Validation of TRNSYS modelling for a fixed slope photovoltaic panel

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Abstract: TRNSYS stands for transient system simulation software. This paper describes a procedure that was used to validate a TRNSYS model for estimating electricity yields from a fixed slope photovoltaic (PV) panel. The objective was to find how close to reality predicted energy yield for a specified panel can be, at a location near one of the weather stations listed in the software's database. The software was used to predict daily total incident radiation on a horizontal plane and electrical energy yields from a 90 Wp panel when sloped at $34°$ facing north at a test site in Cape Town, South Africa. The panel and other system components were then installed and tested to give actual electrical energy yields. The site was 5 km from a TRNSYS listed weather station. A local weather station logging 10-min data of actual total incident radiation on a horizontal plane enabled comparison with the model's estimate. Analysis of electrical energy yield gave statistical kappa values of 0.722 and 0.944 at actual to model acceptance ratio levels of 90% and 80%, respectively. Regression analysis of measured and model incident horizontal plane energy gave a coefficient of 0.782 across the year. It was thus concluded that within limits of meteorological phenomena behaviour, TRNSYS modelling reliably predicted energy yields from the PV panel installed in the neighbourhood of one of the software's listed stations.

Key words: TRNSYS, PV panel, solar radiation, horizontal surface radiation, electricity yield

1. Introduction

Many people in least developed countries do not have access to electricity. In tropical Africa for example, out of a mid-2013 population of about 880 million people [1], 591 million had no access to electricity [2]. Attempts at electrifying the region through national grids have made little impact. In some cases, hopes for a quick solution have faded. In Tanzania for example, Bleeker reports that 90% of the population rely on paraffin for lighting [3]. He adds that connecting to the grid in future is doubtful because of high grid extension costs. In Nigeria, there is 60%–70% inaccessibility. Moreover, the crisis is expected to continue until renewable energy and energy efficiency are aggressively pursued [4]. Sambo et al. [5] list issues—such as the use of substandard parts—to be addressed in getting quality PV installations in the country.

PV panels are assemblies of current generating cells. The total current generated is primarily a function of the amount of solar radiation incident on the panel and the number of cells arranged in parallel. The panel voltage depends mainly on the number of cells connected in series and mildly on incident radiation. A MATLAB based method to estimate actual energy output of a panel at a given location is described in [6]. A simpler model is given in [7]. Furthermore, there is industry specific software to assist in different design and selection circumstances. It includes PVsyst, RETScreen, PVWatts, HOMER, and WATSUN-PV among others [8–13]. Many of these are better suited for large systems. Mottillo et al. [13] for example modelled a 56-m^2 array in

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WATSUN-PV. When they modelled the same system in TRNSYS on 4 different days, results were reported to agree with experimental data on sunny days but to underestimate yields on cold and on cloudy days. A smaller 9.29-m^2 panel area is reported by Mao et al. [14] in a TRNSYS – PVF-CHART simulation comparison. Although close agreement between the two is reported, no experimental data to validate the models are given. In Malaysia, Al Riza et al. [15] simulated 4 parallel connected 100 Wp multicrystalline silicon PV panels in TRNSYS. They validated the model over a period of 10 days and concluded that for a 1.2 kWh daily lighting load the model adequately predicted the yield.

The work being reported now considered an even smaller standalone system, such as one suitable for a homestead attempting to emerge from energy poverty. Would TRNSYS modelling give a reliable energy yield prediction for this home across a period longer than indicated in the above citations? In answer to this question, the rest of the paper is organized as follows: Section 2 describes a sample PV system layout to serve the home; Section 3 introduces the TRNSYS PV model. Experimental work to validate it at a location in the neighbourhood of one of the software's listed weather stations is described in Section 4. Results are analysed and conclusions drawn in sections 5 and 6, respectively.

2. PV system for an energy poor home

For purposes of this work, we define an energy poor home as that in which electricity is not being used. Apart from muscle power, the other sources of energy are mainly biomass, used for cooking and lighting. Some energy poor homes also use kerosene for lighting. When sufficient funds become available to support self-generation, it is supposed that lighting receives first priority. Consequently, a standalone PV panel system is more likely to be the first step in overcoming energy poverty for those with no hope of accessing the grid.

2.1. Domestic lighting system layout

The essential components required to upgrade a home from energy poverty are shown in Figure 1. Their brief descriptions are:
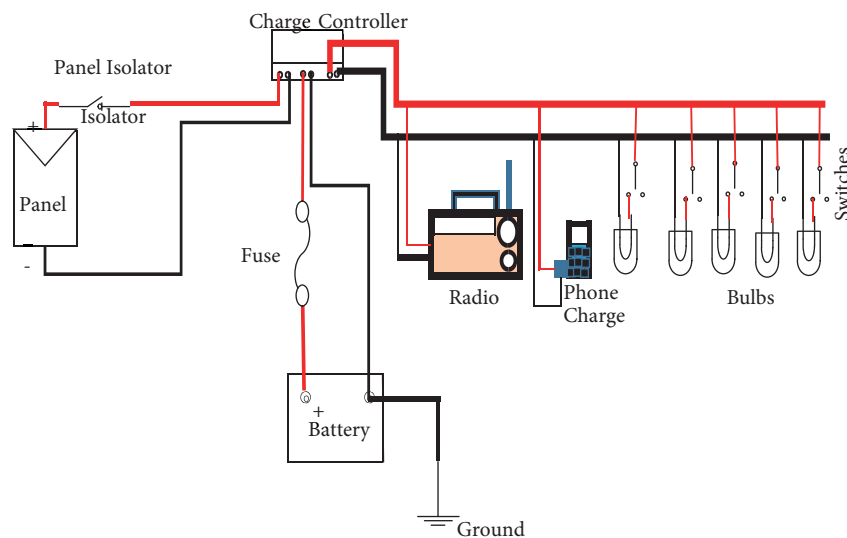

Figure 1. Suggested start-up PV system for an energy poor home.

- The panel – could be mono, or polycrystalline or amorphous silicon based. Operating voltage (V) and peak power rating (Wp) are the key specifications looked for by a user.

- The battery – stores electrical energy produced by the panel for later use. The main specifications the consumer is interested in are the voltage and the capacity in ampere hours (Ah).

- The charge controller – limits the battery charging voltage to a safe rated level. The user is principally interested in the voltage and peak current that can be handled by the controller.

- DC – Light bulbs. Suitable types include incandescent and light emission diodes.

- Connecting wires and switches.

3. PV energy TRNSYS modelling for Cape Town, South Africa

TRNSYS was developed at the solar laboratory of Wisconsin University [16], and has been in use for almost 40 years. It is normally used to analyse thermal-fluid systems but it has an extensive library of components that enable users to apply it in other areas. In the present case, the PV part of the electrical library was used to formulate a model for the university site located at 33.9° S, 18° E, and 68.5 m above sea level. The nearest TRNSYS listed weather station is: ZA - Cape Town – 688160, about 5 km away. Daily PV energy yield and total horizontal surface incident radiation results were extracted for comparison with experimental data.

3.1. The PV energy yield model and its elements

A basic PV TRNSYS model, shown in Figure 2, consists of the following elements:
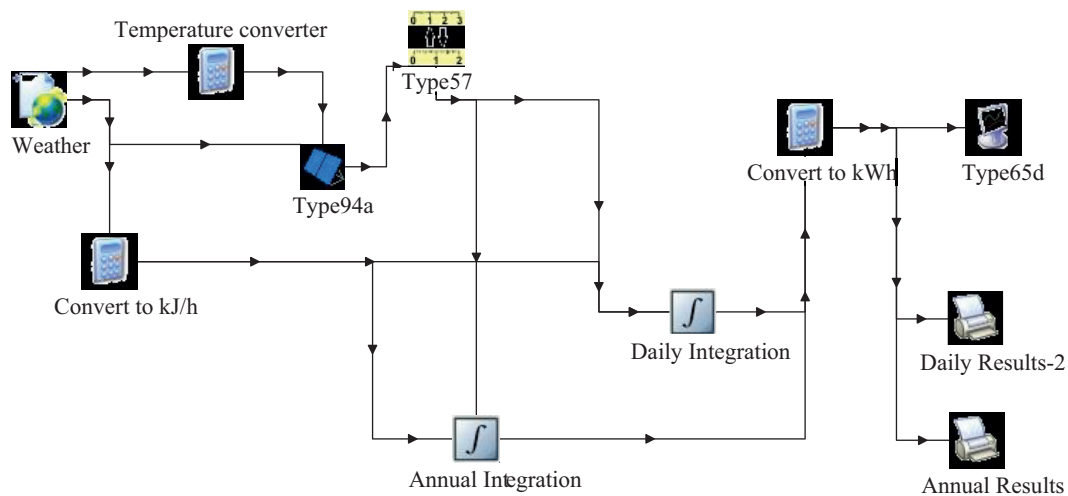

Figure 2. TRNSYS model used in deriving Cape Town's PV energy yield.

- Weather – data for the site were approximated to those observed at the nearest weather station from a weather meteonorm file accompanying the software. The modeller specifies the slope of the surface and the diffuse radiation model to be used in the computations.

- Temperature converter – to absolute Kelvin scale because the PV panel performance equations use this scale.

- Converters of units – Two change panel total incident radiation and maximum power output from W to kJ/h. Two others change daily and annual energies to kWh while also computing 1st law panel efficiencies.

- Type 94a – The PV panel: In this case, a 90 Wp panel from one South African manufacturer was used.

- Integration elements – determine total daily and annual energy incident on panel and that yielded by the panel in kJ.

- Type 65d – plots and displays a graph of daily results for the whole year.

- Daily and annual results – record respective total incident solar, output electric energy, and 1st law efficiency for filing.

3.2. The total incident horizontal surface energy yield

The slope surface parameter in the weather element of Figure 2 was set to $0°$ so that element Type 94a could be horizontal. Then the daily integration results of the 'convert to kJ/h' element yielded the daily incident energy at element 'Daily Results - 2'. This was read off in the output file after the simulation for each day.

4. Experimental work

4.1. Aim and objectives

The aim was to establish a level of confidence in using TRNSYS software, to predict PV panel electrical energy yield before attempting its use in guidance for small system components selection for use in different places. The specific objective in this experiment was to answer the question: Do TRNSYS's energy yield results of a typical South African assembled 90 W(p) mono crystalline silicon panel, using Cape Town airport weather data, agree with actuals at a site a few kilometres away from the airport?

4.2. Theoretical basis – a summary

Many researchers have described factors influencing the electrical energy yield of a PV panel [17,18]. In summary, they can be grouped into 3 categories: astronomy and geography based, panel design and manufacture, and lastly panel installation, usage, and maintenance. The first group is mainly controlled by nature, i.e. sun–earth–moon system dynamics and local physical and geographic climate. These contribute directly to incident beam radiation on a horizontal surface and to general diffuse radiation at the site as functions of time. In the experimental work, these have been directly measured every 10 min at the site since May 2013.

The second group is influenced by the scientific and technical expertise that is used in making the PV panel. A monocrystalline panel such as used in these experiments has an output current–voltage $(I - V)$ characteristic modelled by TRNSYS type 94a to approximate Eq. (1) [16].

$$I = I_L - I_D \left[\exp \left(\frac{V + IR}{a} \right) - 1 \right] \tag{1}$$

The panel's output current $\boldsymbol{I}$ is thus modelled to depend on 4 parameters: generated current $\boldsymbol{I_L}$, p-n junction diode current $\boldsymbol{I_D}$, panel internal resistance $\boldsymbol{R}$, and the indicative quality of manufacture—junction temperature dependent—parameter $\boldsymbol{a}$.

Some authors and researchers, e.g., [19–21], use a 5-parameter model that includes a shunt resistor $\boldsymbol{R_2}$, thereby giving the output current as in Eq. (2).

$$I = I_L - I_D \left[\exp \left(\frac{V + IR_1}{a} \right) - 1 \right] - \frac{V + IR_2}{R_2} \tag{2}$$

TRNSYS, however, recommends the latter equation as best suited for amorphous silicon modules in the form of a type 94b component. This experiment used a monocrystalline silicon panel. The peak power, $\boldsymbol{V_{mp}I_{mp}}$, directly computed from measured current $\boldsymbol{I_{mp}}$ and corresponding voltage $\boldsymbol{V_{mp}}$ at terminals of a maximum power point tracking (MPPT) battery charge controller, was thus compared with the simulation results of Eq. (1).

The third group of factors interact with the above two to yield a specific energy quantity for a particular installation and maintenance at the user's premises. The present work refers to the installation of a South African manufactured 90 Wp monocrystalline panel, atop a flat roof of a 2-storey building at a fixed $34°$ slope facing north. Apart from the grey painted roof, there were no nearby surfaces (where 'near' means up to 200 m) that could cast a shadow or reflect light onto the panel.

4.3. Tools and equipment

- 1 – Monocrystalline silicon solar panel 90 W(p); V_{oc} = 22.4 V; I_{sc} = 5.50 A; V_{mp} = 18.4 V; I_{mp} = 4.90 A; Manufacturer: SetSolar, Cape Town.

- 1 – MPPT charge controller 10 A;

- 1 – Battery: Deep cycle lead-acid; 12 V; 105 Ah.

- 1 – bulb: MR - 16 Dichroic halogen lamp; 50 W, 3000 h

- 2- Multimeters: The UNI-T UT53 Multimeter and the UNI-T UT203 clamp meter

- Interconnecting wiring

- Weather station – Campbell Scientific. The relevant parts of the station used in the experiment were: 1 Kipp Zonen CMP06 Pyranometer, ISO First class; 2 SP LITE silicon pyranometers with integrated fixture; an 8-channel Campbell Scientific measurement and control data logger.

- Ground-mounted support stand consisting of: a welded and painted rectangular steel frame of 25 mm × 25 mm angle sections; 20 mm diameter mild steel shaft mounted in three lockable plain bearings welded to the frame, coaxial with two central holes on the rectangular frame and inclined at a $34°$ to the horizontal.

- Two weather-proof enclosures: one for the battery and charge controller, the other for the electric bulb. The bulb's enclosure allowed free air circulation for cooling and visual check indicating the state of the circuit.

4.4. Set up and procedure (Figure 3)

Figure 3 shows the experimental setup. The detailed procedure followed was:

- The 90 Wp solar panel was bolted onto the rectangular frame of the stand facing true north.

- The battery, charge controller, and bulb were wired up in line with Figure 1.

- Half hourly readings of panel current and voltage at the charge controller terminals were made and recorded every day from 0500 to 2000 hours using the UT203 multimeter. The voltage reading was crosschecked using the UT53 meter, just in case there was disagreement exceeding 0.1 V.
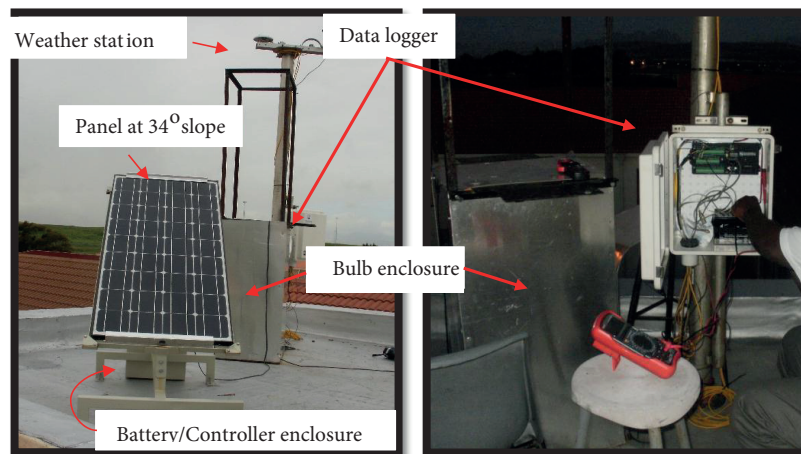
Figure 3. Experimental setup.

Out of a possible total of 558 data sets during the period, 533 or 95.5% were obtained. At the end of each day, the data were entered in an Excel spreadsheet to compute instantaneous half hourly power and the day's photoelectric energy yield by numerical integration using the ordinary trapezium rule.

The weather station is a long established, calibrated unit (installed in May 2013), recording weather data every 10 min. During the experiments, the main concern was routine maintenance work, i.e. checking that the station battery voltage was acceptable (≥ 12.0 V) and that the pyranometer surfaces were clean. The data recorded with the logger were: total radiation on a horizontal plane, I_h – read from the Kipp Zonen pyranometer and reconciled with the reading of the unshaded SP LITE silicon pyranometer.

After the experiments, the TRNSYS model results were compared with the experimental ones in a statistical analysis.

5. Results and analysis

Table 1 shows a typical day's results and energy yield computation. Figure 4 shows the TRNSYS modelling results for the 18 days. Figure 5 compares the experimental and model results.

In Figure 5, two things are noted: that the airport weather station data used in the TRNSYS software could be used to predict total energy yield in nearby locations, and that daily energy yield variations from the TRNSYS model seem to be 'gentler' than those of an actual PV installation.

From a statistical viewpoint, however, these results are too few to warrant a parametric analysis. Therefore, they had to be transformed into a categorical form for nonparametric analysis. According to [22], this is the recommended treatment for small samples.

For the transformation, four possible model acceptance levels were analysed: actual yields to model ratios of 80%, 85%, 90%, and 95%. In practical terms this meant that if a day's actual yield was below the acceptance level, the model was unsuitable and therefore its result unacceptable for planning purposes. The reason for an 80% cut-off level stems from a separate consideration of the battery storage system. At this level, users choosing recommended deep cycle batteries can hope to have 4.5 consecutive days of overestimation by the model without discharging the batteries to a target 30% limit: ($0.8^{4.5} = 0.366$). Those using ordinary car batteries, however, would need to take the 90% level in order not to discharge the batteries below a target of 60% limit in the same overestimation period. Table 2 gives the κ test measures of agreement between the model

Table 1. Typical day's results: 12 December 2013.

| Time	Voltage (V)	Current (A)	Power (W)	Cum. energy (kWh)	Time	Voltage (V)	Current (A)	Power (W)	Cum. energy (kWh)
0500	14.12	0.05	0.7	-					
0530	14.15	0.08	1.1	0	1300	14.51	6.75	97.9	0.317
0600	13.99	0.10	1.4	0.001	1330	15.06	6.59	99.2	0.367
0630	14.21	0.12	1.7	0.002	1400	15.82	6.23	98.6	0.416
0700	14.35	0.16	2.3	0.003	1430	15.73	6.21	97.7	0.465
0730	14.38	0.15	2.2	0.004	1500	14.44	6.06	82.5	0.511
0800	14.41	0.72	10.4	0.007	1530	14.49	5.58	80.9	0.554
0830	14.29	0.38	5.4	0.011	1600	14.50	5.39	78.2	0.598
0900	14.48	1.01	14.6	0.016	1630	14.48	4.54	65.7	0.629
0930	14.48	4.33	59.8	0.035	1700	15.94	3.89	62.0	0.661
1000	14.47	4.08	59.0	0.064	1730	14.48	3.46	50.1	0.689
1030	15.03	5.99	90.0	0.102	1800	14.45	2.48	35.8	0.711
1100	14.49	5.03	72.9	0.142	1830	14.35	1.38	19.8	0.725
1130	14.53	5.59	81.2	0.181	1900	14.30	0.59	8.4	0.732
1200	14.52	5.76	85.9	0.223	1930	14.41	0.03	0.4	0.734
1230	14.65	6.65	97.4	0.269	2000	Day's total energy:		0	0.734
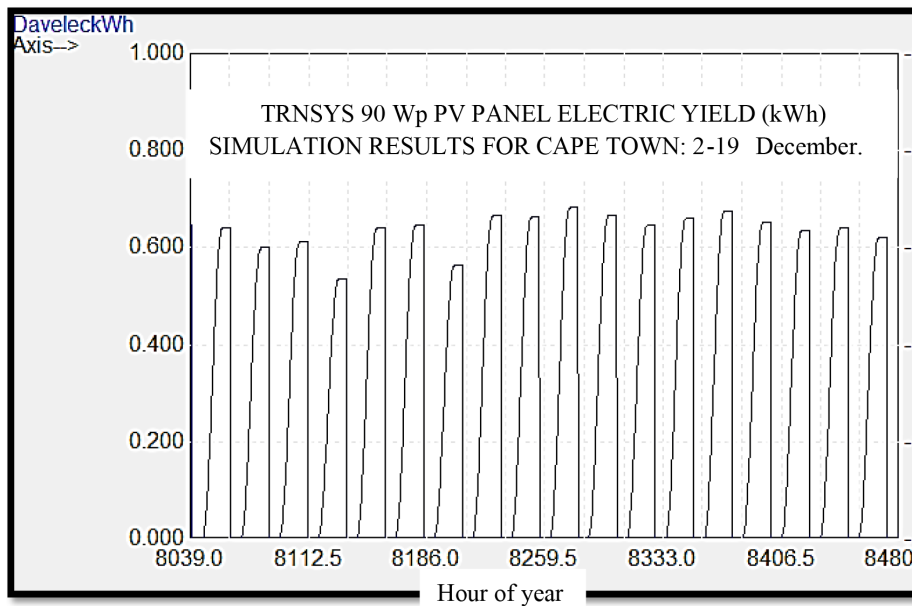
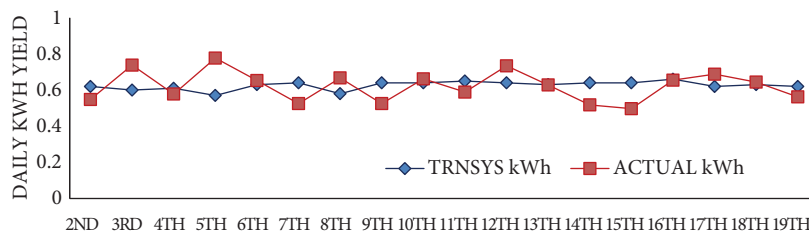**Figure 4.** Screen shot of TRNSYS model results.

Figure 5. Model and experimental results compared.

and experimental results for the 4 scenarios. Peat [23] suggests that κ values of 50%, 70%, and 80% respectively indicate thresholds of "Quite good", "Good", and "Very good" measures of agreement between two data sets. The results therefore show that TRNSYS's model prediction was a reasonable approximation to actual panel performance.

Table 2. Kappa (κ) analysis of transformed model and experimental results for different acceptance scenarios.

Cut-off model acceptance level	κ	Agreement level
Actual: Model = 80%	0.944	Very good
Actual: Model = 85%	0.778	Good
Actual: Model = 90%	0.722	Good
Actual: Model = 95%	0.556	Quite good

The second experiment used site weather data for the months August 2013 to July 2014 from the data logger and compared them with the software's airport data. The two correlated as evidenced in Figure 6 and in the regression analysis of Table 3. There were 342 valid points out of a possible 365 (93.7%). For the 342 days, the mean daily energy yield was 5.048 and 5.244 kWh/m^2 for measured and model, respectively. Regression analysis yielded a regression coefficient R of 0.782. According to Cohen [24], a strong relationship is implied if R $\geq$ 0.5. It is, however, noted that in many closely controlled experiments in science and engineering, researchers report coefficients in the range 0.9 to 0.99 as indicators of very close relationships [25]. For less controlled variables as in Cohen's human behaviour cases and in meteorological data in this paper's experiments, Taylor [26] and Frost of Minitab statistical software indicate that lower values can still predict a strong relationship. Hence, the result further confirmed the closeness between TRNSYS model results and actuals for this site.

Table 3. Regression analysis between experimental data and TRNSYS total incident radiation on a horizontal plane at CPUT Bellville campus.

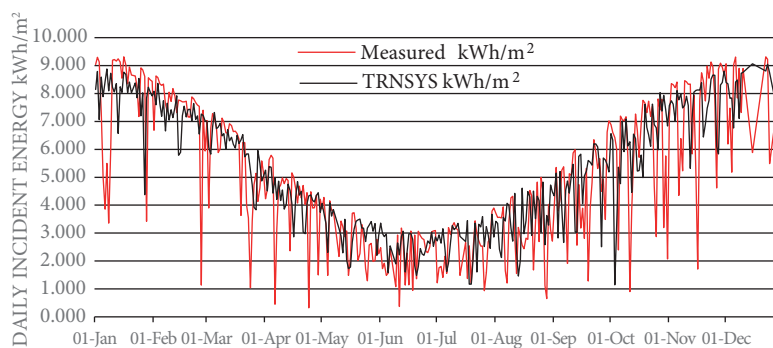| Multiple R	0.782
R Square	0.611
Adjusted R Square	0.610
Standard Error	1.557
Observations	342

Figure 6. Aug 2013 to July 2014 CPUT horizontal plane total radiation flux comparison.

6. Conclusion

TRNSYS modelling for predicting electrical energy yield from a 90 Wp panel has been validated for a site in Cape Town. Model reliability was tested at two levels: first, a limited period experiment was done on site in December 2013. Results were found to agree closely with the predicted yields. In a second and longer test, measured data on daily total incident radiation on a horizontal plane over a period of 1 year were compared with the software's prediction. The two correlated with a regression coefficient of 0.782 and hence a shared variance of 0.681. Given that the two sets of data were of uncontrollable weather parameters, it can be said that the results showed a strong relationship. Hence, it is concluded that TRNSYS could—within limitations of natural weather phenomena—be used to predict energy yields from the said PV panel at a place in the neighbourhood of the software's listed weather station. Subject to testing at other sites and with other panel sizes, this opens opportunities to apply the modelling to guidance on selecting fixed panel slopes, panel sizes, and battery types and numbers for homes nearby software listed stations.

Acknowledgements

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