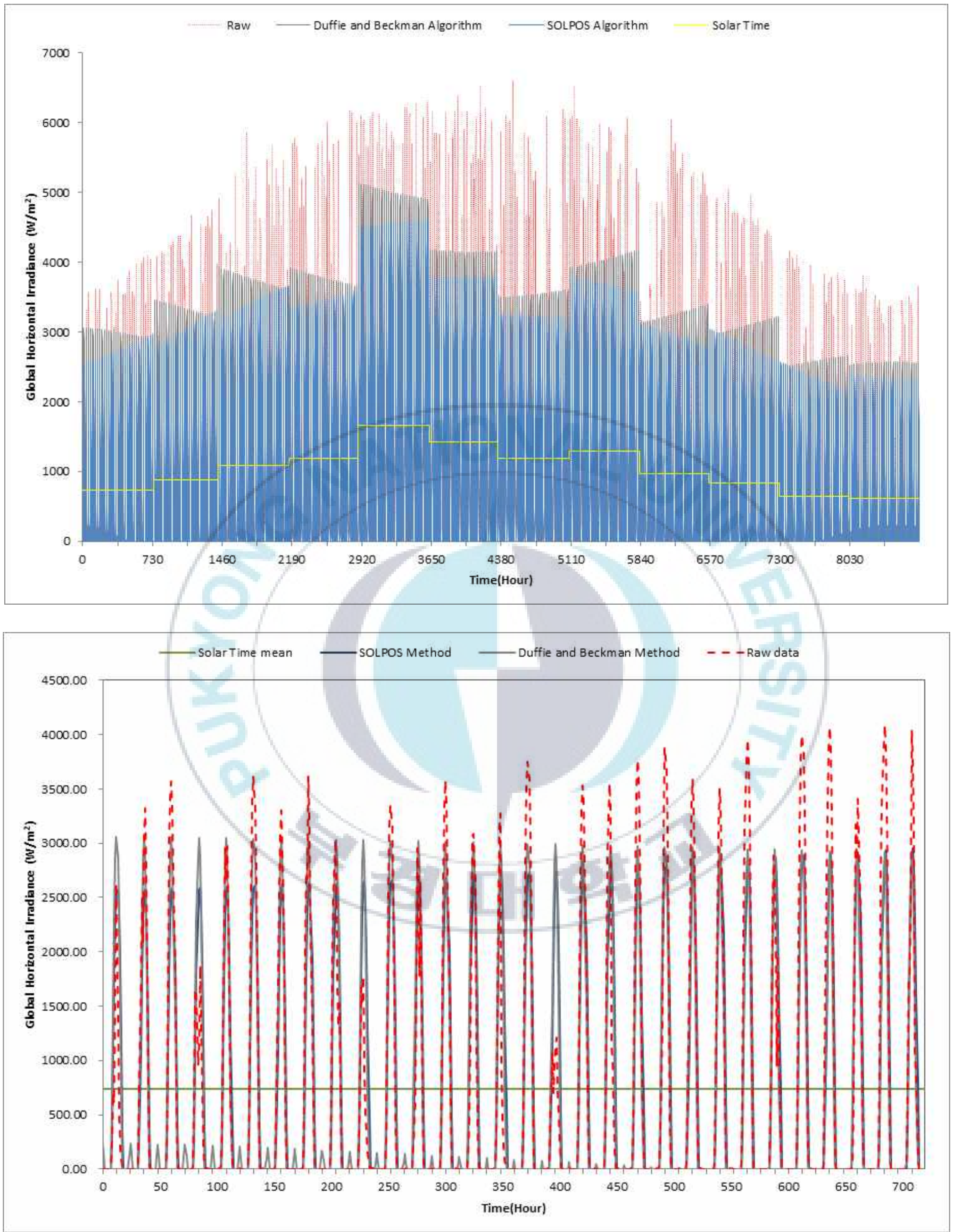




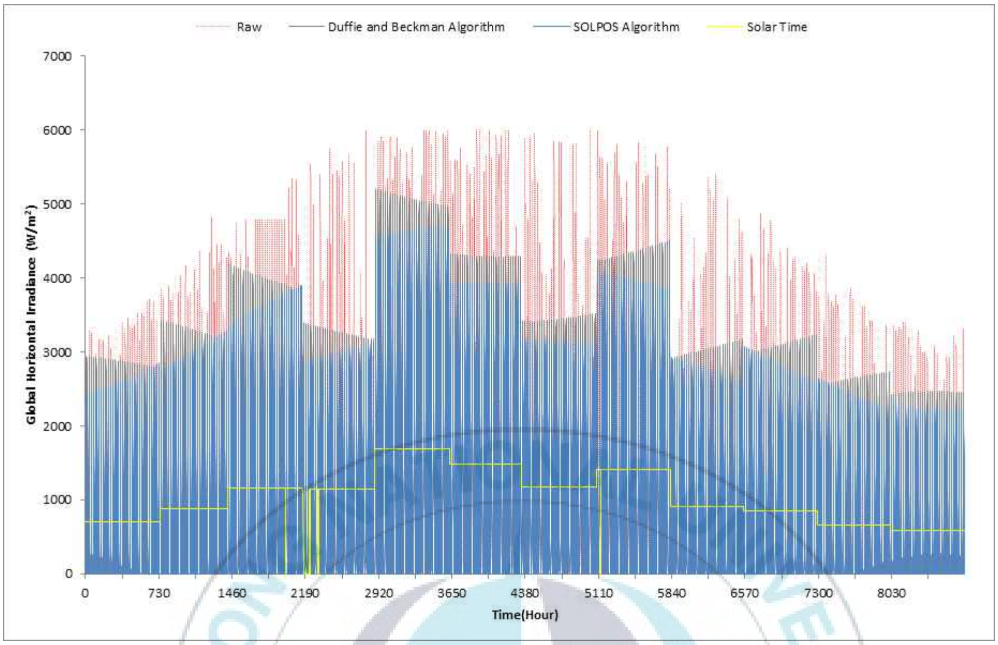
[Figure 4-11] Hourly irradiation at Soyang Dam (unit: W/m^2)

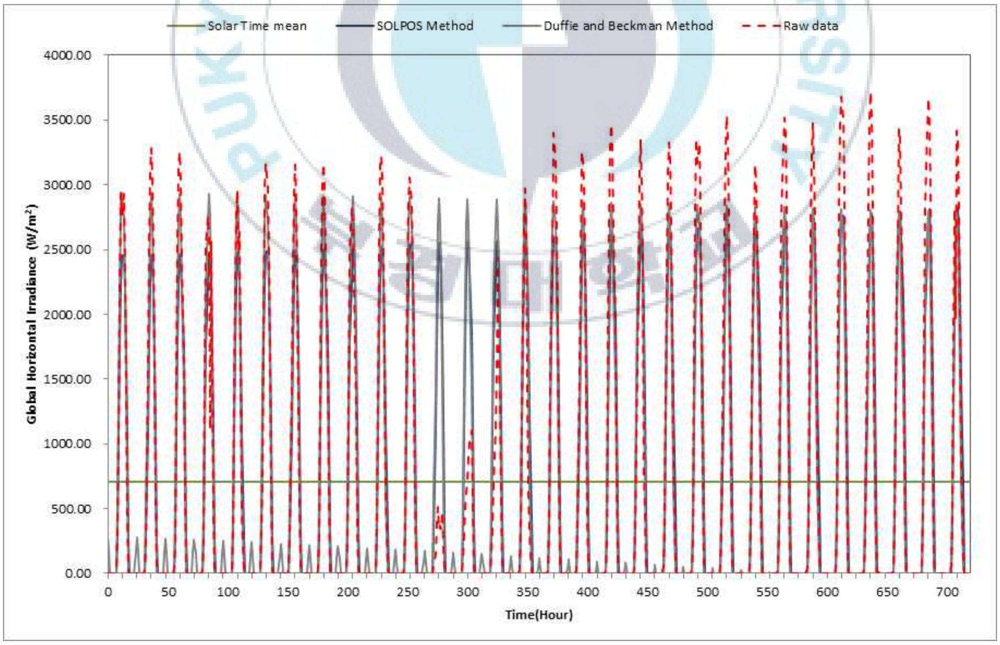


[Figure 4-12] Hourly irradiation at Su-eo Dam (unit: W/m^2)

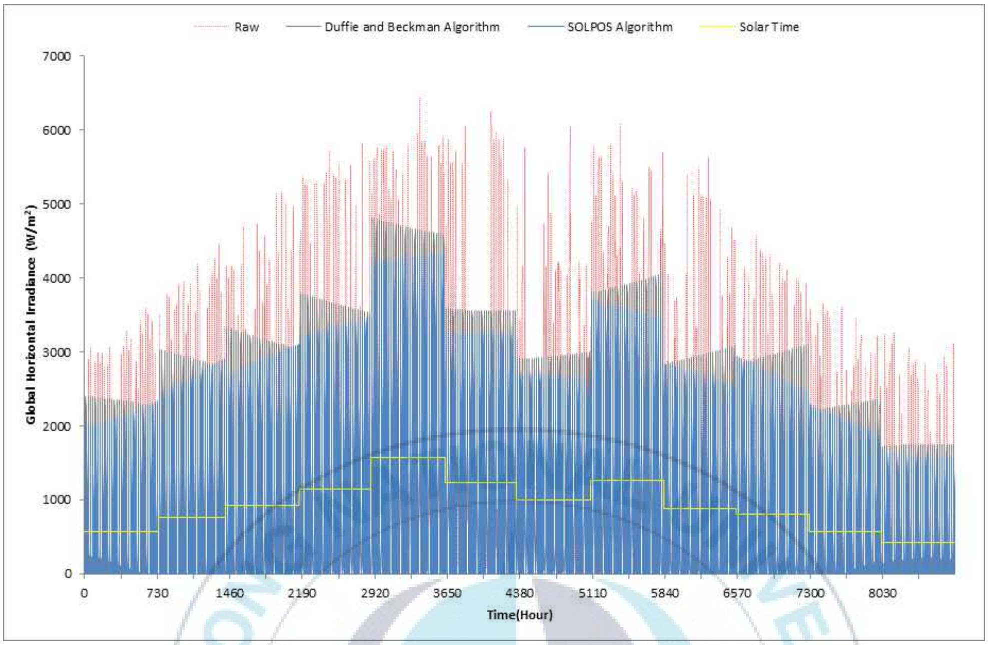


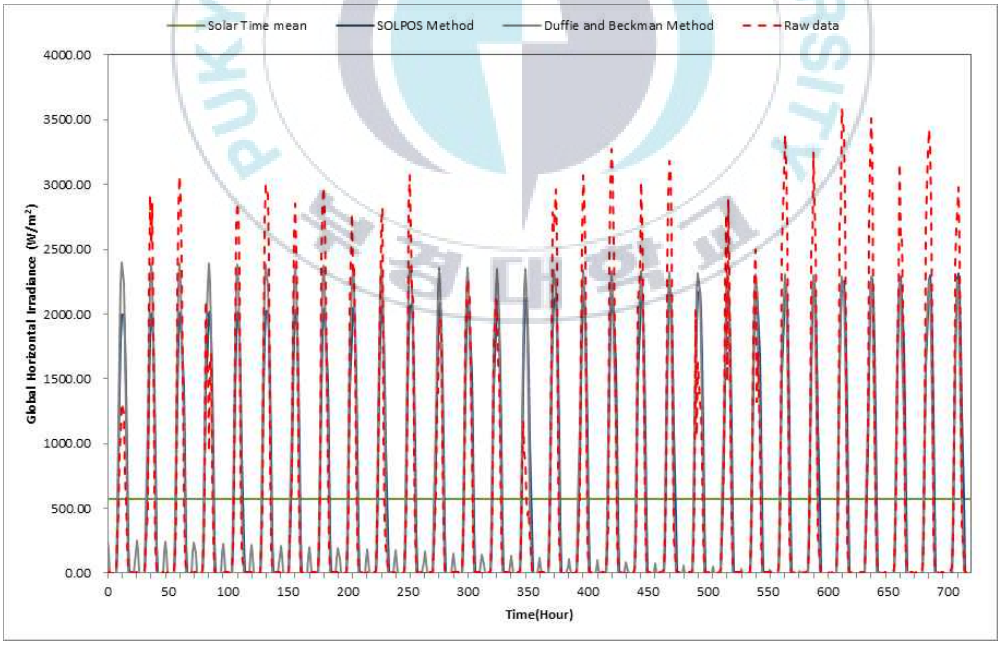
[Figure 4-13] Hourly irradiation at Yongdam Dam (unit: W/m^2)



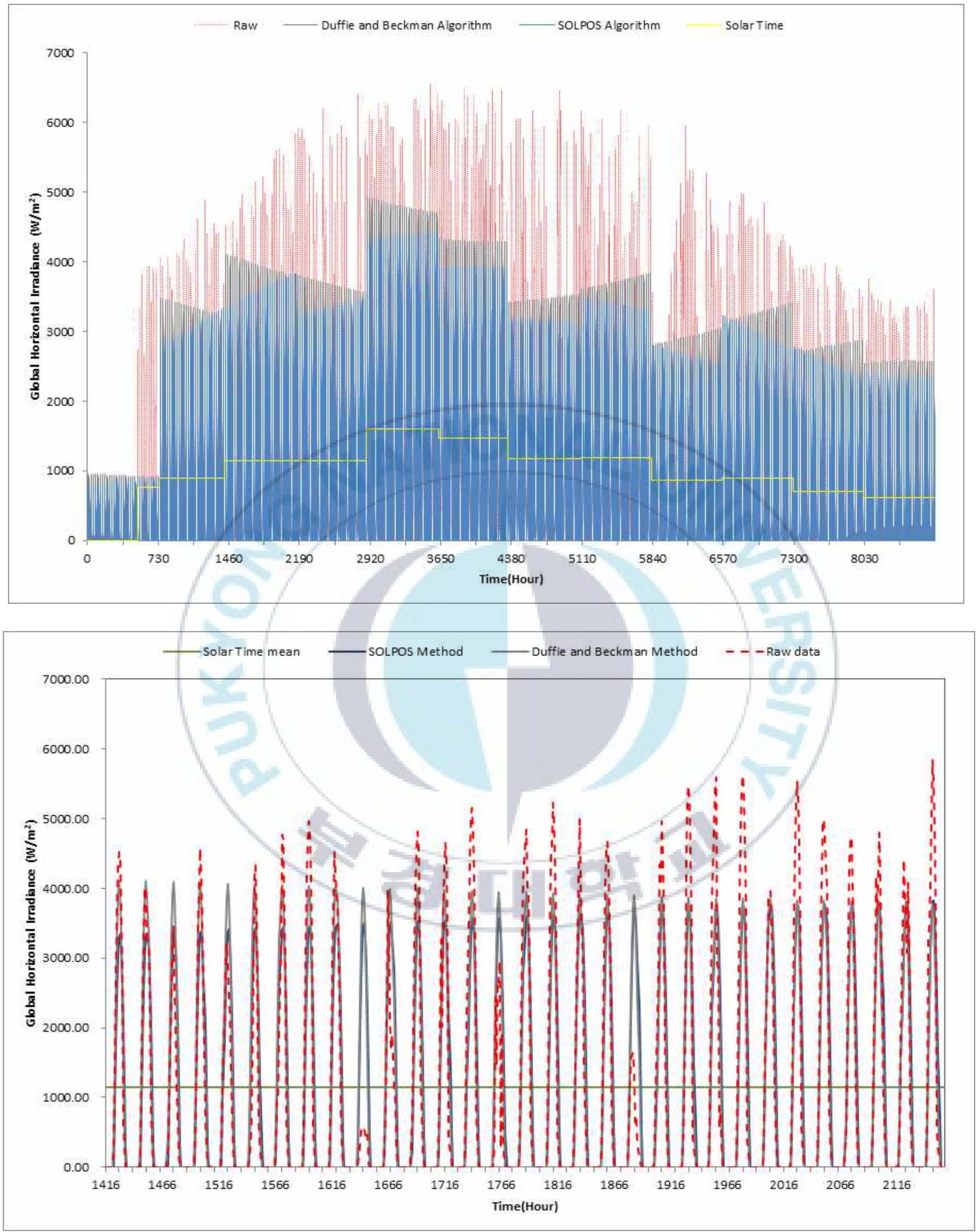


[Figure 4-14] Hourly irradiation at Yimha Dam (unit: W/m^2)





[Figure 4-15] Hourly irradiation at Chungju Dam (unit: W/m^2)



[Figure 4-16] Hourly irradiation at Hapcheon Dam (unit: W/m^2)

2. Solar Radiation Conversion and Error Analysis

Error analysis was conducted to quantitatively evaluate and validate solar radiation data converted into time units. The error was calculated by subtracting the actual measured solar radiation value from the converted time unit solar radiation, and the smaller the solar radiation data error, the more appropriate the conversion method is. The error analysis method uses Root Mean Square Error (RMSE), Mean Bias Error (MNE), and Mean Absolute Percentage Error (MAPE) methods according to the formulas below.

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{t=1}^{n} e_t^2} \tag{4.1}$$

$$\mathrm{MBE} = \frac{1}{n}\sum_{t=1}^{n} e_t \tag{4.2}$$

$$\mathrm{MAPE}(\%) = \frac{100}{n}\sum_{t=1}^{n}\left|\frac{e_t}{y_t}\right| \tag{4.3}$$

n : number of times by time zone used in solar radiation data

e_t : the difference between the converted solar radiation data and the actual measured solar radiation

y_t : Actual measured solar radiation

The average annual error analysis results of solar radiation values in hours measured at 16 domestic dams and solar radiation values in hours measured through the three previously mentioned conversion methods are shown in [Table 4-1] in Korea.

[Table 4-1] Error analysis of annual irradiation data

Site	Error	Arithmetic Mean	Solpos	Duffie & Beckman
Soyang Dam	RMSE(W/m^2)	832.1	455.69	432.01
	MAPE(%)	41.67	27.1	24.47
Chungju Dam	RMSE(W/m^2)	820.15	411.75	386.38
	MAPE(%)	41.32	26.89	24.16
Yimha Dam	RMSE(W/m^2)	869.09	444.03	422.49
	MAPE(%)	41.38	26.83	24.2
Hapcheon Dam	RMSE(W/m^2)	813.15	424.57	402.61
	MAPE(%)	41.44	27.03	24.26
Daecheong Dam	RMSE(W/m^2)	816.69	454.22	414.55
	MAPE(%)	41.31	27.6	24.9
Yongdam Dam	RMSE(W/m^2)	816.78	540.17	483.59
	MAPE(%)	41.38	28.24	25.16
Seomjin-gang Dam	RMSE(W/m^2)	798.9	411.67	389.31
	MAPE(%)	41.54	26.82	24.35
Boryeong Dam	RMSE(W/m^2)	763.51	403.82	395.87
	MAPE(%)	41.36	26.93	24.6
Bohyeon-san Dam	RMSE(W/m^2)	821.53	480.11	431.17
	MAPE(%)	41.41	28.07	24.97
Daeam Dam	RMSE(W/m^2)	827.48	411.8	387.62
	MAPE(%)	41.43	26.73	24.13
Seonam Dam	RMSE(W/m^2)	791.5	453.99	422.43
	MAPE(%)	41.43	27.58	24.85
Gucheon Dam	RMSE(W/m^2)	839.56	428.64	400.23
	MAPE(%)	41.47	26.97	24.0
Su-eo Dam	RMSE(W/m^2)	855.78	457.97	422.85
	MAPE(%)	41.4	27.23	24.34
Gunwi Dam	RMSE(W/m^2)	830.12	407.78	397.32
	MAPE(%)	41.3	26.63	24.02
Seongdeok Dam	RMSE(W/m^2)	764.92	408.18	391.57
	MAPE(%)	41.35	26.98	24.43
Gimcheon Buhang Dam	RMSE(W/m^2)	853.64	455.03	419.1
	MAPE(%)	41.56	27.27	24.51

The Duffie & Beckman algorithm uses the cumulative monthly solar radiation obtained from the solar radiation values in time, but the average annual solar radiation varies from the time-unit solar radiation values, depending on the values of the variables used for the conversion. This is also related to the average daily solar radiation value obtained from calculating the time-unit solar radiation value.

In the Duffie & Beckman algorithm, the cumulative monthly solar radiation is divided into the daily average solar radiation, and then converted into solar radiation in time units using the Global irradiance formula provided by Collares-Pereira and Rapl[34]. Through this process, low solar radiation in the morning and noon hours increases and high solar radiation in the evening hours decreases. Consequently, converting the cumulative monthly solar radiation to solar radiation per hour tends to result in errors as shown in [Figure 4-1~ 16] and increase the margin of error at sunrise or sunset. As a result, solar radiation errors at sunrise or sunset result in increased MAPE, as shown in [Table 4-1]. In this paper, it is more important to analyze the power generation prediction of PV systems occurring in time units than to analyze the error of solar radiation per year. Therefore, it is more necessary to simulate the monthly EPP using the actual irradiation data and the converted time-unit irradiation data rather than analyzing the solar radiation error itself and trying to determine the cause.

Ⅴ. PV Generation Simulation

1. PV Generation Overview

Using the converted solar radiation data obtained in Chapter 3, we run SAM software to predict the annual power generation of water photovoltaic PV systems. SAM software can simulate PV system power generation and loss power by comprehensively considering geopolitical location, meteorological characteristics, characteristics of PV modules installed in the field, and inverter output. Furthermore, the SAM program simulates the EPPs produced by specific PV systems on a time-by-time basis based on the features of the PV modules being built in practice and the solar radiation information over time. [28]

In this paper, Boryeong Dam, Chungju Dam, and Hapcheon Dam, which have PV systems installed on the domestic water surface, were selected for power generation simulation analysis. We input the time-unit solar radiation information transformed by the three methods mentioned in Chapter 3 into the SAM program to estimate the monthly average power generation value (R1~R3), and then compare it with the actual monthly average power generation data (R0). The current status of PV system power generation facilities for experimental measurements is shown in [Table 5-1], [Table 5-2] and [Table 5-3].

[Table 5-1] PV System Power Plant in Boryeong Dam

Module	Nominal Efficiency	16.65%
	Maximum Power	320 Wdc
	Maximum Power Voltage	39.06 Vdc
	Open Circuit Voltage	46.22 Vdc
	Short Circuit Current	8.21 Adc
Inverter	Efficiency	98.3%
	Maximum AC Power	1,000 kWac
	Maximum DC Voltage	1,100 Vdc
	Maximum MPPT DC	830 Vdc
	Minimum MPPT DC	550 Vdc
System Design	Module Capacity	2,004.48 kWdc
	Inverter Capacity	2GWac
	Tracking	Fixed

[Table 5-2] PV System Power Plant in Chungju Dam

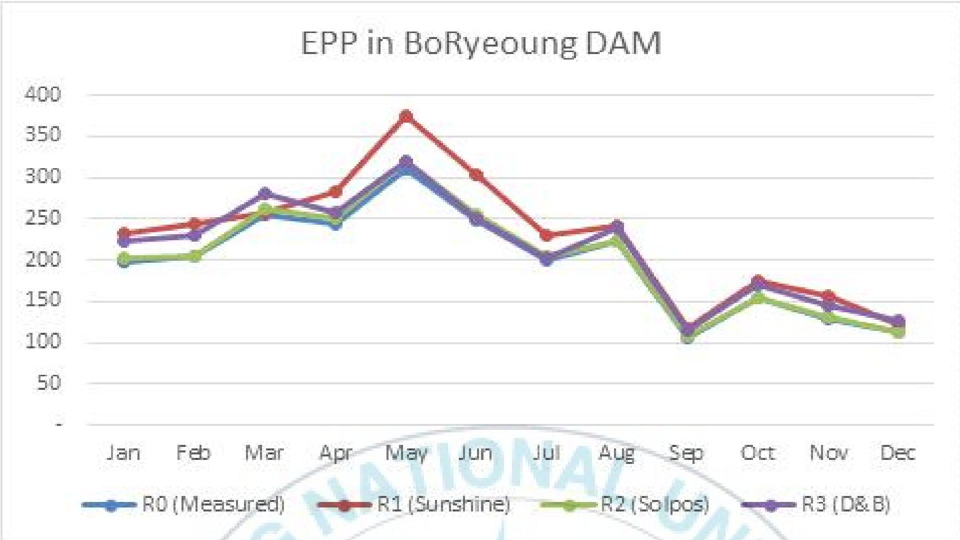
Module	Nominal Efficiency	17.82%
	Maximum Power	350 Wdc
	Maximum Power Voltage	38.96 Vdc
	Open Circuit Voltage	47.53 Vdc
	Short Circuit Current	9.65 Adc
Inverter	Efficiency	98.5 %
	Maximum AC Power	1000 Wac
	Maximum DC Voltage	1100 Vdc
	Maximum MPPT DC	830 Vdc
	Minimum MPPT DC	550 Vdc
System Design	Module Capacity	2994.84 kWdc
	Inverter Capacity	3000 kWac
	Tracking	Fixed

[Table 5-3] PV System Power Plant in Hapcheon Dam

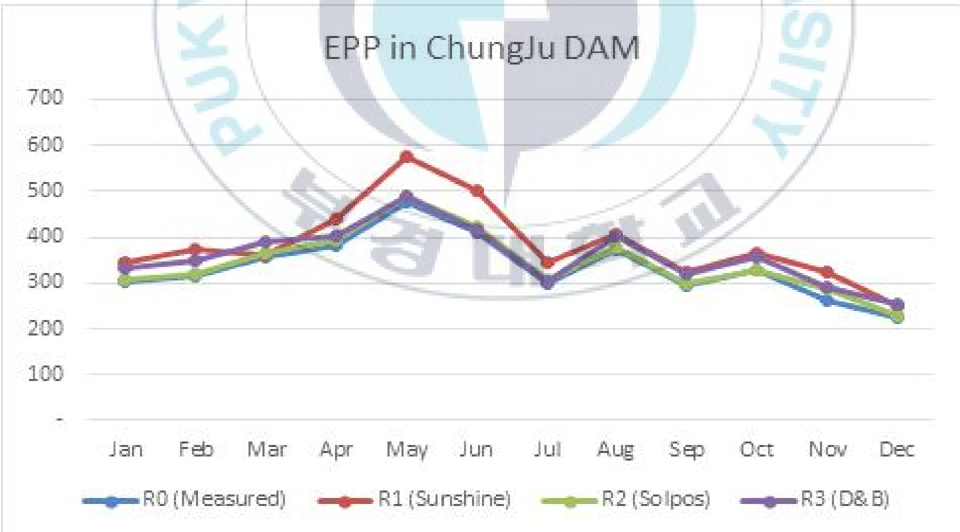
Module	Nominal Efficiency	15.5%
	Maximum Power	300 Wdc
	Maximum Power Voltage	36.22 Vdc
	Open Circuit Voltage	45.22 Vdc
	Short Circuit Current	8.91 Adc
Inverter	Efficiency	97%
	Maximum AC Power	500 kWac
	Maximum DC Voltage	950 Vdc
	Maximum MPPT DC	850 Vdc
	Minimum MPPT DC	460 Vdc
System Design	Module Capacity	496.8 kWdc
	Inverter Capacity	500 kWac
	DC to AC Ratio	-
	Tracking	Fixed

2. PV Generation Simulation Results

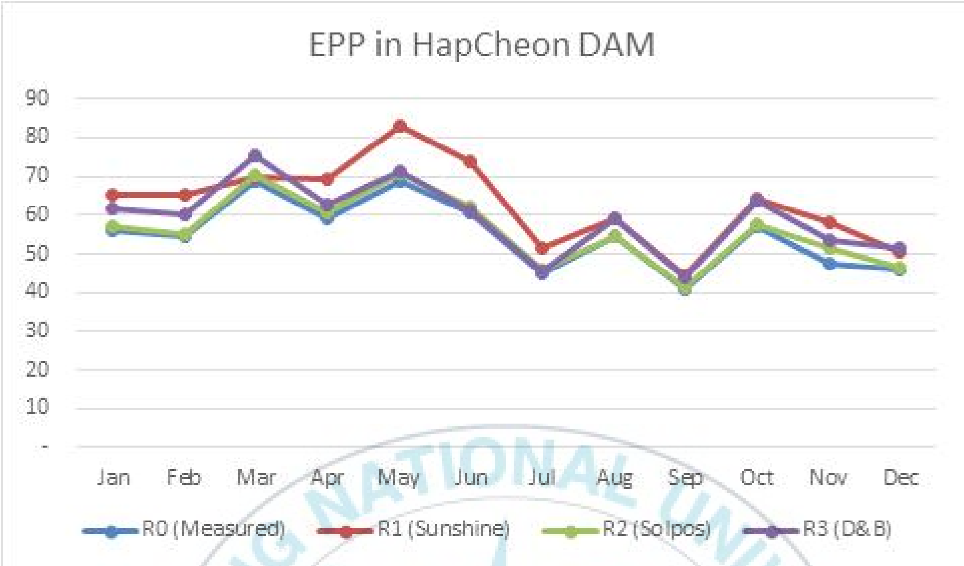
The monthly power generation produced by the Boryeong Dam-Chungju Dam-Hapcheon Dam and the amount of solar radiation converted into time units were shown in [Figure 5-1], [Figure 5-2] and [Figure 5-3]. In the figure below, R0 represents the amount of power actually developed in each dam, and R1-R2-R3 represents the estimated power generation by applying solar radiation by arithmetic mean method, Solpos method, and Duffie & Beckman method, respectively.



[Figure 5-1] Comparison of Monthly Average PV System Power Generation in Boryeong Dam (unit: MWh)



[Figure 5-2] Comparison of Monthly Average PV System Power Generation in Chungju Dam (unit: MWh)

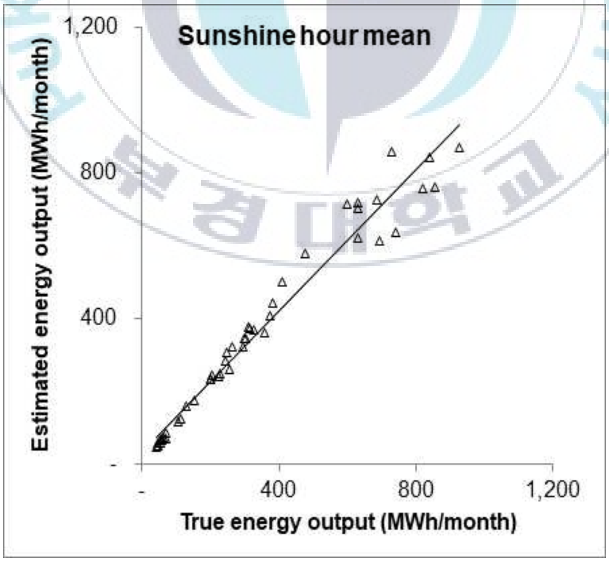


[Figure 5-3] Comparison of Monthly Average PV System Power Generation in Hapcheon Dam (unit: MWh)

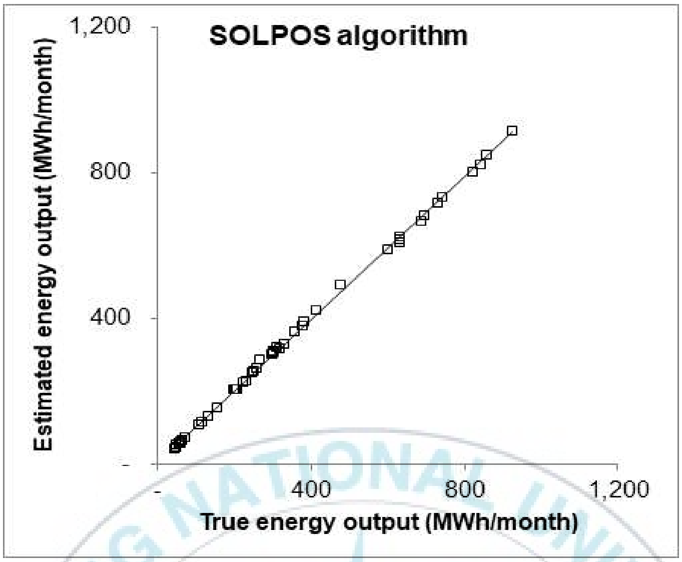
The power generation estimate calculated by the arithmetic mean method(R1) shows a relatively large difference from the actual power generation(R0), and the margin of error tends to increase from April to July. The power generation estimate calculated by the Solpos algorithm method(R2) shows the pattern of trend most similar to the actual power generation(R0), and the power generation estimate calculated by the Duffie & Beckman algorithm method(R3) also shows similar patterns to the actual power generation(R0), but the error occurs significantly compared to R2.

3. EPP Error Analysis

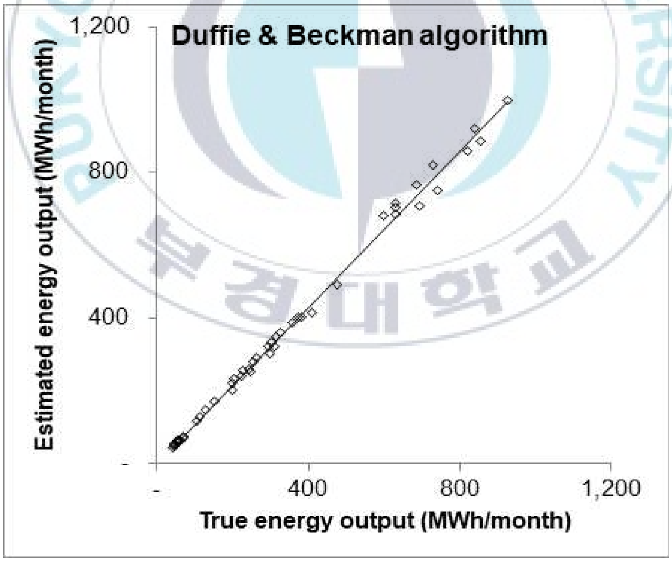
[Figure 5-4], [Figure 5-5] and [Figure 5-6] are the comparative distribution curves of monthly generation patterns and actual generation. is a comparison of monthly EPP change patterns. A straight line passing through the origin indicates the amount of power actually produced, and a marker around the straight line indicates the estimated amount of power generation, which means that the further the distance between the straight line and the mark, the greater the error. In the lower generation range, all three methods tend to be similar to the actual generation, but as the power generation increases, the estimated generation by Solpos method is similar to the actual generation, while the estimated generation by Duffie & Beckman method is more error-prone.



[Figure 5-4] EPP Error Analysis by Arithmetic Mean Method



[Figure 5-5] EPP Error Analysis by Solpos Algorithm Method



[Figure 5-6] EPP Error Analysis by Duffie & Beckman Algorithm Method

The calculations of RMSE, MBE and MAPE for PV system generation for each dam are as shown in [Table 5-4]. MAPE by arithmetic mean method has the highest error rate of 14.47%, 14.07%, or 14.35%, because the arithmetic mean method does not take into account the effect of actual solar radiation fluctuations when converting monthly solar radiation to solar radiation in time.

Among the three solar radiation conversion methods, the estimated generation error by the Solpos method is shown to be the lowest. The estimated power generation and actual power generation have a MAPE of 1.6%, 2.25%, or 2.33%, which is seen as the most objective way to estimate power generation by converting monthly cumulative solar radiation to solar radiation in hours. The estimated power generation and actual power generation of Duffie & Beckman was 8.09%, 7.32%, or 7.94%, slightly higher than the Solpos method.

[Table 5-4] Error Analysis Results for each dam

Site	Error	R1 (Sunshine Hour Mean)	R2 (Solpos)	R3 (Duffie & Beckman)
Boryeong Dam	RMSE(MWh)	34.6	4.56	16.37
	MBE(MWh)	29.52	3.58	14.68
	MAPE(%)	14.47%	1.6%	8.09%
Chungju Dam	RMSE(MWh)	54.81	9.75	25.08
	MBE(MWh)	48.32	7.46	23.07
	MAPE(%)	14.07%	2.25%	7.32%
Hapcheon Dam	RMSE(MWh)	8.74	1.66	4.71
	MBE(MWh)	7.9	1.27	4.28
	MAPE(%)	14.35%	2.33%	7.94%

Ⅵ. Conclusion

In this study, accumulated solar radiation data from domestic emergency-use dams were converted into solar radiation data in hours using arithmetic mean method, SOLPOS algorithm, and Duffie & Beckman, and compared to the actual solar power generation.

The EPP estimated by the arithmetic mean method showed a greater margin of error (MAPE 14.0% - 14.4%) than the actual value, because the arithmetic mean method does not take into account the degree of actual solar radiation variation. Based on the Solpos algorithm method, the estimated EPP is significantly similar to the actual EPP patterns and has a low margin of error (MAPE 1.6% to 2.3%) because Solpos method involves solar radiation changes over solar time and converts solar radiation by time. EPP estimated through Duffie & Beckman algorithm method is similar to actual EPP pattern, but margin of error (MAPE 7.3% to 8.0%) is higher than Solpos method.

The following conclusions can be reached through this study. When predicting EPP of a site scheduled for construction of a water solar power plant where no existing solar radiation data exists, it is reasonable to adopt the Solpos algorithm and convert it to usable solar radiation data. In order to increase the universal applicability and reliability of the Solpos Act, additional case studies are needed overseas, not domestically.

The Solpos transformation method proposed in this paper may not accurately predict all time-series power generation values over a day, but it is expected to help design and analyze solar power projects through prediction of power generation over a larger range.

Ⅶ. Reference

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