Simulation of Rooftop Photovoltaic Shading using TRNSYS

Sleiman Farah*, David Whaley, Wasim Saman

University of South Australia, School of Engineering, Barbara Hardy Institute
Adelaide, Australia
sleiman.farah@mymail.unisa.edu.au

Abstract—The shade effect of a rooftop photovoltaic (PV) collector on a roof is usually ignored in building energy simulation in Transient System Simulation (TRNSYS) software. This disregard is due to either the unavailability of a suitable shading component in the simulation software or to an assumption that the shade on opaque surfaces, such as roofs, has small impact on the indoor temperature and the subsequent heating and cooling energy usage. However, for a relatively large collector area, ignoring the collector shadow on the roof may produce inaccurate results. In this paper, a novel component is developed in MATLAB to simulate the shade effect of a collector using TRNSYS. The component is based on an isotropic diffuse sky model to calculate the beam and diffuse radiation blocked by the collector. The preliminary results show that 782 degree-hours of cooling can be saved, however, 1649 degree-hours of additional heating is required. The results indicate that for a large collector area the collector shade on the roof should be considered to be able to accurately estimate a dwelling's heating and cooling energy usage.

Keywords-Solar; Shade; Photovoltaic; TRNSYS; Heating and cooling

I. INTRODUCTION

Australia has a significant amount of installations of rooftop photovoltaic (PV) collectors, with approximately one in six houses having a small scale rooftop PV system installed on the roof [1, 2]. While these collectors provide electricity, they also block beam solar radiation from reaching the roof surface. Rooftop PV collectors also block the view of both sky and ground from the roof; reducing the diffuse radiation reaching the roof surface. Therefore, to achieve an accurate energy simulation of a rooftop PV collector interacting with a building, the collector's shading effect should be considered.

Several building energy simulation software, such as EnergyPlus, Integrated Environmental Solutions (IES) and Transient System Simulation (TRNSYS) can simulate complex building models [3, 4]. Among these software, TRNSYS seems the most complete software; having an extensive library of components and the flexibility for the user to develop and add customized components [5]. The latest version of TRNSYS includes the feature of importing 3-dimensional (3D) building models developed using TRNSYS3d plugin in SketchUp [6]. The 3D building model can include shade elements which are used by TRNSYS building component (Type56) to calculate the solar radiation reaching transparent surfaces such as windows. For instance, the effect of adding an overhang shading element above a window is considered in the software and therefore reduces the amount of solar radiation reaching the window. However, the effect of a shading element on an opaque surface, such as that of a solar collector on a roof, is not considered in the calculation of incident solar radiation on the surface [7]. This limitation may not have a significant impact on the energy usage of the building simulation when the shading element is relatively small. However, impact of the shading element should not be ignored when the shading element area is large, such as that of a solar collector, which could cover a significant area of a roof.

II. TRNSYS SHADING COMPONENTS

A few shading components are available in TRNSYS such as Type34, Type64, Type67 and Type1252. Type34 can calculate the solar radiation reaching a vertical receiver which can be either a wall or a window. This component reads solar radiation inputs, such as total and diffuse horizontal radiation, and calculates solar radiation reaching the receiver taking into account the geometrical parameters of the obstruction, such as depth and width of an overhang. The component uses the isotropic diffuse sky model to calculate the beam, sky diffuse and ground-reflected radiation [8]. The beam radiation that reaches the receiver is calculated using an algorithm that calculates the irradiated fraction area of the receiver. The shading effect on sky diffuse and ground-reflected radiation is considered by the calculation of sky and ground view factors taking into account the obstruction geometry [8]. However, Type34 considers only vertical receivers and obstruction elements positioned outside the receiver boundaries; making this component unsuitable for simulating the shade of a collector on a roof where the obstruction element (collector) is usually located within the receiver (roof) boundaries.

Type64 uses the angular heights of the obstruction to calculate the amount of obstructed radiation. This component considers the same angular heights of the obstruction geometry from an arbitrary location for all considered surfaces. By contrast, Type67 considers the angular heights of the obstruction geometry from the center of each of the considered surfaces; making the shading effect modelled in Type64 a special case of the model in Type67. Both of these components read the angular heights for different absolute values of azimuth angles provided by the user in an external file; this file provides the geometric information of obstructions for 360º around the considered surfaces [8]. The use of Type67 seems suitable when the area of the considered surface is relatively small and the obstruction is relatively far from the receiver; allowing a relatively precise description of the obstruction geometry by the angular heights measured from the center of the considered surface. However, for the simulation of the shade effect of a rooftop PV collector on a roof, the use of Type67 is unsuitable as the roof area is

usually large and the collector is close to the roof; making the representation of the collector by one angular height inaccurate.

Type1252 is used to calculate the beam radiation blocked by an obstruction near the considered surface. Similar to the previous components, Type1252 requires geometric parameters of the obstruction, such as the start and end angles of the obstruction [8]. The use of this component for modelling the shading of solar collector on the roof does not consider the diffuse radiation blocked by the collector. In addition, modelling the shading based on one start and one end angle of the obstruction may lead to significant errors, especially in the case of a large roof space.

This review reveals that the available shading components in TRNSYS cannot correctly simulate the shading effect of a rooftop PV collector. In addition, these components do not make use of the obstruction 3D data available in the SketchUp model. The use of these components requires additional input to describe the obstruction geometry and position which may lead to discrepancies with the SketchUp 3D model.

This paper therefore presents a method used to develop a TRNSYS component in MATLAB using Type155 to evaluate the shading effect of a rooftop PV collector on the heating and cooling energy usage. The developed component simulates the effect of the collector shade by considering beam and diffuse radiation blocked by the collector (prevented from reaching the roof). The developed component use the 3D data available in the SketchUp model; maintaining consistency between the TRNSYS model and the 3D model, and minimizing the number of inputs required to describe the geometry of both the collector and the roof.

III. METHODOLOGY

A. Collector Shading Component

The calculation of solar radiation blocked by the collector and solar radiation reaching the roof is based on the isotropic diffuse sky model. This model considers that solar radiation consists of three elements: beam, sky diffuse and ground-reflected radiation [9]. Each of these elements is treated separately by the developed component to calculate the solar radiation reaching the roof. Based on the isotropic diffuse sky model, and without the existence of an obstruction, such as the solar collector, the total solar radiation (I_T) reaching a tilted surface such as the roof can be represented by equation (1)

$$I_T = I_{bT} + I_d VF_{sky} + I \rho_g VF_{gnd} \qquad (1)$$

where I_{bT}, I_d, VF_{sky}, I, ρ_g, and VF_{gnd} are the beam radiation on the inclined surface, the sky diffuse radiation on a horizontal surface, view factor from the roof to the sky, total radiation on a horizontal surface, ground reflectance, and view factor from the roof to the ground, respectively. Nevertheless, with the existence of a rooftop PV collector, equation (1) is modified as shown in equation (2) to account for the radiation blocked by the collector

$$I_{T,O} = I_{bT} f + I_d VF_{sky,O} + I \rho_g VF_{gnd,O} \qquad (2)$$

where $I_{T,O}$, f, $VF_{sky,O}$, and $VF_{gnd,O}$ are the total radiation on the inclined surface, the irradiated fraction of the surface area, the

view factor from the roof to the sky, and view factor from the roof to the ground, respectively. To calculate $I_{T,O}$, the variables f, $VF_{sky,O}$, and $VF_{gnd,O}$ should be calculated. The remaining variables in equation (2) are available from the weather file (TMY2) data.

1) Irradiated fraction

The fraction of the irradiated roof is calculated based on tracking the sun location and the 3D position of both the roof and the collector. The position of the sun is tracked by both the azimuth and zenith angles available from the weather data file, while the 3D position of the roof and the collector are obtained from the 3D model developed in SketchUp. The exact positions of the roof and collector vertices are obtained by calling a function developed in MATLAB. This function uses the strict format of the 3D model file to identify the 3D coordinates of the required vertices. Based on the sun location at a specific time, another function developed in MATLAB calculates the projection of the collector shadow on the plane containing the roof and then calculates the intersection area between the shadow and the roof. Considering the intersection area in the calculation of f is necessary as a part of the collector shadow may fall outside the roof. The value of f is obtained as the ratio of the unshaded area to the total area of the roof. The f value is necessary for the calculation of the beam radiation reaching the roof while the calculation of the isotropic sky and ground radiation requires the calculation of sky and ground view factors.

2) View factors

The calculation of sky and ground view factors from the roof without the existence of an obstruction is given in equation (3) and equation (4) respectively [9].

$$VF_{sky} = \frac{(1+\cos\beta)}{2} \qquad (3)$$

$$VF_{gnd} = \frac{(1-\cos\beta)}{2} \qquad (4)$$

where β is the slope of the roof relative to the horizontal. However, the existence of an obstruction can reduce the view of both the sky and ground from the roof, which requires modifying equation (3) and equation (4) as shown in equation (5) and equation (6)

$$VF_{sky} = \frac{(1+\cos\beta)}{2} - VF_{sky,o} \qquad (5)$$

$$VF_{gnd} = \frac{(1-\cos\beta)}{2} - VF_{gnd,o} \qquad (6)$$

where $VF_{sky,o}$ and $VF_{gnd,o}$ are the view factors of the sky and ground from the roof blocked by the collector, respectively. The calculation of $VF_{sky,O}$ and $VF_{gnd,O}$ considers that the same part of the obstruction may be blocking either the sky or the ground view depending on the considered location on the roof. As can be seen in Figure 1. for the same part of the collector, part C, the collector blocks the ground view for location A and the sky view for location B. Similarly, two different parts of the collector can

block either the sky or the ground view from the same location on the roof.
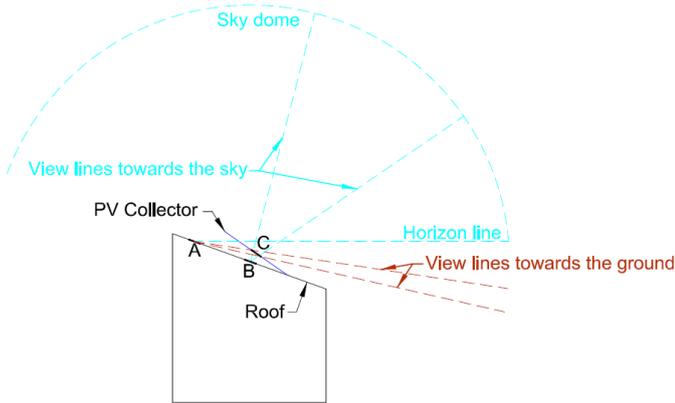

Figure 1.   Ground and Sky Views Blocked by the Collector.

Therefore, to account for this dual blockage of sky and ground view, both the collector and the roof have been subdivided into small triangles. The subdivision is achieved by using MATLAB meshing function distmesh2d which uses Delaunay triangulation to provide a well-shaped mesh [10, 11]. The meshing allows identifying whether a considered part of the collector mesh is blocking either the sky or the ground view from the considered part of the roof mesh depending on the relative height position of collector part and the roof parts. When the centroid of the considered part of the collector mesh is lower than the centroid of the considered part of the roof mesh, this part of the collector is considered to be blocking the ground view from that part of the roof, otherwise, this part of the collector is considered to be blocking the sky view.

B. Component integration into TRNSYS

The integration of the developed component into TRNSYS is based on TRNSYS capability of calling MATLAB using Type155. The developed component requires seven inputs, i.e. the solar zenith angle, solar azimuth angle, beam radiation on the inclined surface (roof), sky diffuse radiation on a horizontal surface, total radiation on a horizontal surface, incidence angle of beam radiation and ground reflectance. These inputs, which are similar to the inputs of Type34, provide the necessary information to calculate the parameters of the isotropic diffuse sky model.

In addition, the component reads an external text file which contains the file name of the 3D SketchUp model, as well as the alphanumeric values of the surfaces representing the collector and the roof. The alphanumeric values can be found in Object Info window in the 3D SketchUp model. This information allows the component to access the 3D SketchUp file and extract the coordinates of the collector and roof vertices.

The component provides three outputs namely, total and beam radiation on the roof, as well as the incidence angle of beam radiation on the roof. The connection of these outputs to the building model requires adding a new orientation in Type56. The new orientation replaces the default orientation of the roof, and the radiation calculation of the new orientation is set to be calculated by an external component; allowing the outputs of the developed component to be connected to Type56.

C. TRNSYS Model

To simulate the shading effect of the collector, two simple rooms are modelled in SketchUp and imported into TRNSYS. The two rooms have exactly the same size, orientation and construction material. The only difference between the two rooms is the inclusion of a solar collector on one of the roofs. The solar collector is added as a shading component into the SketchUp model as can be seen in the perspective view in Figure 2. The dimensions of the room and PV collector are shown in the front and side view in Figure 3.
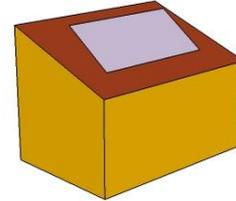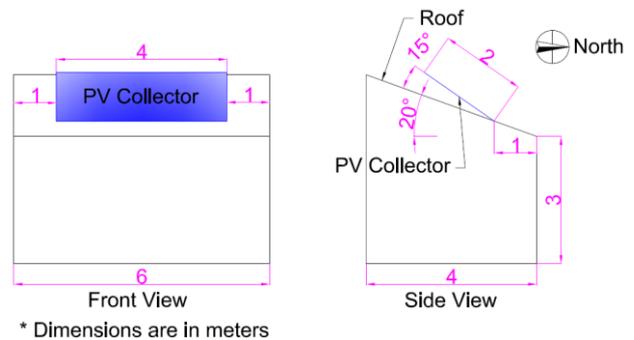

Figure 2.   Perspective View of the Modelled Room with Collector.

Figure 3.   Schematic Front and Side Views of the Room with Collector.

The model developed in TRNSYS considers the weather file of the city of Adelaide, South Australia; latitude of approximately 35°S. The weather file provides the necessary data of ambient conditions and solar radiation required to calculate the indoor dry-bulb temperature.

In addition to ambient conditions, the indoor dry-bulb temperature depends on the room envelope properties. In this study, the room envelope properties, summarized in TABLE I. , are the default properties generated by TRNSYS. The model does not consider any internal heat gain, such as heat gain from occupants, lighting or other appliances.

TABLE I.   ENVELOPE THERMAL PROPERTIES

	Thermal Resistance (ºC/W)	Solar Absorptance	Emissivity
External Walls	2.2	0.6	0.9
Ground Floor	25.6	0.6	0.9
Roof	3.4	0.6	0.9

IV. RESULTS AND DISCUSSION

The simulation results show that the monthly average of indoor dry-bulb temperature reduction is approximately 0.2 ºC–0.4 ºC as shown in Figure 4. The temperature reduction is higher in summer, such as in January and February, which can be

beneficial for reducing the cooling demand. In contrast, during winter periods, e.g. May–July, the temperature reduction can increase the required heating load. This result suggests that although the temperature reduction is relatively small in winter, the collector shade has a noticeable effect on both heating and cooling demand. However, not every temperature reduction in summer contributes to reducing the cooling energy usage.
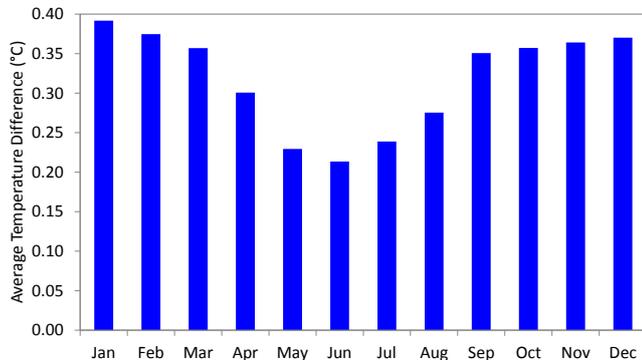

Figure 4.   Monthly Average Temperature Difference.

To further investigate the collector shading effect, a heating setpoint of 20 ºC and a cooling setpoint of 22.5 ºC are considered for any time of the day. The selected setpoint temperatures for heating and cooling correspond to the setpoint temperatures adopted for living spaces in the Nationwide House Energy Rating Scheme [12]. The setpoints allow identifying whether a temperature reduction increases heating or reduces cooling energy usage. The temperature reduction for an indoor temperature between the two setpoints is considered to have no effect on heating and cooling demand. Based on these setpoints, the results shown in Figure 5. reveal that the reduction in temperature increases the heating energy usage by a larger amount than the reduction of cooling energy usage, i.e. an increase in the overall heating and cooling energy usage, when the collector shading is considered. The results reveal that 358 degree-hours have no effect on heating and cooling demand, while 1649 degree-hours of additional heating is required. The cooling reduction is 782 degree-hours; almost half of the additional degree-hours required for heating.
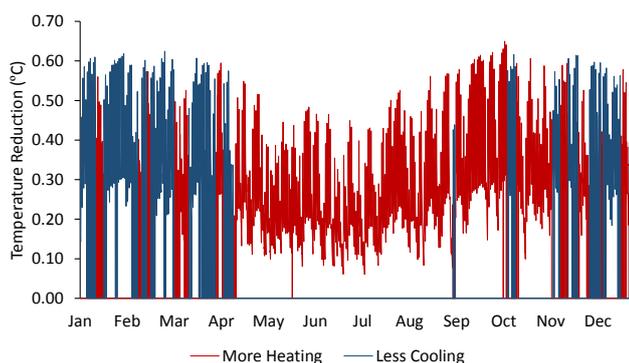

Figure 5.   Collector Shade Effect on Heating and Cooling Energy Usage.

The results indicate that both heating and cooling demand are affected by the collector shading, with the effect on additional heating being more significant than the cooling reduction. However, this result can be influenced by other factors which have not yet been considered in this preliminary modelling. Some of these factors are the internal heat gains from occupants, lighting and other appliances, as well as the existence of windows on the building envelope. These factors are likely to increase the indoor temperature; therefore increasing the cooling degree-hours and reducing the heating degree-hours simultaneously. This likely change of cooling and heating degree-hours indicates that the collector shading should be considered for both heating and cooling energy simulation of buildings.

V.   SUMMARY AND CONCLUSIONS

This study presented a modelling component able to overcome a limitation in Transient System Simulation (TRNSYS) software of simulating the shade effect of a rooftop photovoltaic (PV) collector. The component uses the isotropic diffuse sky model to calculate beam, sky diffuse and ground-reflected radiation reaching the roof taking into account the obstruction of the PV collector. The component was developed in MATLAB and added into a building model developed in TRNSYS to investigate the collector shading effect on indoor temperature and heating and cooling requirements. The results indicate that the collector shading can have a significant effect on increasing the heating requirement, which may exceed the benefits on reducing cooling requirement.

The research presented in this paper shows the capability of the developed component in simulating the collector shade effect on a single roof surface.

VI.   LIMITATIONS AND FUTURE WORK

Further research is required to address some of the limitations of this study, such as the interaction of collector shade with a single roof surface and the simple building model used to demonstrate the capability of the developed component and shading effect. Work is underway to address these limitations as well as exploring the collector shade effect on heating and cooling energy usage for different roof absorptivity, different roof angles and room orientations.

ACKNOWLEDGMENT

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