PHOTOVOLTAIC MODULE THERMAL/WIND PERFORMANCE: Long -Term Monitoring and Model Development For Energy Rating

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Abstract

In order to predict the energy production of photovoltaic (PV) modules, it is necessary to predict the module temperature as a function of ambient temperature, wind speed, wind direction, total irradiance, and relative humidity. This paper presents a mathematical model to predict the module temperature based on the field monitored real data of module temperature, ambient temperature, wind speed, wind direction and relative humidity.

1. Background

Institute of Electrical and Electronics Engineers standard, IEEE PAR 1479 "Recommended Practice for the Evaluation of Photovoltaic Module Energy Production" requires the module temperature to predict power/energy production as a function of ambient temperature, wind speed, wind direction, total irradiance and relative humidity. Since the thermal properties of each module type may differ from others, a mathematical model to obtain- the actual module temperature from the ambient data is needed. A group of modules with varying technologies were installed to gather data at NREL's Solar Radiation Research Laboratory (SRRL) on top of South Table Mountain in Golden, Colorado, where PV modules experience climatic patterns of four distinct seasons. Parallel work was carried out at the Arizona State University Photovoltaic Testing Lab (ASU-PTL), Mesa, Arizona, where the modules experience hot desert climate at the ASU East Campus. It was expected to develop a relationship of PV module temperature to ambient conditions based on the data collected.

2. Data collection and module information

To obtain ambient conditions, a weather station was installed along with PV modules being tested. The latitude-tilted, P_{max}-loaded PV modules were open-rack mounted in both locations. The weather station provided ambient temperature, relative humidity, and wind speed and wind direction. Reference cell gave out the global irradiance. As to PV module, temperature at backskin and open circuit voltage were collected. The data were sampled every 5 seconds, and averaged every 5 minutes and stored. The data collection for both sites was carried out over a 2-year period between 2000 and 2002. The quality of the collected data was verified periodically by normalized module temperature raise from ambient at adjusted 800 W/m^2 irradiance. The modules used in the project are listed Table 1. This periodical verification was carried out using a set of randomly selected data points, neglecting the influence of all the ambient parameters except temperature and irradiance.

Table 1: Module Information

	Cell Technology	NREL Site Module Number	PTL Site Modules Number
1	a-Si	3	4
2	Mono Si	1	2
3	CIS	1	2
4	EFG-Poly Si	1	2
5	Poly Si	1	2
6	CdTe	1	2

3. Method of data analysis

The method of Neural Networks was used to analyze the data collected. The objective of the analysis was to obtain a relationship between module temperature and the ambient conditions (ambient temperature, relative humidity, wind speed, wind direction and global irradiance).

Neural networks are composed of simple elements operating in parallel. These elements are inspired by biological nervous systems. As in nature, the network function is determined largely by the connections between elements. A neural network may be trained to perform a particular function by adjusting the values of the connections (weights) between elements. As shown in Figure 1, the network is adjusted, based on a comparison of the output and the target, until the network output matches the target. In the current work, the target is the measured module temperature, the inputs are monitored ambient parameters, the neural network is a mathematical model/equation and the adjusted weights are the corresponding coefficients of the ambient parameters.

MATLAB and its Neural Networks Toolbox were used in this project to carry out the data analysis.

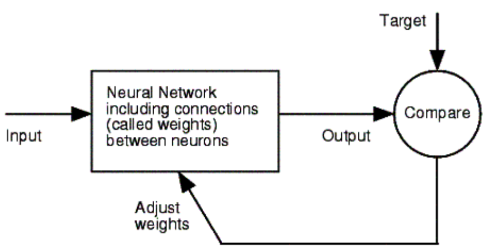

Figure 1: Basic Block Diagram of Neural Networks

4. Results and Discussion

The first effort made was to develop a model to predict PV module temperature based on five inputs: ambient temperature, relative humidity, wind speed, wind direction and global irradiance. The intended equation to predict the module temperature is:

$T_{module} = w1*T_{ambient} + w2*\mathit{Irradiance} + w3*\mathit{WindSpd} + w4*\text{WindDir} + w5*\text{Humidity} + \text{const}$

The results (coefficients w_1, w_2, w_3, w_4, w_5 and const) are presented in table 2.

The second effort was made to develop a model to predict PV module temperature based on 3 inputs only. They are ambient temperature, wind speed, and global irradiance. The intended equation to predict the module temperature is as follows:

$T_{module} = w1*T_{ambient} + w2*\mathit{Irradiance} + w3*\mathit{WindSpd} + \text{const}$

The results (coefficients w_1, w_2, w_3, and const) are presented in table 3.

An evaluation was carried out on one module (#7NREL, a-Si) by using information presented in tables 2 and 3. Figures 2 through 9 show the evaluation results based on different set of coefficients as noted in the above equations.

A linear regression **analysis of these plots**, in general, indicate that the R^2 values of the lines are 1 (or near 1) and they pass through the origin (near origin) at 45^o angle irrespective of any coefficient set used (Figures 2&3: module's own coefficient set with 5 or 3 inputs; Figures 4&5: multiple modules' coefficient set of the same technology with 5 or 3 inputs; Figure 6&7: multiple modules' coefficient set of multiple technologies of the same site with 5 or 3 inputs; or Figure 8&9: multiple modules' coefficient set of multiple technologies of different sites with 5 or 3 inputs). These plots seem to indicate that the 3-parameter model is superior to the 5-parameter model as the errors in the measurement accuracy of the last two parameters may have stronger influence, on the coefficient values, than that of those two parameters themselves. These figures clearly indicate that the simple 3-parameter model with the overall average coefficient set (provided in the last row of Table 3) could be used to predict the module temperature as shown in the following equation:

$T_{module}\ (^oC) = 0.943*T_{ambient} + 0.028 * \mathit{Irradiance} - 1.528*\mathit{WindSpd} + 4.3$

where the unit for $T_{ambient}$ is ^oC; irradiance is W/m^2; wind speed is m/s.

It is to be noted that the above model has been validated using a single module of only one particular technology. A detailed analysis on the technology independency of the above coefficient set will be carried out in a future publication.

A brief **analysis** on the values of the derived coefficients shown in **Table 2 and Table 3** is presented in this paragraph. The module temperature is primarily dictated by the ambient temperature and irradiance, irrespective of location or technology type. The ambient temperature sets the base temperature of the module and the irradiance predominantly sets the temperature raise of the module, which is about

0.028°C per W/m². The wind speed and ambient humidity slightly influence the module temperature whereas the wind direction influence is negligibly small. The module temperature is decreased by about 1.45°C per m/s wind speed increase. The humidity coefficients for the modules at the PTL site range from 0.089°C to 0.181°C per RH%, and at the NREL site they range from –0.010°C to 0.018°C per RH%. These coefficient values could lead to believe, though not possible, that the relative humidity has little or no influence on the temperature of the NREL site modules whereas it has a profound influence on the temperature of the PTL site modules. Considering the year-round dry condition of the PTL site (10% ~ 30 % relative humidity), it may be concluded that the humidity contribution to the module temperature in a dry condition is negligibly small as well.

Table 2: Coefficients for the five input parameter model

Technology	Module	Tamb w1	Irradiance w2 (°C/W.m⁻²)	WindSpd w3 (°C/ms⁻¹)	WindDir w4 (°C/deg)	Humidity w5 (°C/RH%)	const (°C)
Amorphous Si	1PTL	0.945	0.025	-1.255	0.009	0.181	-2.1
	2PTL	0.946	0.025	-1.304	0.010	0.158	-1.8
	3PTL	0.981	0.028	-1.647	-0.007	0.102	3.1
	4PTL	0.993	0.028	-1.697	-0.016	0.090	4.7
	5NREL	0.979	0.023	-1.280	-0.001	0.018	3.2
	6NREL	0.959	0.029	-1.433	-0.006	0.006	5.7
	7NREL	0.947	0.026	-1.222	-0.001	0.015	4.6
	Average	0.964	0.026	-1.406	-0.002	0.082	2.5
Monocrystalline Si	1PTL	0.959	0.030	-1.537	0.003	0.157	0.1
	2PTL	0.955	0.031	-1.518	0.002	0.164	0.1
	3NREL	0.969	0.025	-1.315	-0.004	0.007	4.5
	Average	0.961	0.029	-1.457	0.000	0.109	1.57
Copper indium diselenide	1PTL	0.950	0.030	-1.611	0.004	0.089	1.4
	2PTL	0.987	0.028	-1.414	-0.002	0.128	1.3
	3NREL	0.968	0.029	-1.373	-0.005	-0.010	6.0
	Average	0.969	0.029	-1.466	-0.001	0.069	2.9
EFG-Polycrystalline Si	1PTL	0.949	0.028	-1.571	-0.005	0.103	2.7
	2PTL	0.961	0.029	-1.564	-0.007	0.128	2.5
	3NREL	0.969	0.022	-1.224	-0.003	0.006	4.9
	Average	0.960	0.026	-1.453	-0.005	0.079	3.4
Polycrystalline Si	1PTL	0.944	0.031	-1.713	-0.003	0.127	2.7
	2PTL	0.957	0.031	-1.789	-0.008	0.125	3.5
	3NREL	0.961	0.028	-1.384	-0.005	0.012	5.5
	Average	0.954	0.030	-1.629	-0.005	0.088	3.9
Cadmium telluride	1PTL	0.976	0.033	-1.786	-0.004	0.091	3.3
	2PTL	1.012	0.033	-1.720	-0.006	0.126	2.4
	3NREL	0.935	0.027	-1.385	-0.006	0.002	6.7
	Average	0.975	0.031	-1.631	-0.005	0.073	4.1
	Overall average	0.964	0.028	-1.488	-0.003	0.083	2.961

Table 3: Coefficients for the three input parameter model

Technology	Module	Tamb w1	Irradiance w2 (°C/W.m⁻²)	WindSpd w3 (°C/m.s⁻¹)	const (°C)
Amorphous Si	1PTL	0.930	0.025	-1.321	2.7
	2PTL	0.937	0.025	-1.373	2.7
	3PTL	0.947	0.027	-1.610	4.1
	4PTL	0.943	0.027	-1.605	4.2
	5NREL	0.958	0.023	-1.353	4.4
	6NREL	0.952	0.029	-1.604	5.4
	7NREL	0.930	0.026	-1.288	5.5
	Average	0.943	0.026	-1.450	4.1
Monocrystalline Si	1PTL	0.935	0.029	-1.562	3.5
	2PTL	0.930	0.031	-1.542	3.6
	3NREL	0.961	0.025	-1.425	4.5
	Average	0.942	0.028	-1.509	3.9
Copper indium diselenide	1PTL	0.944	0.030	-1.644	3.8
	2PTL	0.959	0.027	-1.406	3.4
	3NREL	0.979	0.029	-1.472	4.7
	Average	0.960	0.029	-1.507	4.0
EFG-Polycrystalline Si	1PTL	0.920	0.028	-1.548	4.0
	2PTL	0.922	0.029	-1.529	4.0
	3NREL	0.962	0.022	-1.326	4.9
	Average	0.935	0.026	-1.468	4.3
Polycrystalline Si	1PTL	0.914	0.031	-1.701	4.7
	2PTL	0.917	0.030	-1.747	4.8
	3NREL	0.948	0.028	-1.550	5.6
	Average	0.926	0.030	-1.666	5.1
Cadmium telluride	1PTL	0.952	0.033	-1.770	4.5
	2PTL	0.975	0.032	-1.689	3.9
	3NREL	0.933	0.027	-1.544	6.1
	Average	0.953	0.031	-1.667	4.8
	Overall average	0.943	0.028	-1.528	4.328

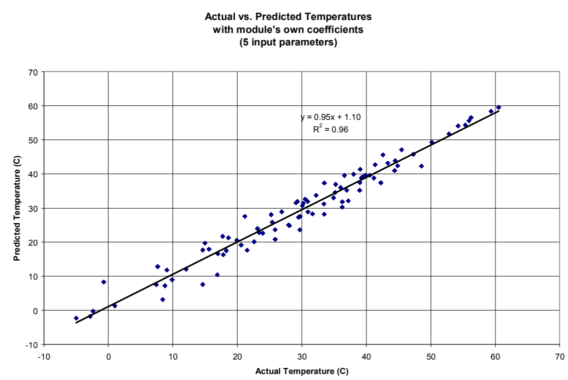

Figure 2: Actual vs. Predicted temperatures
(With module's own coefficients – 5 inputs)

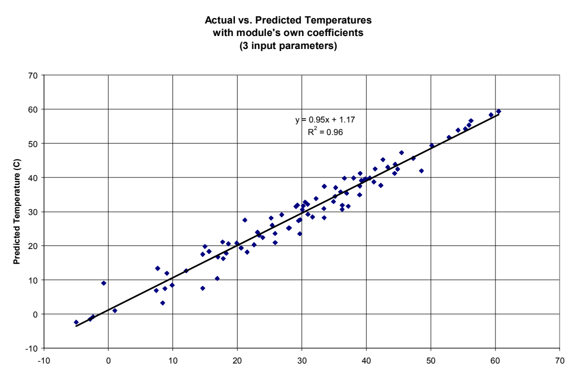

Figure 3: Actual vs. Predicted temperatures
(With module's own coefficients – 3 inputs)

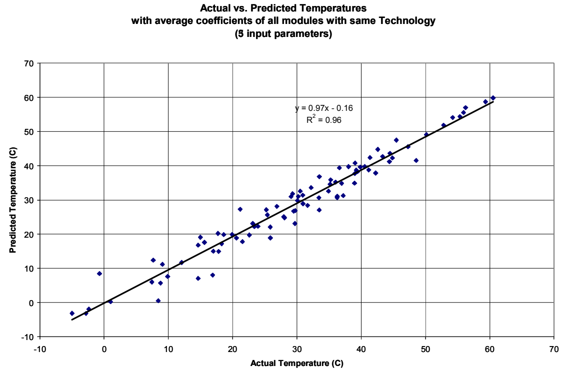

Figure 5: Actual vs. Predicted temperatures
(With average coefficients of all modules with same technology – 3 inputs)

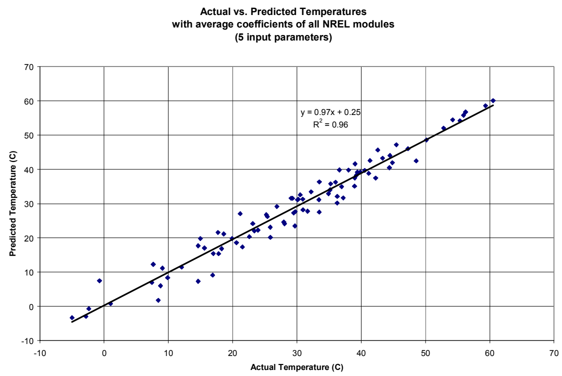

Figure 6: Actual vs. Predicted temperatures
(With average coefficients of all NREL modules – 5 inputs)

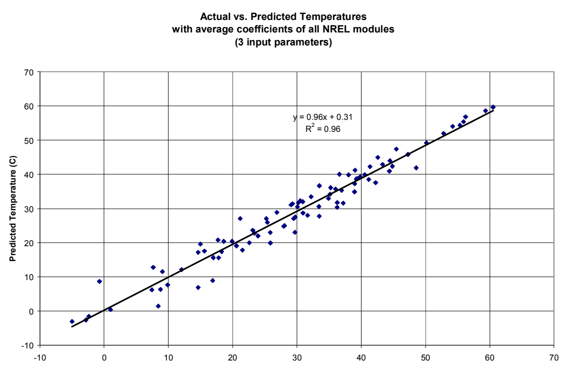

Figure 7: Actual vs. Predicted temperatures
(With average coefficients of all NREL modules – 3 inputs)

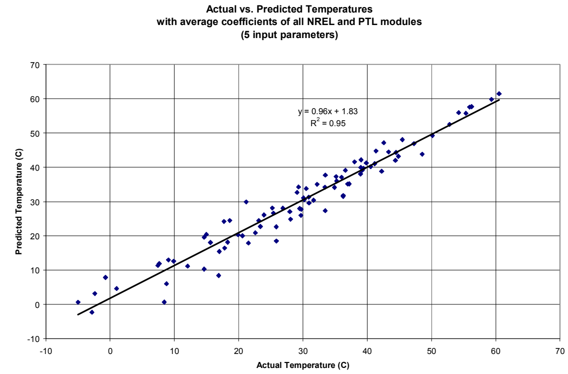

Figure 8: Actual vs. Predicted temperatures
(With average coefficients of all NREL modules – 5 inputs)

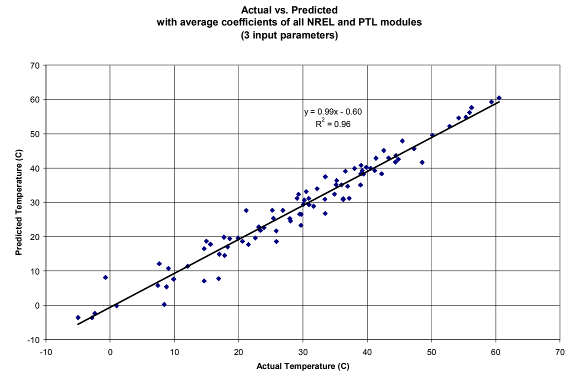

Figure 9: Actual vs. Predicted temperatures
(With average coefficients of all NREL and PTL modules – 3 inputs)

5 Conclusions

The reduction and analysis work performed on a long-term collected data indicate that the derived coefficients for ambient temperature, wind speed and irradiance are fairly independent of site location and technology type. A simple linear relationship between the module temperature and the ambient conditions (ambient temperature, irradiance, humidity, wind speed and wind direction) exists, and is established as shown in the following empirical equation:

$$T_{module}\ (^{o}C) = 0.943*T_{ambient} + 0.028*Irradiance - 1.528*WindSpd + 4.3$$

where the unit for $T_{ambient}$ is ^{o}C; irradiance is W/m^2; wind speed is m/s.