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Daylight illuminance calculation model and process for Building Integrated Photovoltaics (BIPV) Systems

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Abstract: In this paper, we propose a Daylight Calculation Model and Process (DICMP) for Building-Integrated Photovoltaics (BIPV) systems. In the field of solar energy application, BIPV system is being incorporated increasingly into the construction of new buildings in recent years. The trade-off when using BIPV technology is that it has the risk of diminishing the daylight availability that is useful for natural lighting, which is yet another valuable resource for minimizing a building's energy use and adding to its sustainability. Our research presents a calculation and process study for assessing the daylighting illuminance (DI) contributes to interior space when BIPV systems are used. Though, there are already common tools and software programs for calculating daylight illumination inside buildings, they either lack of accuracy or are very complicated to compute. And they are either not adaptive for manual calculation or BIPV system. This paper focuses in discussion of development and application of DICMP for BIPV system. This calculation model and process is important because the BIPV systems are semi-transparent, which allows them to admit natural light while also absorbing much of the solar energy to generate electricity through the PV panels. Our DICMP combines the addresses various sky conditions and takes into account light reflections of ground and opposite buildings. For verification, we have done computational simulations theoretically. According to our initial comparative studies, though there are some flaws in the clear sky condition, the simulation result has proved the effectiveness of DICMP. Especially for the overcast situation, the calculation results can match the simulation closely. For further study, a variety of equipment can be installed for measurement on an experimental prototype house. The calculation will be improved by adjusting its parameters. In sum, the paper summarizes our findings offering a valuable method taking practical factors from many aspects for designers of how to calculate DI for BIPV systems accurately and quickly.

Keywords: Daylight Illuminance; calculation model; BIPV System

1. Introduction

As energy crisis and sustainability issues have caught attention globally, solar energy is one of the best solutions introduced into different fields. Photovoltaic materials are used to replace conventional building materials in many parts. With the ability of generating electricity from sunlight, Building Integrated Photovoltaics (BIPV) system is a technology applied photovoltaics-materials architectural components in parts of the roof, facades of buildings. BIPV are being incorporated into the construction of new buildings increasingly. BIPV systems contribute enormously to a building's ability to generate electricity which can lead to Net Zero Energy Buildings (NZEBs). However, using BIPV has the risk of diminishing the daylight availability that is useful for natural lighting, which is yet another valuable resource for minimizing a building's energy use and adding to its sustainability. The BIPV materials are semi-transparent. They can generate electricity for the building, but they also reduce the indoor daylight level because of their opaque solar cells within the panels. Hence this may lead to increase the energy consumption of artificial lighting. Because of this, a methodology that combines the evaluation of indoor daylight level and then artificial lighting energy consumption also needs to be included.

Figure 1: Some of the images have shown the details of the experimental house of BIPV system on the roof of the building. There are two rooms and two windows in the house. Some of the images have shown the details of the photovoltaic panel. There are two different kinds of photovoltaic panels which are installed on the two windows. So a comparative study is possible.

This study is part of the BIPV system project. Our work aims to develop a method for estimating the average indoor daylight illuminance for the BIPV system, which is intended for manual calculations (also available for implementation in a computer spreadsheet). It is detailed enough to take all sky conditions (overcast sky, partly cloudy sky & clear sky) and the light reflected from the ground and opposite buildings into account.

2. The Overview of Daylight Calculation

Daylight calculation methods have been studied for decades. The common methods of Daylight Illumination (DI) calculation include ‘Lumen Method’, ‘Daylight Factors Method’ and other sophisticated software tools such as ‘Radiance’ which can handle complex conditions for detailed calculation. There are mainly two common approaches including ‘the Daylight Factor Method’ (the DF method) and ‘the Lumen Method’. By using a daylight factor DF, the DF Method can calculate the illuminance of any point in an interior space theoretically based on a known luminance distribution sky. The main problem with these approaches are low precision (IESNA, 2000) and the inability to calculate the direct sunlight situation. Similar to the DF Method, the Lumen Method is simple enough to allow manual calculations. However, it assumes an over-simplified room geometry (Saraji and Mistrick, 1993). Being the same as the DF method, it excludes the direct sunlight situation.

A number of sophisticated software tools such as 'Radiance' can handle complex room geometries and sky conditions for detailed daylight calculation. Though they are able to model complex room geometries and visualize the interior illuminance distribution, their computing time is too long (Vartiaenen, 2000). Therefore, relatively simple and sufficiently accurate approach is needed for our research in BIPV system.

3. The Calculation Process of the Daylight Illuminance

3.1. The Calculation Process of the Three Components

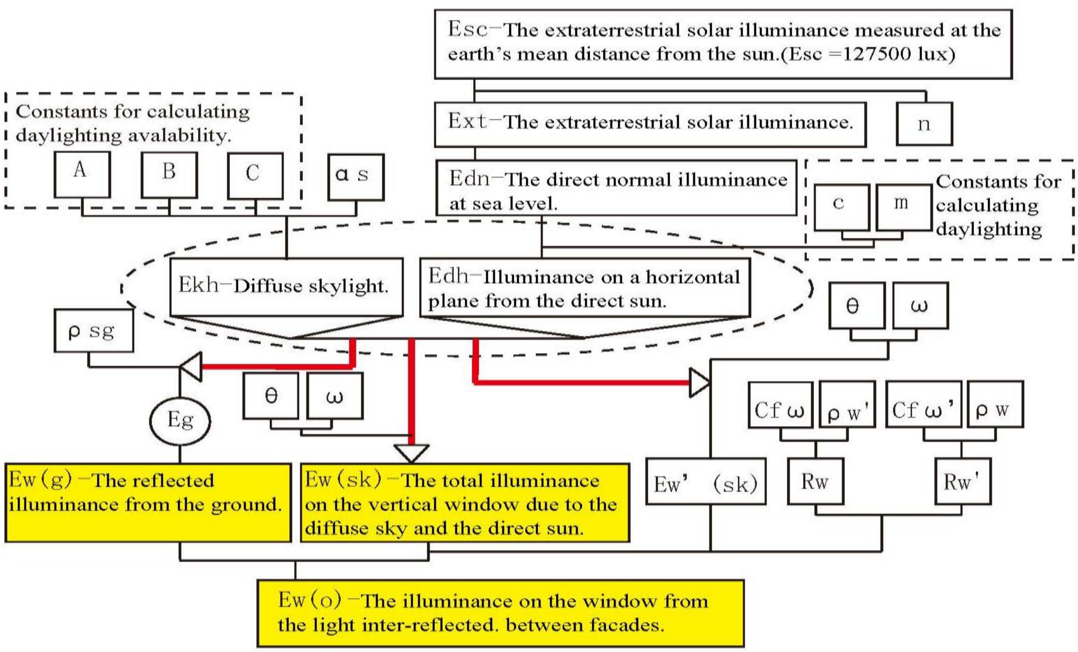

Figure 2: The Calculation Process of the three components of Ew(g), Ew(sk) and Ew(o) of the Daylighting Illuminance.

After modifying and improving usability and accuracy of previous methods, we applied a Daylight Illumination Calculation Model and Process (DICMP) for our BIPV systems research. Several constants, such as the extraterrestrial solar illuminance (measured at the earth's mean distance from the sun), are applied as parameters in the calculation process. The three components include: Illuminance due to the direct sunlight and the diffuse sky (Ew(sk)); illuminance due to the ground (Ew(g)) and illuminance due to the opposite obstructions (Ew(o)). They are the preconditions for indoor DI calculation in DICMP. Therefore, aimed for the three components. Our calculation starts from sun position, then daylight availability, sun and sky illuminance and reflected illuminance of vertical facade.

Table. 1 Parameters Explanation

θ	The angle of incidence of beam sunlight.
ω	The hour angle.
Esc	The extra-terrestrial solar illuminance measured at the earth's mean distance from the sun. (Esc =127500 lux)
Ext	The extra-terrestrial solar illuminance.
Edn	The direct normal illuminance at sea level.
Edh	Illuminance on a horizontal plane from the direct sun.
Ekh	Diffuse skylight.
A,B,C	Constants for calculating daylighting availability.
c,m	Constants for calculating daylighting availability.
α s	Solar altitude.
Eg	The mean ground illuminance.(Eg= Ekh+ Edh*ρsg)
Ew(g)	The reflected illuminance from the ground.
Ew(sk)	The total illuminance on the vertical window due to the diffuse sky and the direct sun.
Ew(o)	The illuminance on the window from the light inter-reflected between facades.
ρ sg	The fraction of the ground that is sunlit.
Rw	A ratio between the illuminance on the opposite façade and the reflected illuminance due to the opposite facade on the window.
Cfω	The configuration factor which depends on the size and shape of the obstruction.
ρ w	The reflectance of the facades.

In this section, how to estimate the three components of DI will be described. By using these illuminance together with the transmittance of window, the mean interior illuminance can be determined. Figure 2 shows the calculation process of the three components of the daylighting illuminance. The following sections show how the three components of daylighting illuminance can be calculated based on the process in Figure 2.

3.2. Daylight Availability

This part of calculation aims to evaluate the amount of light from the sun and sky by concerning a specific time, date and sky condition at a specific location. Because the daylight comes from sun, when concerned the amount of light from the sun and the sky, the position of the sun has to be specified first. Then the illuminance of the direct sunlight can be quantified. The parameters in these calculations are come from Diasty (1998).

Variation of the distance between sun and earth should be taken into account because it may lead to variation of extra-terrestrial radiation flux in the range of $\pm$3% (Duffie and Beckman, 1980). Edn, corrected for the attenuating effects of the atmosphere, can be estimated from the extra-terrestrial solar illuminance. So we use equations for calculation with the parameters from IESNA, 2000. For diffuse light from the sky, it is an important component which depends on the conditions of the sky. The sky cover method is utilized to evaluate the amount of cloud cover. The total horizontal illuminance due to diffuse skylight Ekh can be expressed as a function of the solar altitude.

3.3. Sun and sky illuminance on the ground & vertical facade

Whether the ground receives direct sunlight can be determined by the following instructions. The equations have been generated for the situation when the ground is partly sunlit when meeting the conditions. The equation shows that the window will receive direct sunlight if the associate conditions it can be satisfied. The situation when the daylight from the diffuse sky blocked by obstacles around has also been addressed in the calculation. In the end, the total illuminance of vertical window from direct sunlight and the diffuse sky can be evaluated.

3.4. Reflected illuminance of vertical facade

Two sources-light reflected from the ground and the light reflected from the opposite façade-contribute to the reflecting light on the vertical façade. Ew(o)-the illuminance on the vertical window from the light inter-reflected between facades can be calculated.

In the end, the three components of DI of the reflected illuminance from the ground (Ew(g)), the total illuminance on vertical windows caused by diffuse sky and direct sun light (Ew(sk)), and the illuminance on windows from the light reflected between facades (Ew(o)) are all calculated for our system. These components can be used for further calculation in the following sections as the luminous sources on the vertical windows.

3.5. The calculation of illuminance on work plane (ceiling, window wall, working plane)

By utilizing the three illuminance components and taking the transmittances of windows into concerned, the mean illuminance on work plane can be evaluated (Tregenza, 1995). Ac, Av and Ap are respectively the area of the interior surfaces of different parts of the room. For semi-transparent BIPV modules, Aw is the area of the whole module excluding the solar cell area. The above formulas are the direct interior illuminance on the individual surface. The window transmittance parameters and their typical values for all scenarios are given by Tregenza's paper. By using the three illuminance components (Ew(g), Ew(sk), Ew(o)) as the luminous sources, the mean direct illuminance on the receivers of the room surfaces of ceiling, walls and working plane (Eci, Evt, Ept) can be calculated.

The mean illuminance over all room surfaces from inter-reflected light Er can be calculated by using the mean direct illuminances of Eci, Evi and Epi. Then the final illuminance on various working planes Ep can be calculated by making sum of Epi and Er. Therefore, the average illuminance on the working plane can be determined.

4. Results and Discussion

Through programming, the calculation methodology described above can be implemented through spreadsheet program. The role of the spreadsheet program can be used in the further experimental research. The calculation results can be the reference to the simulation and experimental data for comparison.

Since the project is located in Wuhan, China, we use the local information and conditions for calculation. By entering into a spreadsheet software the primary parameters of day numbers, hours, latitude, the hourly indoor daylight illuminance can be calculated.

In this stage, for comparison and insurance, another computational method by applying the software tool DIVA-for-Rhino is introduced. DIVA-for-Rhino is an optimized daylighting and energy modeling plug-in for the Rhinoceros - NURBS modeler. The plug-in was initially developed at the Graduate School of Design at Harvard University and is now distributed and developed by Solemma LLC. DIVA-for-Rhino allows users to carry out a series of environmental performance evaluations of individual buildings and urban landscapes. The simulation core of DIVA comes from the well-known software tools Radiance, which has been widely recognized as a suite of programs for the analysis and visualization of lighting in design.

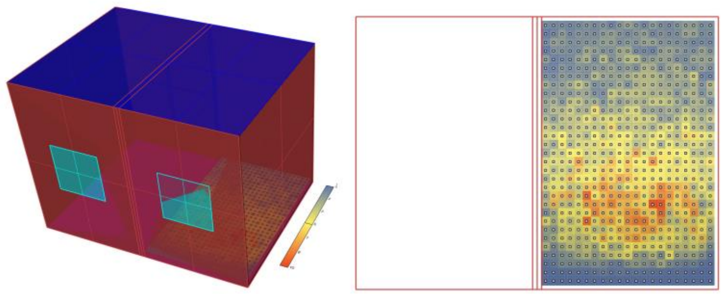

Figure 3: The daylight simulation in DIVA-for-Rhino. Display of the 3D model and horizontal illuminance from the daylight simulation results in DIVA-for-Rhino

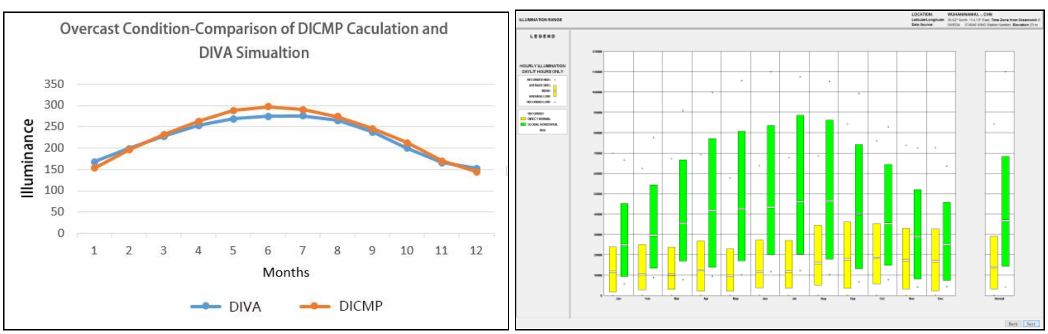

Figure 4: The comparison of indoor daylight values in DIVA, DICMP and Hourly Illumination (daylight hours only, Climate Consultant, Data source: SWERA)

First, the models for simulation are generated based on the experimental BIPV house. Second, we download the local climate files (Eqw format) from the weather data website of Energy Plus. By entering the primary parameters, the hourly indoor daylight illuminance can be calculated in DIVA (Figure 3). The simulation result can be used to compare with the results of daylighting illuminance from the calculation spreadsheet. From the comparison, the simulation results in DIVA is consistent with the spread sheet programing result of daylighting illuminance.

After several rounds of simulation in DIVA, for the overcast situation, the calculation result of our DICMP can be well matched to the analysis of DIVA. This has been shown in the Figure 4. We calculated and simulated the daylighting illuminance (lux) on the time of 2 pm on the 15th day of every month from January to December. The blue line presents the illuminance results simulated by DIVA, and the orange one shows the results from our DICMP calculation. We can see that the differences within these two is quite small. Moreover, by comparing them with the Hourly Illumination (Climate Consultant, Data source: SWERA), we can find them have the same trend from the 1st month to the last month. This can further prove the rationality of our calculation and simulation by comparing the detailed illuminance density. Another aim has been achieved is that, DICMP

Though lots of tests have verified the DICMP, we have to admit that there are flaws for the situation of clear sky condition. The main problem we find is that the DICMP results can't match the simulation in summer months. The DIVA analysis can match the results for the first three months. However, following DIVA results have shown that the illuminance has the trend to decrease in summer time, which is opposite compared to DICMP. This will be our future study to find out the exact reasons. For now, we proposed the cause can be the differences of calculation method. For outdoor daylight illuminance, it goes up from January. It usually reach the peak in the midsummer. The simulation from DIVA goes down should be the reason by taking account of the shape of the test room and the window position. As the altitude of sun becomes higher, the sunlit area in the room becomes smaller. Though the density of sunshine increases, the mean illuminance of the room decreases. For further study, a variety of photovoltaic panels and devices will be installed for measurement on an experimental prototype house. The DICMP can be improved by adjusting the parameters.

8. Conclusion

In this study, our purpose was not to investigate the principle of daylighting model in details and develop an entirely new daylighting illuminance theory. Instead, we set up a suitable DICMP as an important part of the energy performance of the semi-transparent BIPV system. Compared to the previous methods, DICMP is not only simple enough for manual calculation, but it also allows for computer spreadsheet programing by taking different sky conditions into account.

In the project, the method of assessing the DICMP for BIPV systems have been discussed for the modules. It can estimate the average indoor DI by taking the direct daylight, the diffuse daylight, the reflected light (from the opposite building and ground) and all sky conditions into concerned. The DICMP enables researchers to calculate the hourly indoor daylight illuminance by implementing a spreadsheet program in a short time. As power saving is an important component of BIPV modules, DICMP enables estimating the power saving of the artificial lighting due to the daylight utilization.

According to our comparative studies, though there are some flaws in the clear sky condition, the simulation result has proved the effectiveness of DICMP. It will be our future study to improve it further. Our findings offering a reference and valuable overview for designers of how to calculate DI for BIPV systems quickly, simply and accurately. It is also an essential part for evaluating the performance of the BIPV modules which is sufficient for the requirement of the project.

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