BUILDING INTEGRATED PHOTOVOLTAICS IN A THERMAL BUILDING SIMULATION TOOL

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ABSTRACT
A simple approach for calculation of the electrical yield from building integrated PV (photovoltaic) systems has been implemented in BSim2002 - a program package for thermal simulation of energy and indoor climate conditions in buildings. The module – SimPv - takes advantage of the building model geometry and solar distribution routines of BSim to simulate solar irradiation on a face fitted with PV. The routines also handle shades from local and distant obstacles.

The electric yield is calculated in SimPv from a very limited number of data on the PV system. Output is summarised from each individual face containing areas with PV.

SimPv is intended as a simple tool to help the engineer or architect at the early stage of the building design to evaluate the potential for implementing PV in the building envelope, allowing detailed analyses of the shading problem at any time of the year. The influence from shadings can be visualised dynamically and the impact on the electrical yield calculated for any period of the year. Thus, SimPv is not a detailed PV design tool, but a decision making design phase tool.

Results from simulations with SimPv have been compared with results from the PvSyst program. This paper discusses the calculation approach used in SimPv and results from an inter-model comparison exercise.

INTRODUCING BSIM
BSim (Wittchen, Johnsen & Grau, 2000-2003) is a computational design tool for analysis of indoor climate, energy consumption, moisture and daylight performance of buildings. BSim integrates different computer models that make it possible to carry out a complete thermal, moisture and daylight analysis of a building. The analyses are made, considering typical indoor use of the building, the influences from the outdoor environment, and various types of typical equipment, internal loads and controls for heating, cooling and ventilation.

The core of the system is a common building data model shared by the design tools, and a common database with typical building materials, constructions, windows and doors. Figure 1 shows a typical screen picture from BSim.

Figure 1. Screen picture from BSim. At the right, four views show the model graphically and at the left a hierarchic tree structure shows the individual objects of the model, e.g. the construction ConcreteFloor.

A more general description of the BSim2002 package is given in (Grau, Wittchen & Grau, 2003).

PV SIMULATION APPROACH
A very important problem to analyse when the building designer considers integrating PV systems in the building envelope, is the shading issue. Even limited partial shading can cause the electrical production from the system to approach zero. The reduction due to shading is seldom proportional to the shaded area, e.g. if no special arrangement is made, shading of one solar cell in a 36-cell array, can reduce the collective production from that array to 10% or less (Hagemann, 2002) & (Sick & Erge, 1996).
In SimPV an estimate of the yield from a building integrated PV system is calculated for a given location on the building model. Shadows striking the solar cells, which will reduce the yield to almost zero, are taken into account. The yield is calculated as:

\[ Q_{pv} = \varepsilon_1 \cdot (I_{df} + I_{dir} \cdot (I_0 - \frac{A_{shd}}{A_{pv}}) \cdot f) \cdot A_{pv} \cdot F_{pv} \]

where:

- \( \varepsilon_1 \) is the total efficiency (solar cells, converter, cable-losses etc.) in the solar cell system. The system efficiency is defined in the materials part of the program database as shown in figure 2.
- \( I_{df} \) is the diffuse solar power on the PV-array.
- \( I_{dir} \) is the direct solar power on the PV-array.
- \( f \) is a factor indicating if a part of the area is shaded.
  - \( f = 1 \) if \( A_{shd} \leq 0 \);
  - \( f = \text{ShdEff} \) if \( A_{shd} > 0 \) and \( \text{PropShadRed} = 0 \);
  - \( f = 1 - F_{pv} \) if \( A_{shd} > 0 \) and \( \text{PropShadRed} = 1 \).
- \( A_{pv} \) is the total area of the solar cell system.
- \( A_{shd} \) is the shaded area of the PV system.
- \( F_{pv} \) gives the active fraction of the total PV area \( A_{pv} \).
- \( \text{ShdEff} \) is a user-defined efficiency for the shaded area of a PV system. In most PV systems, the efficiency will be in the magnitude of 10 %, but use of amorphous solar cells or special attention wiring the individual cells in the panels according to local shading patterns, can increase the number.
- \( \text{PropShadRed} \) is a user given property flag indicating that the actual PV-array has proportional yield reduction when hit by partial shading. Most PV-arrays will have a dramatically reduced electrical output if even a small part of the active area is shaded. It is though possible, by means of wiring or use of amorphous solar cells to have a reduction proportional to the shaded area.

Analogue to this, the nominal yield can be calculated as if no shading hits the area as:

\[ Q_{pv} = \varepsilon_1 \cdot (I_{df} + I_{dir} \cdot A_{pv} \cdot F_{pv}) \]

This result can be used to calculate the "performance ratio" which express how large a yield is possible from an area compared to the actual yield taking into account losses from shadings.

Results from SimPv are given as monthly summations of the electrical production from each surface with integrated PV. Calculations are though made on time step basis (maximum ½ hour) and results are thus calculated with this resolution to take into account the varying shading over the day. The results calculated on hourly basis is saved in a result file and can be merged with the overall result file of BSim. It is thus possible to compare the hourly electrical output from a PV system with other electrical requirements elsewhere in the thermal building model, e.g. consumption of electricity for the engines in the mechanical ventilation system.

![Figure 2. System definitions in the materials database.](image)

![Figure 3. User interface for SimPv simulation results. The No shading reduction flag makes it possible to turn shading on and off and easily calculate the performance ratio.](image)
tion of the electrical production without taking into account the effect from shading. This is helpful if the user wants to find locations for PV or to analyse the influence of shadowing or the performance.

The monthly results are interesting for estimates of the total electrical production from a PV system, but not for analyses of the daily variations. It is thus planned to incorporate the results from SimPv in the result analyses of tsbi5 (the thermal simulation tool of BSm2002), to be able to compare the PV-output with, for instance, the electricity need of the ventilation system hour-by-hour. This will make it possible to make an approximate sizing of the PV-system that never creates more electricity than needed inside the building at any time. Such analyses are interesting when the price of buying and selling electricity to the public grid differs.

SHADING CALCULATIONS

Shadows on a PV area originates from various sources as the building itself, neighbouring buildings or obstacles and mounting system for PV-panels. The shadows from the building and distant obstacles are dealt with, using the defined geometry in the building model. Shadows from the mounting system do however have to be defined individually for each PV-area.

Shading calculations in the SimPv module are made using another build-in application, XSun. This is originally an implementation of polygon clipping for determination of shades on windows located in a plane surface, e.g. the facade of a building (Grau & Johnsen, 1995). PV-panels and the shading objects are approximated by convex or concave polygons. Using polygon clipping, the fully or partly exposed regions of the PV-panels are calculated as regions of polygons, each polygon receiving a fraction of full solar radiation, dependent on the factor of transparency of the shading objects. For each PV-panel, an overall reduction factor, \( f_{sun} \) is calculated as

\[
f_{sun} = \frac{I}{A_{PV}} \sum_{k=1}^{n} A_k f_k
\]

where:

\( f_{sun} \) is the fraction of the direct solar radiation reaching the PV-panel, compared to the direct radiation that would reach the PV-panels without any shading.

\( A_{PV} \) is the PV-panel area.

\( n \) the number of polygons in the calculated radiated region (the PV-panel).

\( A_k \) is the area of polygon \( k \).

\( f_k \) is the factor of transparency for polygon \( k \).

XSun can be used in two different ways in BSim:

(1) For visual, animated analysis of shading conditions at any time of the year.

![Figure 4. Example sketch of mounting system for PV-panels and indication of shading edges.](image)

Figure 4. Example sketch of mounting system for PV-panels and indication of shading edges.

When dealing with local shadows from the mounting system, the program assumes that it is symmetrical along all edges of the PV-panel. Local shadows are the defined by a frame distance and a recess. The frame distance is the distance from the solar cells closest to the edge and to the shading edge (point a or b in figure 4). The recess is the distance perpendicular to the solar cells to the same shading point.

Besides local shadows, more distant geometrical objects as overhangs and side fins, or other shading objects, e.g. surrounding buildings or trees, may obscure PV-panels. The shading objects may be transparent in any degree, from non-transparent to completely transparent.
To be called as a calculation routine to generate a value of the reduction factor \( f_{\text{sun}} \) for each PV-panel at any given time of the year. This routine is used both in SimPv and in the thermal simulation tool, tsbi5, which is part of the BSim2002 program package.

In SimPv the \( f_{\text{sun}} \) factor is used to calculate the \( A_{\text{shd}} \) area as:

\[
A_{\text{shd}} = A_p (1 - f_{\text{sun}})
\]

**SOLAR INCIDENCE**

Calculation of incident solar radiation on PV-panels and windows and includes the following tasks:

First, the position of the sun is calculated for a certain day of the year at a given time. According to the sun's position, the shading objects are projected onto the surface with the actual surface (PV-panel or window). As the sun is at an infinite distance, the projection is a parallel projection in the direction of the sun. The projection gives the patch of the shadows on the surface.

Each sunlit surface is represented as a polygon receiving full radiation. By clipping this polygon against all the projected shadow patches in turn, the result becomes a region of polygons within the surface receiving full radiation, or a fraction of radiation dependent on the degree of transparency of the shading objects. For each surface, the overall reduction factor, \( f_{\text{sun}} \) is calculated as described earlier.

**MODEL COMPARISON**

An example was set up to compare the results from the SimPv module with the results from PvSyst. The model consists of three surfaces equipped with an array of solar cells, a flat roof, a 45° sloping surface and a vertical face. Each of the faces has a PV system of 20 panels, measuring 0.66 \( \times \) 1.32 m\(^2\) (figure 6). The model was rotated for comparison of results on different orientations (facade and tilted roof).

To make the comparison possible, the overall system performance used as input parameter in SimPv originates from a detailed simulation performed in PvSyst.

Results from the simplified calculation approach used in SimPv and BSim2002 have been compared to the detailed simulations performed by PvSyst.

Annual differences in the calculated electrical production were found up to 15% on selected surfaces. However the average discrepancy between the two tools was found as low as 2%. A comparison of the monthly electrical production from a south facing 45°-tilted surface is shown in figure 7. There is an almost perfect match during the summer months and a somewhat larger difference during the months with less solar incidence and lower solar altitude.
The program are specifically designed to focus on the shading problem of any building integrated PV-installation. SimPv is not a PV design tool and does not take into account losses if the geometry of the building requires special wiring or other special features of the electrical part of the installation. It is thus not possible to analyse the influence of a poor system design, e.g. high quality solar cells connected through long, thin wiring to an oversized AC/DC converter.

For the time being there is no thermal connection between the building model and the PV system in BSim. There is for instance not transfer of heat from solar cells integrated in windowpanes to the room inside the window. To evaluate this energy flow it is necessary model the window using the optical and thermal properties of a window with integrated solar cells.

**CONCLUSIONS**

A simple model has been developed for early design analyses of the possible electrical yield from a building integrated PV-system. In the early design phase SimPv is a valuable tool for selecting appropriate locations for integration of PV in the building skin.

The model has been implemented in a simple design tool, SimPv, which is integrated into a thermal building simulation package, BSim2002. The advantage is the reuse of the building model and the calculation of shadows from the building itself and the neighbouring buildings.

The simplified routines in SimPv have shown satisfactory accuracy, when compared to results from the advanced PV simulation tool PvSyst. An average discrepancy of 2% was found when comparing the electrical output from PV systems integrated in surfaces with different orientations and inclinations.

Due to the simplified routines in SimPv the tool must not be considered a design tool, but only a rough calculation of the yield to help the building owner decide to have building integrated solar cells or not. When the decision is made, an advanced PV design tool must come into action.

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**REFERENCES**


**INTERNET SOURCES**

Danish Building and Urban Research: www.dbur.dk

Esbensen Consulting Engineers: www.esbensen.dk

Danish Technological Institute: www.teknologisk.dk

BSim2002: www.bsim.dk

PvSyst: www.pvsyst.com