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Modelling and Simulation of BIPV/T in EnergyPlus and TRNSYS

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Abstract

A BIPV/T model, called BIPVTSYSTEM, was developed and implemented into EnergyPlus, a building energy simulation software that currently lacks BIPV/T modelling capabilities. The EnergyPlus model was based on the same equations of TRNSYS Type 567 but with a few modifications in regards to its thermal-fluidic relations. This new EnergyPlus object will assist users using EnergyPlus in large scale community modelling that will employ both façade and roof integrated BIPV/T systems. EnergyPlus's BIPVTSYSTEM and a modified version of TRNSYS Type 567 were both used to conduct a yearlong simulation of a BIPV/T system. The factors contributing to the discrepancies of the results between the two models were attributed to the different weather data interpolation methodologies, sky temperature computations, and electrical models employed by both software.

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Keywords: TRNSYS; EnergyPlus; BIPV/T; Simulation; Modelling

1. Introduction

Building Integrated Photovoltaic-Thermal (BIPV/T) systems is a prevalent research topic [1] and may become a well-established sustainable commercial technology in the future. BIPV/T systems can form part of the façade or roof of a building [2], hence, the thermal-fluidic performance of the system is intrinsically coupled with the building envelope. BIPV/T simulation tools are needed to model the thermal-fluidic performance of the BIPV/T system, electrical generation of the PV, and thermal relationship between the BIPV/T system and the building.

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EnergyPlus is an open source building energy simulation software that is widely used to model the passive performance of an individual building or large communities and the mechanical systems serving these buildings [4]. Research has been conducted on neighborhoods employing BIPV/T systems by using EnergyPlus in conjunction with external software to simulate building performances [4, 5]. An additional process and software is required because EnergyPlus V8.0 alone does not offer BIPV/T modeling capabilities. Only a part of the analysis is conducted using EnergyPlus V8.0, and the interim results are further analyzed in a separate process, in order to completely simulate BIPV/T systems [4, 5]. This is a tedious and inefficient process; a complete BIPV/T model is needed. In this project a program module was developed and implemented into the original EnergyPlus V8.0 source code, resulting in a modified version of EnergyPlus V8.0 with BIPV/T system modelling capabilities.

The new BIPV/T model created is called BIPVTSYSTEM object, each object is to be paired with a single PV panel and a single roof surface of the same size as the panel. This is done to achieve greater accuracy since the BIPV/T energy balance equations, the PV electrical model, and the surface energy balance equations (in EnergyPlus), assume a single averaged temperature node (e.g. single PV temperature, single surface temperature). The BIPVTSYSTEM object was used to conduct a yearlong simulation, its results were compared against TRNSYS Type 298, a BIPV/T system that was developed based on Type 567 (original TRNSYS BIPV/T type) and implemented into TRNSYS [6].

Nomenclature

ε_{Sky}	Emissivity of the sky (-)
η_{PV}	Efficiency of the PV (-)
$\eta_{PV,Ref}$	Reference efficiency of the PV (-)
$(\tau\alpha)_n$	Transmittance-absorptance (-)
$Area_{PV}$	Effective area with PV cells (m^2)
C_p	Specific heat of the air (J/kg/K)
Eff_I	PV efficiency modifier, function of incident solar radiation (-)
Eff_T	PV efficiency modifier, function of PV temperature (-)
I_{mp}	Current at the maximum power point (V)
I_{ref}	PV reference radiation (W)
I_t	Total radiation on the tilted surface (W)
IAM	Incidence angle modifier (-)
$\dot{m}$	Mass flow rate of the air (kg/s)
$Power$	Electrical power (W)
$\dot{Q}$	Heat transfer rate (W)
$T_{amb,kelvin}$	Ambient temperature (K)
T_{in}	Air inlet temperature of the first panel
T_{out}	Air outlet temperature of the last panel
T_{PV}	PV temperature (^oC)
T_{ref}	PV reference temperature (^oC)
T_{Sky}	Sky temperature (^oC)
V_{mp}	Voltage at the maximum power point (V)

2. Simulation Conditions and Parameters

The BIPV/T system, as simulated by the two BIPV/T models, consisted of a single row of five PV panels (1 m by 1.2 m) connected in series, with an air channel, all integrated into a surface. The entire row was south facing and was angled 45^o from the horizontal. Both of the EnergyPlus and TRNSYS BIPV/T models used the same hourly CWEC formatted weather file for Toronto, Canada, to conduct a yearlong simulation of the BIPV/T system. A timestep of one was used (resulting in one calculation every hour).

3. EnergyPlus BIPV/T Model: BIPVTSYSTEM

The BIPVTSYSTEM object was developed by using the same thermal-fluidic equations and modifications employed in Type 298 [6], that is, the core thermal-fluidic equations used in both models are identical. The weather data were retrieved using EnergyPlus's built in services; to read in the weather data from the file. Furthermore, in contrast to the modelling option that TRNSYS provides (the option to only model the BIPV/T independently, without a building), the BIPVTSYSTEM object in EnergyPlus must be applied onto the surface of a building. This is because EnergyPlus is a building energy simulation software; hence its focus is on building. However, it must be noted that EnergyPlus contains an extensive list of mechanical system objects and can simulate the performance of these mechanical systems and their effects on the building.

The EnergyPlus BIPVTSYSTEM object uses the Sandia electrical model developed by King et al. [7]. This is in contrast to the simpler electrical model that Type 298 employs [8]. The Sandia model uses empirically determined parameters of a PV panel to predict the electrical performance of the PV. In EnergyPlus, the BIPVTSYSTEM object determines the PV temperature and the Sandia model uses it to compute the voltage and current of the PV panel. In return, the Sandia model computes the cell efficiency and passes it to the BIPVTSYSTEM object for its computations.

4. Results and Discussion

TRNSYS Type 298 and EnergyPlus BIPVTSYSTEM were both used to conduct a yearlong simulation. The results and weather conditions of January 4th, between 8am and 5pm are shown from Fig. 1 to Fig 5. Although TRNSYS Type 298 and EnergyPlus BIPVTSYSTEM object used the same thermal-fluidic equations, there are discrepancies between their temperature, thermal, and electrical outputs. This is shown most prominently in Fig. 1, depicting the various BIPV/T temperature results of both models. The discrepancies between the temperature and thermal results are attributed to the different weather data interpolation methodology and sky temperature model employed by the two programs. In both programs, weather data are retrieved and sky temperatures are computed by separate program modules; Type 298 and BIPVTSYSTEM places a call in the code to obtain these values. The incongruities between the electricity production of the two model are due to the different thermal parameters (e.g., PV temperature), weather data (e.g., irradiation), and electrical models of both programs.

Both program used the same weather file, but there are inconsistencies in the weather data used by each model, as shown in Fig. 2 (a) and (b) and Fig. 3. Upon examining the weather file, it was found that EnergyPlus used the exact weather data values as found in the weather file; that is, for each timestep, TRNSYS interpolates the weather data while EnergyPlus does not. Since this difference in interpolation methodology affects a large number of parameters, such as irradiation and beam incidence angle, in addition to the three weather parameters shown in Fig. 2 (a) and (b) and Fig. 3, it contributes the most to the discrepancies in the temperature and thermal energy generation results of the two programs.

Most likely, TRNSYS' interpolation approach uses a combination of the previous, current, and next hour's weather file data, to determine the current hour's weather data. Evidence supporting that it utilizes weather file data from the previous hour and the next hour, can be seen in Fig. 3, by comparing TRNSYS' weather data with EnergyPlus's weather data (EnergyPlus weather data is the same as the non-modified weather file data). According to EnergyPlus, the ambient temperature at 11am and 1pm are both at -10ºC. At 12pm, TRNSYS' ambient temperature is at -10ºC, proving that the interpolation uses both the previous hour and next hour's weather data, since there cannot be an intermediary temperature value between 11am and 1pm. Lastly, it can be shown that the interpolation also includes the current hour's data as part of the interpolation. In Fig. 2 (b), in order for TRNSYS to compute the wind speed at 11am, it must use data from 10am and 12pm, which are, according to EnergyPlus, 6.7 m/s and 7.2 m/s, respectively. However, TRNSYS' wind speed at 11am is 7.65 m/s, which is greater than either 6.7 m/s and 7.2 m/s. This value can only be possible if TRNSYS used EnergyPlus's 11am wind speed, 8.6 m/s, in its interpolation. These three cases prove that TRNSYS interpolation methodology relies on the previous, current, and following hour's data.

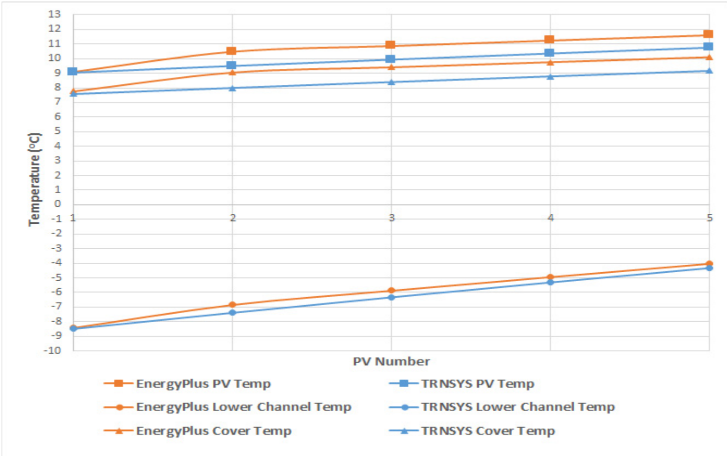

Fig. 1. BIPV/T Parameter Temperatures on January 4th at 1pm

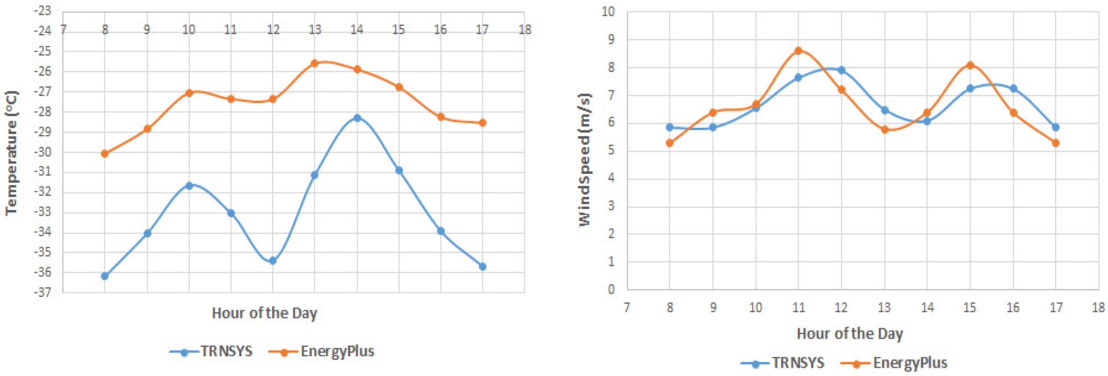

Fig. 2. (a) Hourly Sky Temperature from 8am to 5pm; (b) Hourly Wind Speed from 8am to 5pm

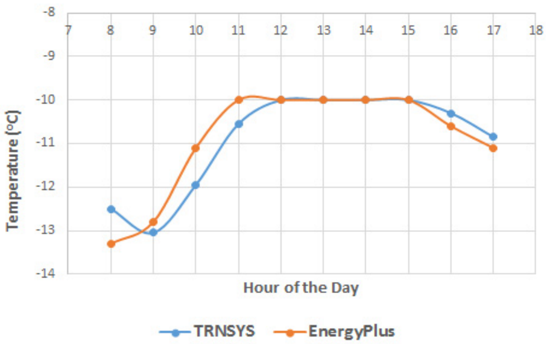

Fig. 3. Hourly Ambient Temperature from 8am to 5pm

There is a significant difference between the computed sky temperatures of the two program, as shown in Fig. 2 (a). This difference is largely attributed to the different methodology employed by TRNSYS and EnergyPlus in computing the sky emissivity. Both TRNSYS (Type 15-3, the weather filer reader) and EnergyPlus uses the same equation shown in Equation (1) to determine the sky temperature,

$$T_{Sky} = \varepsilon_{Sky}{}^{\frac{1}{4}} \left(T_{amb,kelvin}\right) - 273.15 \tag{1}$$

however, they each follow a different approach in estimating the sky emissivity factor, ε_{Sky} [8, 9]. Since ε_{Sky} is evaluated using weather data (the ambient temperature), therefore, the different weather data used by both program also contribute to the difference in the two computed sky temperatures. Together, these two factors, different sky emissivity estimation methodology and different weather data, contribute to the significant discrepancies in the sky temperature, which affects outlet temperature, PV temperature, and PV cover temperature, of each program directly.

The total hourly electricity generated by the five panels combined, as determined by both program, are shown in Fig. 4. For this particular day, TRNSYS computed a total of 17,866 kJ (4.96 kWh) of electricity, while EnergyPlus computed 18,526 kJ (5.15 kWh), for the hours between 8am and 5pm inclusive. There is a 3.7% difference between the two. On the other hand, for a yearlong simulation run, the difference between the amount of electricity generated in a year was 3.23%, with EnergyPlus having computed a higher total electricity generated again. These differences in results are small and are attributed to the different electrical model employed by both program. TRNSYS' electrical model uses reference conditions and linear radiation modifying factors to compute the cell efficiency as shown in Equation (2) and then uses the efficiency to compute the electricity generated for that timestep, as shown in Equation (3) [8].

$$\eta_{PV} = \eta_{PV,Ref}\left[1 + Eff_T\left(T_{PV} - T_{ref}\right)\right]\left[1 + Eff_I\left(I_t - I_{ref}\right)\right] \tag{2}$$

$$Power = Area_{PV}(\tau\alpha)_n \, IAM \, I_t \, \eta_{PV} \tag{3}$$

This is in contrast to the Sandia model's approach in EnergyPlus. The Sandia model first computes the power, as shown in Equation (4), and then uses the power to determine the efficiency [7], as shown in Equation (5),

$$Power = V_{mp} I_{mp} \tag{4}$$

$$\eta_{PV} = \frac{Power}{Area_{PV} \, I_t} \tag{5}$$

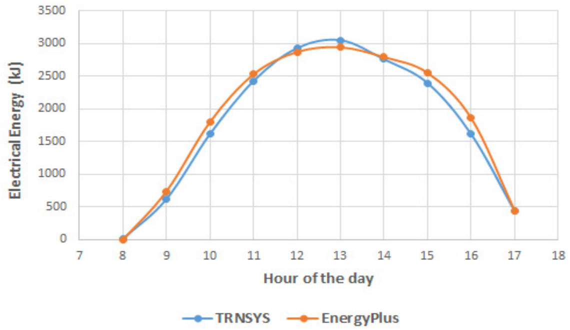

Fig. 4. Hourly Electrical Energy Produced from 8am to 5pm

It should be noted that, although both TRNSYS' electrical model and EnergyPlus's Sandia model estimated the electricity generation differently and there were differences in weather data (e.g. irradiation) between the two programs, the difference between the two results was just 3.23% for the entire year. If the inconsistencies in radiation data were removed, the absolute difference between the two electrical models would be lower.

The hourly thermal energy collected by the five panels combined, (Fig. 5(a)) is evaluated using Equation (6) and the final outlet temperature is shown in Fig. 5 (b).

$$\dot{Q} = \dot{m} C_p (T_{out} - T_{in}) \tag{6}$$

For this particular day, TRNSYS computed that the BIPV/T system would collect 31,811 kJ (8.84 kWh) of heat, while EnergyPlus computed 29,458 kJ (8.18 kWh) of heat collected, a 7.39% difference. For the entire year, the difference between the total amounts of heat generated was 8.58%. The thermal energy collected is greatly affected by weather data because, C_p, T_{out}, and T_{in}, are dependent on the weather data. In addition, the thermal energy collected is also dependent on the PV efficiency (the energy balance equations are solved using an iterative procedure). Therefore, it is expected that the differences in annual thermal energy collected between the models, 8.58%, is greater than the differences in annual electricity generated between the models 3.23%, because the electrical model is less reliant on weather data and the differences between the two electrical models are accrued in the thermal energy computations indirectly.

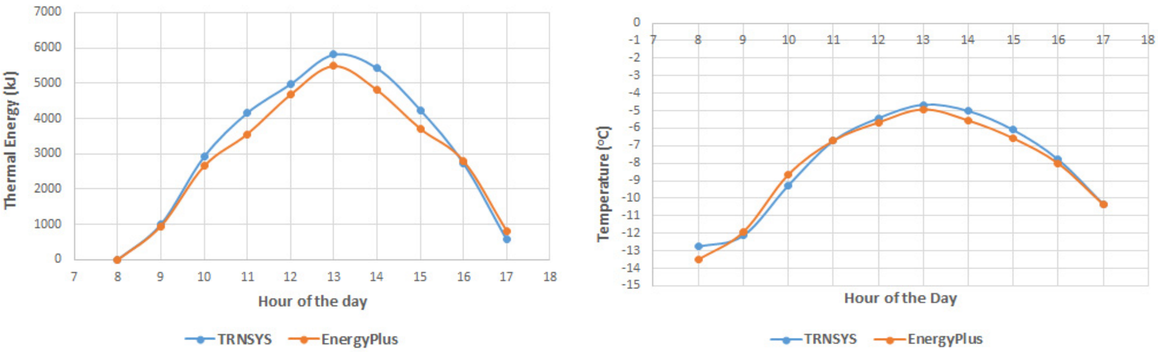

Fig. 5 (a) Hourly Thermal Energy Collected from 8am to 5pm; (b) Hourly Outlet Temperature from 8am to 5pm

5. Conclusion

The differences between the two models are slight, considering there is a sizeable difference in the sky temperature, ambient temperature, and wind speed, in addition to the differences due to the utilization of two different electrical models. Further analysis can discuss the impact of these differences and quantify them.

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