VALIDATING A SIMPLIFIED PV MODEL AGAINST TRNSYS MODEL

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ABSTRACT

The use of renewable energy resources onsite is one of the foundations of a net zero-energy community. This paper outlines the results of the comparison of the PV output estimation between TRNSYS and a simplified model coded in MATLAB. This simplified PV model will be part of an integrated net-zero community energy simulation platform being developed at Ryerson University and will be used for the operational control of the PV outputs of the community. The models used by TRNSYS are regarded as accurate but TRNSYS is complicated to use, requires lots of input data and difficult to integrate into a community optimization algorithm. The discrepancies in the simulation runs between the two models can be attributed to the different methods used in deriving the hourly sky temperature and the PV module temperature but overall the PV output of the simplified model gave satisfactory results.

INTRODUCTION

Solar power is the third biggest renewable power source with photovoltaic (PV) as the dominant technology in Canada [1]. Hydro and wind power are the first and second widely used renewable energy source, respectively. IEA projects that by 2050 PV's share of the global electricity will rise up to 16% from an earlier projection of only 11% [2]. As commercial and residential users invest in solar energy technology, there will be a demand for an easy to use software for the planning and performance evaluation of PV installations as well as for the operational control of aggregated installations.

The actual output of PV modules depends on the solar radiation, the orientation of the modules and performance degradation resulting from actual module temperature, module mismatch, dirt, shading, and from wiring and inverter losses. Near accurate prediction of PV electricity outputs on a tilted surface is important to optimize the commissioning of dispatchable energy sources to meet the energy needs of the community. Towards this end, various models [3] - [11] have been developed to estimate the global solar irradiance on a tilted surface.

The effect of temperature on the electrical performance of PV modules has been studied in [12]-[16]. Although the power output of a solar module increases as it receives more solar energy, it is tempered by the increase in the temperature of the cells as it absorbs the solar radiation, reducing its electrical throughput. Influences other than solar radiation such as wind and air flow have been studied in [13], [16].

The PV model described in this paper is designed to be integrated into a comprehensive net zero-community optimization model. The community will be made up of multiple buildings with different uses, orientations, sizes, thermal and electricity loads and energy sources. An optimal control strategy using simple models with minimal inputs would be needed to speed up the calculations while maintaining an acceptable level of accuracy. The simple easy-to-use PV software model presented in this paper can be utilized to fill this gap.

The software packages chosen as the basis for comparison are TRNSYS (Transient Systems Simulation Tool) [17] and RETScreen [18]. TRNSYS is a commercial software widely accepted as a reliable tool in energy-related work [19], [20]. TRNSYS' PV model performs an iterative process to find the cell temperature that will result in the energy balance depicted in Figure 1. RETScreen's PV project model [21] is an excel-based clean energy project feasibility analysis software tool and is freely available. It is included in this study only to assess the accuracy of its simple PV model in predicting the energy production used to evaluate project savings, costs, emission reduction, financial viability and risks.

METHODOLOGY

The accuracy of the simplified PV model was validated using two statistical parameters: root mean square error (RMSE) and mean bias error (MBE). RMSE is used frequently to measure the deviation of the predicted value from the observed value. In this case TRNSYS output was assumed to be the observed value. To facilitate the comparison, RMSE was normalized by the average of the TRNSYS output. The normalized RMSE is mathematically defined as:

$$RMSE = \frac{\sqrt{\frac{1}{n}\sum_{t=1}^{n}(\hat{y}_t - y_t)^2}}{\frac{1}{n}\sum_{t=1}^{n} y_t} \qquad (1)$$

where n is the period (number of days in the month or the number of months in a year as the case may be), y_t is the TRNSYS output and $\hat{y}_t$ is the output of the model presented in this paper.

The MBE parameter is used to indicate if a model is over- or under-predicting. The MBE was also normalized by the average of the TRNSYS output. The normalized MBE is expressed as:

$$MBE = \frac{\sum_{t=1}^{n}(\hat{y}_t - y_t)}{\frac{1}{n}\sum_{t=1}^{n} y_t} \qquad (2)$$

TRNSYS was used as the baseline because of its popularity in energy research and when compared to 5 other commercial software packages, TRNSYS calculations were found to be the closest to the experimental data [19].

A. Simulation Method

PV performance of TRNSYS and the proposed model was simulated for 1 year with a time step of 1 hour. The hourly results (8760 hours) were integrated to get the monthly and annual summaries shown in the Results section. Since RETScreen takes only monthly values, the monthly daily average global irradiation on a horizontal surface and ambient temperature were calculated from the hourly weather data. These were manually entered into the RETScreen spreadsheet. Wind speed was not entered because RETScreen does not take into account the effect of wind on cell temperature.

B. Test Location

Geographical location used in the simulation was Toronto, Ontario (Latitude 43.8°N, 79.6°W).

C. Data

1. The solar data used for the simulation were from the hourly Typical Meteorological Year 2 (TMY2) [22] datasets derived from the 1961-1990 National Solar Radiation Database (NSRDB) and are based on more recent and accurate data. TMY2 file contains 8760 hours of solar radiation (i.e., direct normal, diffuse horizontal, global horizontal radiation, etc.) and meteorological elements (i.e., ambient temperature, wind speed, etc.) representing the typical hours selected from 30 years of historical data
2. Canadian Solar's poly-crystalline PV panel CSX6P305 was used in the simulation. Data used in the simulation were taken from the manufacturer's datasheet [23]. Table 1 lists the PV panel parameters used in the simulations.

Table 1. Canadian Solar CSX6P305 datasheet

Manufacturer	Canadian Solar
Model	CSXP305
Nominal Maximum Power (STC)	305 W at 25°C, 1000 W/m^2, 1.5 AM
Efficiency	15.9%
Area	1.919 m^2 (1,954 x 982 mm)
Front Cover	3.2 mm tempered glass
Temperature Coefficient of Pmax, β_T	-0.43%/°C
Nominal Operating cell temperature, T_{noct}	45±2°C

SIMULATION

The actual operating temperature of a PV panel depends on the PV material, mounting structure, solar radiation, ambient temperature, wind speed and wind direction. TRNSYS Type562 was used to model the PV panel. Type562 models either a glazed or unglazed PV array and has a mode of operation that calculates the PV electrical output using the user-provided efficiency and coefficients that describe how the efficiency changes with cell temperature and incident solar radiation [24]. Table 2 and Table 3 list the coefficients and reference values needed by TRNSYS to perform the calculations. To derive the PV module temperature TRNSYS takes into account radiative and convective losses and performs an iterative loop, recurrently solving and modifying the cell temperature until the energy balance in Figure 1 sums to 0.

Table 2. Material-dependent coefficients

Parameter	Value
Top surface emissivity	0.9
Back surface Emissivity	0.9
PV surface absorptance	0.9447
Refractive index	1.526
Cover conductivity	4 kJ/hr-m^2-K
Extinction coefficient	4
Resistance to heat transfer of the back of the collector	2 hr-m^2-K/kJ

Table 3. Reference values and other coefficients

Parameter	Value
Reference temperature, T_{STC}	298.15 K (25 °C)
Reference radiation, I_{STC}	0.277 J/m^2 (1 kW/m^2)
Zone temperature	293.15 K (20 °C)
Back radiant temperature	293.15 K (20 °C)
Bottom heat loss coefficient	11 kJ/hr-m^2-K
PV slope, β	40°
Efficiency modifier – radiation, β_I	0.000025 hr-m^2/kJ

Table 4 lists the parameters fed into RETScreen. To be consistent with the other two models, losses were assumed to be zero and inverter efficiency was assumed to be 100%. The temperature coefficient and area were fixed by RETScreen at 0.40%/°C and 2 m^2, respectively.

Table 4. RETScreen Parameters

Parameter	Value
Type	Poly-Si
Power capacity	0.305 kW
Efficiency	15.9 %
Nominal operating cell temperature	45 °C

The simplified PV computer model discussed in the Analysis section was created using MATLAB. It uses Excel spreadsheet to store all data required for the calculations:

1. Weather database. Weather data for different locations and weather stations can be used as long as it is converted to Excel. A GUI interface allows users to pick any weather data. For the purpose of this comparison, TMY2 for Toronto, Ontario was converted to Excel.
2. PV datasheets. Datasheets from different PV manufacturers were compiled and relevant information stored in an Excel database. A dropdown list allows users to choose the PV brand and type.

ANALYSIS

A. Irradiance Model

The classic equation defining the global or total solar irradiance incident on a tilted surface is composed of three components: direct or beam irradiance (I_B), diffuse irradiance (I_D) and reflected irradiance (I_R):

$$I_T = I_{DN} Cos\,\theta + I_{DH} R_d + \rho I_{GH} R_r \tag{3}$$

where I_{DN} is the direct normal irradiance, I_{DH} is the diffuse horizontal irradiance, I_{GH} is the global horizontal irradiance, θ is the angle of incidence of the sun's rays on the tilted surface, R_d is the diffuse irradiance transposition factor, ρ is the foreground albedo and R_r is the transposition factor for ground reflection.

The incident angle θ applied to the measured direct normal irradiance in (3) is calculated using geometry.

Reflected irradiance is the amount of radiation reflected from the ground to the tilted surface. The transposition factor R_r is approximated by the classic isotropic model [25].

Estimating the diffused irradiance on a tilted surface is not as straightforward as the direct and reflected components because diffused irradiance comes from all points in the sky except the sun. Diffuse irradiance is made up of an isotropic diffuse component (uniform irradiance from the sky dome), a circumsolar diffuse component (resulting from the forward scattering of solar radiation and concentrated in the area close to the sun) and a horizon brightening component (concentrated in a band near the horizon and most noticeable in clear skies) [6].

Different methods of estimating diffuse irradiance for solar energy engineering predictions have been proposed. The simplest model by Liu and Jordan [4] assumes that the diffuse irradiation is uniform over the whole sky hemisphere and sets the transposition factor using the simple isotropic approximation.

Hay and Davies [5] modeled the diffuse radiation as composed of isotropic and circumsolar components only. They introduced the anisotropic index A to represent the atmospheric transmittance for beam radiation.

Reindl [6] added the horizon brightening component to the Hay and Davies model.

The Perez model [11] provides a more detailed analysis of the 3 components of the diffuse irradiance using empirically-derived coefficients that are functions of the sky clearness and brightness. The coefficients are location-specific taken from the statistical analysis of the empirical data. Perez has published two different sets of coefficients: in 1987 [10] and in 1990 [11].

B. PV Thermal Model

The fundamental PV heat transfer theory is depicted in Figure 1.

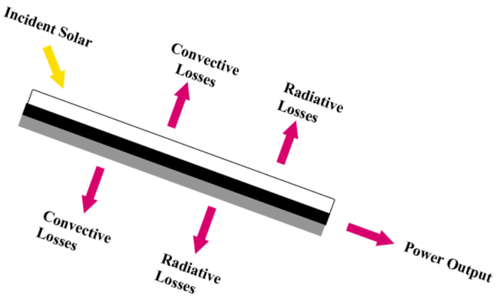


Figure 1. PV energy balance

If the temperature difference between the PV cells and the glass cover is ignored, the radiative heat loss is considered negligible and the temperature is considered uniform in the panel, the PV energy balance can be simplified as a linear function of temperature [13], [16]:

$$\tau\alpha G_T = \eta_{PV} G_T + U_{PV}(T_{PV} - T_{amb}) \qquad (4)$$

Eqn. (4) represents the energy balance of a PV module cooled by losses to the surroundings. The term on the LHS, $\tau\alpha G_T$, is the solar energy absorbed by the PV cells, $\eta_{PV} G_T$ of the RHS represent the losses from the production of electricity and the last term on the RHS are the thermal losses from the PV modules to the surroundings. The radiation that passes through the glass is τG_T where G_T is the solar irradiance on the tilted surface, τ is the transmittance of the PV top cover as a function of the beam, diffuse and reflected radiations and the refractive index of the cover and α is the absorption coefficient of the PV cell. η_{PV} is the nominal PV efficiency at standard test condition, U_{PV} is the heat exchange coefficient, T_{PV} is the PV temperature and T_{amb} is the ambient temperature. The heat exchange coefficient U_{PV} is approximated as a linear function:

$$U_{PV} = U_0 + \lambda_w V_w$$

where the constant U_0 varies from 15-30 W/m^2·K [21]. The term λ_w is an empirical coefficient that ranges from 0-6 W/m^2·K [21] andV_w is the wind speed.

The most known model for PV module efficiency [3] is:

$$\eta_{PV} = \eta_{ref}[1 - \beta_T(T_{PV} - T_{ref}) + \gamma_{rad} \, log_{10} \, G_T] \qquad (5)$$

where η_{ref} is the module's efficiency at standard test condition ($T_{ref} = 25℃, G_{ref} = 1000 \, W/m^2$). β_T is the temperature coefficient of power denoting the percentage of output reduction per 1 ℃ increase in temperature. γ_{rad} is the solar radiation coefficient. These parameters, except for γ_{rad}, are given by the PV manufacturer with β_T written with a negative sign. β_T and γ_{rad} are cell material-dependent coefficients with γ_{rad} most often set to zero [26].

Substituting (5) to (4) with $\gamma_{rad} = 0$ and deriving the PV temperature yields:

$$T_{PV} = \frac{U_{PV} T_{amb} + G_T(\tau\alpha - \eta_{ref} - \beta_T \eta_{ref} T_{ref})}{U_{PV} - \beta_T \eta_{ref} G_T} \qquad (6)$$

It should be noted that (6) ignores radiative heat transfer and takes into account only convective heat transfer (natural and forced).

C. Difference between Simplified Model, RETScreen and TRNSYS Model

Table 5 is a tabulation of the differences in the models used by TRNSYS, RETScreen and the simplified model presented here.

RESULTS

A. Sky temperature

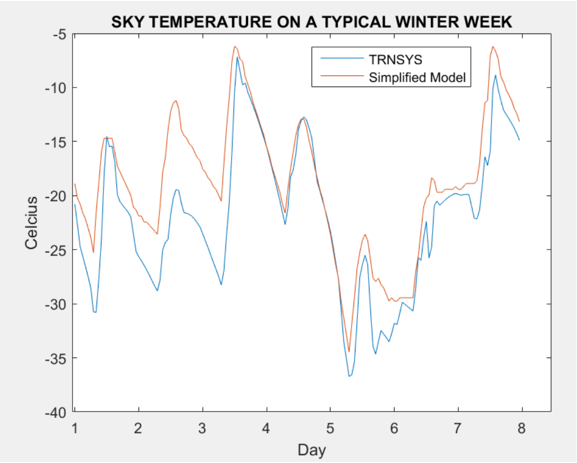
Differences in the calculation of the sky temperature between TRNSYS and the simplified model can be seen in Figure 2 and Figure 3. Information on sky temperature is rarely available and can be computationally complex requiring various weather elements to calculate. TRNSYS uses the sky emissivity as a function of the cloudiness factor of the sky, radiations on the horizontal, local atmospheric pressure, air density, sky emittance, ambient temperature and dew point. The simplified model assumes the infrared radiation from the sky as black body radiation (sky emissivity=1) [27], and estimates $T_{sky} = (\frac{horizontal\ infrared\ radiation}{Stefan-Boltzmann\ constant})^{1/4}$. The model presented here over-estimated the sky temperature during winter (Figure 2) and under-estimated it during the summer (Figure 3).

Table 5. Summary of differences between TRNSYS, RETScreen and simplified model

	TRNSYS	**RETScreen** [21]	**Simplified Model**
Sky diffuse Irradiance	Reindl Model [6]	Isotropic model [4]	Reindl Model [6]
Sky Temperature	Function of cloudiness factor of the sky, radiations on the horizontal, local atmospheric pressure, air density, sky emittance, ambient temperature, dew point [24]	Not used	Estimated using horizontal infrared radiation and the Stefan-Boltzmann constant [27]: $T_{sky} = (\frac{I_{HI}}{\sigma})^{0.25}$
Cell Temperature	Takes into account radiative and convective heat transfers [24]	Function of Nominal Operating Cell Temperature (NOCT)	Takes into account convective heat transfer only (natural and forced). Eq. (5).

B. PV Temperature

Discrepancy in the PV temperature (Figure 4 and Figure 5) is due to the computational differences of the sky temperature and the thermal model assumptions made. Considering only the hours when the PV is producing electricity, the maximum hourly difference in PV temperature was 8.8 °C. The summary statistics (Table 6) of the average monthly PV temperature show a maximum overestimation error of 27.9% for the month of May resulting in an RMS error of 39%. The PV tend to be cooler in the TRNSYS model due to the radiative losses that were taken into account compared to the simplified thermal model that assumed radiative losses are negligible. The rise and fall of the PV temperature coincides with the total tilted irradiation (not shown in the graph).



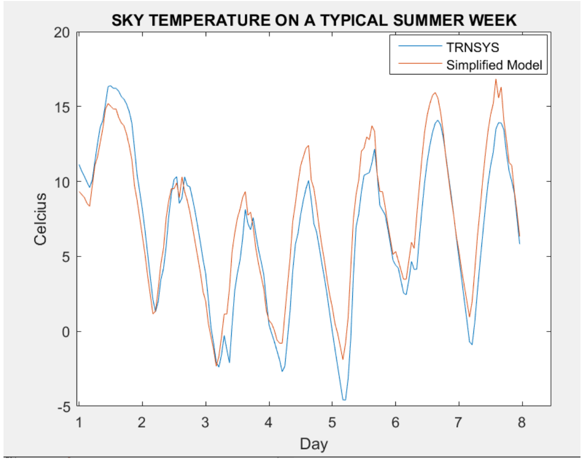


Figure 2. Sky temperature for 7 days – TMY2 typical winter week.

Figure 3. Sky temperature for 7 days – TMY2 typical summer week.

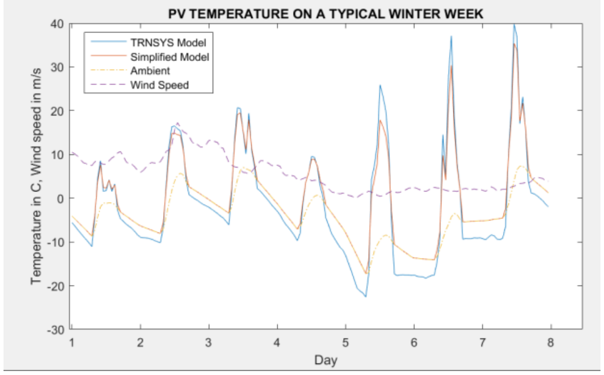


Figure 4. PV temperature for 7 days tilted at 40°, variable wind speed and solar irradiance – TMY2 typical winter week.

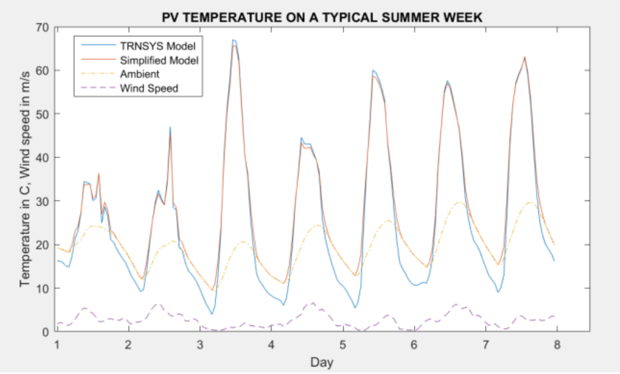


Figure 5. PV temperature for 7 days tilted at 40°, variable wind speed and solar irradiance– TMY2 typical summer week.

Table 6. Average Monthly PV Temperature

PV Temperature - 40° Tilt				
Month	TRNSYS (°C)	Simplified Model (°C)	MBE (%)	RMSE (%)
1	3.21	3.44	6.90%	22.1%
2	6.11	6.27	2.6%	14.4%
3	10.50	10.77	2.6%	6.1%
4	15.09	15.79	4.6%	5.9%
5	22.78	24.21	6.3%	7.6%
6	28.48	29.64	4.1%	5.3%
7	31.76	33.14	4.3%	5.2%
8	32.50	33.69	3.7%	4.5%
9	26.29	27.38	4.1%	5.3%
10	18.65	19.47	4.4%	5.8%
11	8.38	9.47	13.0%	15.4%
12	3.46	4.42	27.9%	39.0%
Annual	17.27	18.14	3.7	5.63

Table 7. Monthly performance of PV module tilted at 40°, with variable speed and variable solar insolation.

Energy Produced – Variable Wind speed - 40° Tilt					
Month	TRNSYS (kWh)	Simplified Model (kWh)	MBE (%)	RMSE (%)	RET Screen
1	23.99	22.55	-6.0	6.6	32
2	31.29	30.12	-3.8	4.1	39
3	36.24	35.58	-1.8	2.1	45
4	36.16	35.97	-0.5	0.6	45
5	39.49	39.45	-0.1	0.3	50
6	38.70	38.78	0.2	0.3	49
7	39.70	39.81	0.3	0.3	50
8	37.39	37.40	0.0	0.3	48
9	32.04	31.76	-0.9	1.0	41
10	26.42	25.60	-3.1	3.5	34
11	13.85	13.22	-4.5	6.4	18
12	17.15	16.12	-6.0	7.7	21
Annual	372.41	366.38	-1.6	4.9	474

C. PV Output

The effect of the warmer PV module can be seen in Figure 6 and Figure 7 and in the summary statistics of Table 7. The simplified model underestimates the PV output during the cold months of the year but the overall PV performance was satisfactory. On an annual basis the RMS error did not exceed 5% and the output is underestimated by only 1.6%. The maximum RMS error was 7.7% on a month-by month basis and MBE never exceeded 6%.

RETScreen's Photovoltaic Project Model [21] uses a simple isotropic model and does not take into account reflected radiation resulting in lower total radiation incident on the PV panel as shown in Figure 8. However, the electricity produced from the RETScreen model is considerably higher than

TRNSYS with an annual RMSE of 28.09% and overestimating by 27.2%. This could be attributed by the way RETScreen calculates the cell temperature as a function of the nominal operating cell temperature.

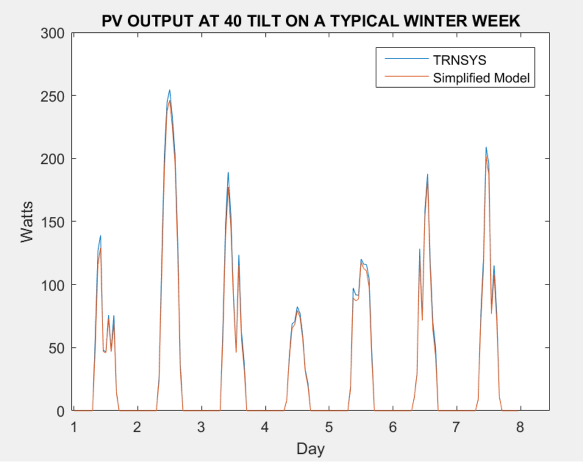


Figure 6. Comparison of PV power output for 7 days in winter at 40° tilt, variable wind speed, variable solar irradiance

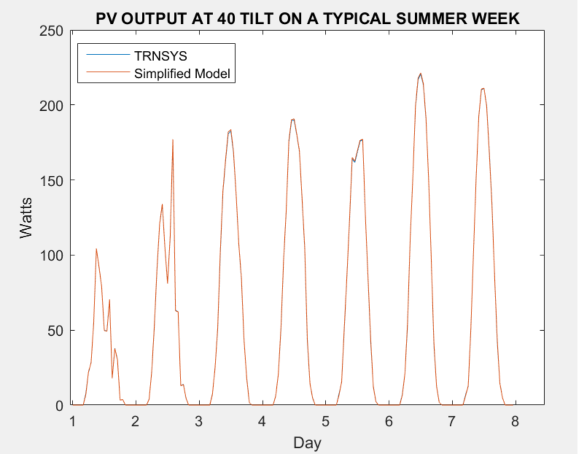


Figure 7. Comparison of PV power output for 7 days in summer at 40° tilt, variable wind speed, variable solar irradiance

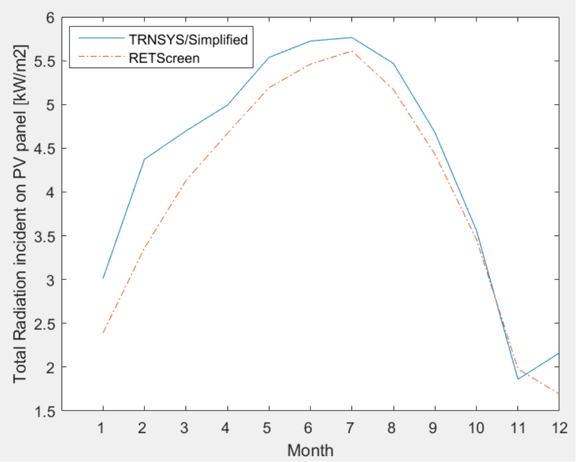


Figure 8. Total radiation calculated by RETScreen for a surface tilted at 40° is lower than both TRNSYS and the simplified models.

CONCLUSIONS AND FUTURE WORK

This paper presented a simple, easy-to-use, fast and relatively accurate algorithm that can be used to maximize the utilization of the PV installations in a net-zero community. One year simulation using TRNSYS and a simplified PV model was run using various wind speeds and solar irradiance and the results compared. RETScreen was included to assess its accuracy in predicting monthly PV electricity output. The same weather data, PV module specs, and material coefficients were used. The results show that on a monthly basis the PV electricity throughput of the simplified model has a worst case RMS error of 7.7% and that it in the worst case it is underestimating by 6% during December and January. On an annual basis RETScreen has the worst performance.

On an hourly basis, the maximum temperature difference between TRNSYS and the simplified PV energy balance was 8.4 °C. This could be attributed to the differences in the calculated sky temperatures and the disregard of the radiative losses.

The fundamental heat transfer model may not be applicable to PV panels due to the following field operating conditions that are not captured by the formula [28]: (1) the upper surface temperature of the PV panel will vary with time due to the small scale wind fluctuations over the surface; (2) free stream turbulence present in naturally occurring wind due to trees and roofs and wind flow between structures increases the rate of heat transfer from the PV surface; (3) the tilted position of the PV panel causes the edge of the panel to act as obstacle to incoming wind, dropping the wind speed to almost zero after coming into contact with the edge of the panel (separation) and causing turbulent flow during the reattachment resulting in a higher heat transfer rate.

MATLAB has a feature that can convert MATLAB code to C or C++ but the simplified model's use of incompatible built-in MATLAB functions is producing errors during the conversion process. For future work, syntax and careful use of MATLAB functions must be observed to ensure that the code can be converted to a C++ library for general use.

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