Modeling and Simulation of Solar Irradiance Conversion Using the Pyranometer App

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Abstract: - Solar irradiance is the amount of light energy that the sun emits and reaches the earth. The Pyranometer app is used to gather sample data. This predictive model calculated the electricity a solar module generates based on solar irradiance. It can calculate the voltage, current, and power a solar module can produce from solar irradiance. The study used a developmental-evaluative design using simulation modeling created using Matlab® and Simulink®. The evaluation of the model's accuracy was confirmed on a parallel run with an existing renewable solar energy facility to assess functionality, performance, robustness, workmanship, and the overall recommendation of the model. Findings revealed promising results that the designed model could, with reliable accuracy, simulate a solar module's performance from a given amount of irradiance.

Keywords: solar module, irradiance, pyranometer, predictive model, simulation modeling.

I. Introduction

One of the most critical metrics of interest for scientists to comprehend the Earth and its climate system is the solar irradiation incident on the Earth's surface [3]. In solar photovoltaic power forecasting, advances in computer technology and sensors make numeric modeling methods a hotspot (Sheng, Xiao, Cheng, Ni, & Wang, 2018). Computer simulation devices are needed to predict photovoltaic systems' energy production to make informed economic decisions. Measurement of solar irradiance in watts per square meter (W/m2)! The iPhone is a gadget for fun and educational purposes only [7]. Highly accurate "pyranometers do daily measurements of solar radiation." These instruments measure weather, climate, solar energy production, agriculture, and other fields.

Solar radiation can be harnessed and transformed into usable energy sources, such as heat and electricity, using various techniques [5]. Any given point on the Earth's surface receives different amounts of solar radiation depending on geographic location, time of day, season, local landscape, and local weather. Forecasting solar irradiance is an essential first step toward predicting the performance of a solar energy conversion system's performance and ensuring the electricity grid's stable operation [8]. Solar systems' success in transmitting solar radiation depends on their inclination angle to the horizontal plane, independent of climatic conditions. Sunlight will fall steeply to extract maximum power from solar panels. Optimum fixed tilt angles of solar panels should be updated monthly and seasonally [9]. To predict the amount generated, solar power involves the knowledge of the Sun, atmosphere, and other parameters [1]. Measuring solar irradiance provides knowledge to make crucial investment decisions [10].

One of the most promising nations is the Philippines, among developing countries that use solar energy as a secondary source of electricity using photovoltaics which turns heat from the Sun into a stream of electrons through the photovoltaic effect. However, most homeowners will buy, set up, and configure the solar panel anywhere they want without knowing how much voltage, current, and power of harnessed solar irradiance, where the homeowners only have a trial and error in installation. Moreover, no existing software model can convert an amount of voltage, current, and power of harnessed solar irradiance. Hence, the researcher would measure the solar irradiance using the developed software model to ensure the location is suitable for harnessing solar irradiance before installing solar panels. Thus, the researcher was inspired to create a computer software model that will convert the solar irradiance measured by the pyranometer app into voltage, current, and power.

Research Objectives

The study aims to develop a computer software model for converting the amount of solar irradiance measured from the pyranometer app. Specifically, this study intends to attain the following purposes:

1. Design and develop a computer software model that will convert the amount of solar irradiance measured by the pyranometer app in terms of:
   1.1 Voltage;
   1.2 Power, and;
   1.3 Current.
2. Determine if the data generated from the developed model and the solar panel differ;
3. Evaluate the developed computer software model in terms of:

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3.1 Functionality;

3.2 Performance;

3.3 Robustness, and;

3.4 Workmanship.

Conceptual Framework of the Study

The framework of the study uses energy from the sun, which varies on the geographical location and time of the day. A pyranometer app for iOS was used to collect the sample data because irradiation data was barely recorded in isolated rural areas around the world [4]. While MATLAB software is used as simulation modeling via Simulink®, the researcher would now develop a computer software model that will convert the amount of solar irradiance measured from the pyranometer app in W/m2 to specific electricity variances like the voltage, current, and power. Moreover, the researcher will evaluate the development of the computer software model's functionality, performance, robustness, and workmanship.

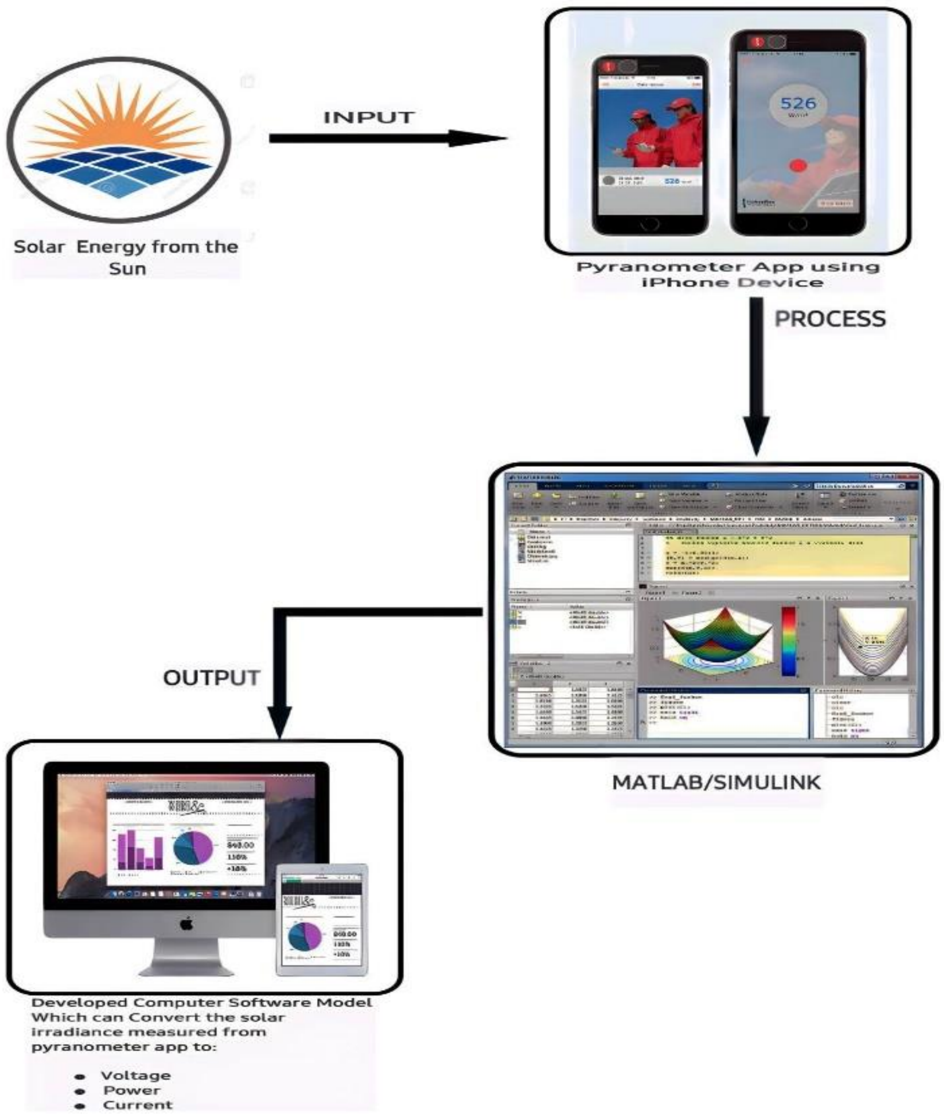

Fig. 1 Conceptual Framework of the Study

II. Methodology

Simulation Modeling was used extensively in industry as a decision-support tool in numerous industrial problems, including estimation of facility capacities, testing for alternative methods of operation, product mix decisions, and alternative system architecture [2]. Simulation helps the researcher to understand how well a system performs under a set of parameters.

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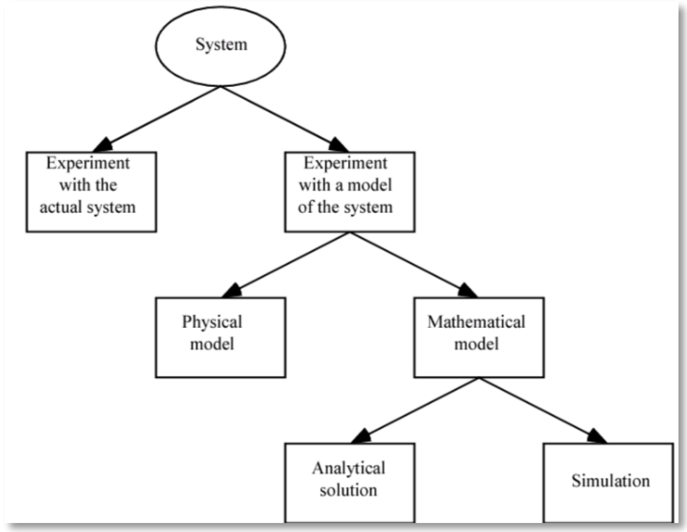

Fig. 2 The Simulation Modeling

Experiment with the actual system. The investigation was the real working of systems based on the situations prevalent during experimentation. In this stage, the researcher has been testing the existing set-up and configuration of the solar panel to assess how the system calculates the amount of power, current, and voltage of solar irradiance.

Experiment with a model of the system. The model was a logical framework, based on certain assumptions, of the working of thing/s. A model helps predict the behavior of the system under different situations. In this stage, the researcher has conducted an assessment of the developed software model to assess the model in calculating the amount of power, current, and voltage of solar irradiance using MATLAB/SIMULINK. The result of the developed software model and the actual system's experiment will be verified and validated to check its consistency.

Physical Model. The physical model was the smaller or larger physical copy of a modeled object. The physical model helps in the visualization of the object effectively taken into consideration. At this stage, the researcher was able to apply the purposes and functions needed for the developed software to run at his best.

Mathematical Model. The mathematical model was the model that was composed of symbols and logic. The mathematical model was used to explain the system study the effects of different components, and make predictions about the behavior of the system. In this stage, the researcher initially coded all mathematical formulas and parameters considering all assumptions using the solar irradiance amount measured from the pyranometer app to a specific amount of power, current, and voltage.

Analytical Solution. Analytical was a mathematical abstraction that extended to address various working conditions, thanks to some assumptions about how a process is evolving. The accuracy of the model is considered through the validity of the hypothesis to derive the mathematical formulation. In this stage, the researcher will check the coded formula and adjust it to ensure that the exact wording has the best result.

Simulation. The simulation of a system is represented as the running of the system's model. It can be used to explore and gain new insights into new technology and estimate the performance of systems too complex for analytical solutions. The simulation model always abstracts away from the real world. In this stage, the researcher conducts a series of simulations to gather all the results for validating and determining the effectivity of the developed software model in converting the amount of solar irradiance measured from the pyranometer app into current, voltage, and power.

Research Instrument

The standardized adapted evaluation form from the Rochester Institute of Technology was used as an instrument in this study. The researcher will use the said research instrument in conducting the proposed software model. Determining the effectiveness of the computer software model, the evaluators used the following scale:

Table 1: Research Instrument Likert-Scale

GRADE	INTERPRETATION	REMARKS
A+	96.1-100	
A	93.1-96	Superior
A-	90.1-93	

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B+ B B-	86.1-90 83.1-86 80-83	Above Average
C+ C C-	76.1-79 73.1-76 70-73	Average
D+ D D-	66.1-69 63.1-66 60.1-63	Below Average
F	<60	Failing

Data Gathering

First, the researcher sent a request letter for the Home Owner's approval to ask permission to conduct the study. The researcher has held the survey on 3 Saturdays, and 2 Sundays from 8:00 am to 5:00 pm with a time interval of 1 hour, using the pyranometer app to measure the solar irradiance of the sun. The data gathered was analyzed using a simulation of MATLAB/SIMULINK, where the data inputted. Thus, using simulation modeling of the computer software model will check the effectiveness of the results in converting the solar irradiance measured from the pyranometer app in terms of voltage, current, and power. It will compare to the actual set-up of the solar panel. The researcher evaluated the developed computer software model to test the functionality, performance, robustness, and workmanship of the computer software model using the Adapted-Evaluation Form. The answer was collected, tabulated, analyzed, and interpreted.

Data Analysis Procedure

The data gathered was formulated to get the mean and mode to evaluate the proposed computer software model. The researcher followed the assessment method used by a private graduate college in New York City at the Rochester Institute of Technology. In its Engineering Design Guide and Environment (EDGE) software, RIT uses this assessment method. EDGE is an open-source platform to support project developers and development teams. The researcher believes that the material is adequate for the evaluation of the developed system. The form involves grading the prototype/model from A+ (96 percent and higher) being the most top to F (60 percent and lower) being the most economical. It also involves grading the prototype/model in various factors such as Functionality, Performance, Robustness, and Workmanship. Using the evaluative analysis, the researcher interpreted the results of the proposed computer software model.

III. Results and Discussion

Measuring Solar Irradiance using Pyranometer App

A pyranometer app for iOS used to collect the sample data because irradiation data barely recorded in isolated rural areas around the world (Antonanzas-Torres et al., 2015). The method used does not have the accuracy of an irradiance meter of high precision but has the advantage of being readily accessible on any smartphone (Al-Taani & Arabasi, 2018).

Table 2: Solar Irradiance Sample

Time (AM)	Irradiance (W/m^2)	Time (PM)	Irradiance (W/m^2)
April 18, 2020			
8:00	260	1:00	318
9:00	308	2:00	310
10:00	289	3:00	280
11:00	380	4:00	0
12:00	324	5:00	0
April 19, 2020			
8:00	220	1:00	396
9:00	287	2:00	347

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10:00	268	3:00	212
11:00	400	4:00	0
12:00	387	5:00	0
April 25, 2020			
8:00	156	1:00	230
9:00	147	2:00	217
10:00	265	3:00	118
11:00	279	4:00	0
12:00	267	5:00	0
April 26, 2020			
8:00	260	1:00	378
9:00	287	2:00	367
10:00	320	3:00	225
11:00	396	4:00	0
12:00	387	5:00	0
May 2, 2020			
8:00	267	1:00	318
9:00	273	2:00	297
10:00	286	3:00	283
11:00	379	4:00	0
12:00	326	5:00	0

The data shows two data sets collected, five samples in the morning and five in the afternoon. Table 2 shows the gathered data using the software Pyranometer app installed on iPhone 5s in measuring solar irradiance. The data was gathered with a 1-hour interval from 3 Saturdays and 2 Sundays from 8:00 am to 5:00 pm. See Figure 2 for the line graph interpretation of the data.

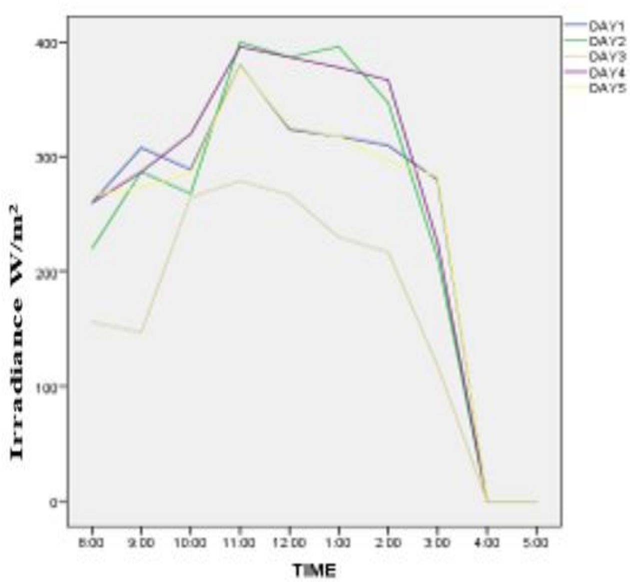

Fig. 3 Solar Irradiance Data Graph

Results: Day 1 = April 18, 2020

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Day 2 = April 19, 2020

Day 3 = April 25, 2020

Day 4 = April 26, 2020

Day 5 = May 2, 2020

The line graph shows a consistently high amount of solar irradiance (W/m2) recorded at 11:00 am on 3 Saturdays and 2 Sundays. No solar irradiance was recorded during 4:00 – 5:00 pm on 3 Saturdays and 2 Sundays. There was a sudden increase and decrease in solar irradiance between 8:00 - 5:00 pm. If the weather was sunny, there was an increase in solar irradiance (W/m2), but it decreased if it was cloudy or a rain shower.

Simulation of Computer Software Model

The Simulation Modeling used in the construction of the computer software model. Standard process the development wherein the system model was divided into two categories, first, which was an Experiment with the actual system, included analysis of the actual flow of data and how the solar irradiance was calculated. Second, an Experiment with a model of the method consists of the logical framework based on certain assumptions needed to create an accurate model that can convert the amount of Solar Irradiance. There are two categories, The physical model is composed of electrical components, wirings, electrical references, sensors, and a converter connected into one accurate model to convert solar irradiance. Second, Mathematical modeling is used to insert all-important formulas in the solar cell, which is the most important for getting accurate calculations. It allows the configuration will work at its constant stage, and the output will vary on any Solar Irradiance amount inputted. It also has two categories, the first Analytical solution, in which the accuracy of the model was considered the constant validity of the assumption to derive the mathematical formulation. Second, Simulation is represented as the running of the system's model. It was advantageous to validate the results accurately. MATLAB Simulink Software was used in the development of the computer software model. First, download the Pyranometer app using the iOS device for measuring the solar irradiance. Second, input the gathered data into the MATLAB Simulation Model. See Figure 4 to convert into voltage, power, and current.

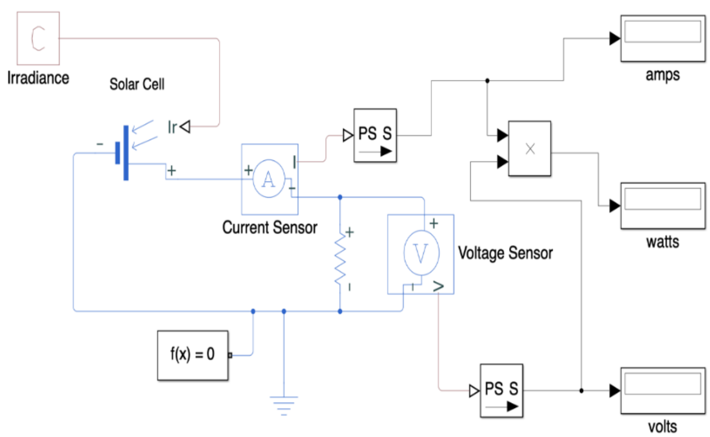

Fig. 4 Computer Software Model

The sample data was sent to a solar cell block [6]. The block diagram of a single solar cell is represented in Figure 5 as a resistance, Rs, connected in series with a parallel arrangement made up of the following elements:

- Current source
- Two exponential diodes
- Parallel resistor, Rp

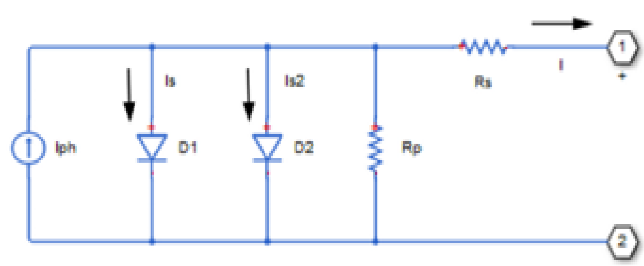

Fig. 5 Block Diagram of a Single Solar Cell

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The Simulink® solar cell block has a built-in formula to convert the irradiance to current, as shown below.

The output current *I* is:

I = Iph - Is(e^((V+I*Rs)/(N*Vt))-1) - Is2*(e^((V+I*Rs)/(N2*Vt))-1) - (V+I*Rs)/Rp*

Where:

Is and Is2 are the diode saturation currents

Vt is the thermal voltage

N and N2 are the quality factors (diode emission coefficients)

Iph is the solar-generated current.

Where:

I_{ph} is the solar-induced current:

$I_{ph}=I_{ph0}\times I_r I_{r0}$

where:

Ir is the irradiance (light intensity) in W/m2 falls on the cell.

I_{ph0} is the measured solar-generated current for the irradiance I_{r0}.

I_s is the first diode's saturation current.

I_{s2} is the second diode's saturation current.

V_t is the thermal voltage, *kT/Q*, where:

k is the Boltzmann constant.

T is the temperature simulation parameter value for the device.

Q is an electron's actual charge.

N is the first diode emission coefficient's quality factor (diode emission coefficient).

N_2 is the second diode emission coefficient's quality factor (diode emission coefficient).

V is the voltage across the electrical ports of the solar cell.

Assumptions:

The simulation model based on the following assumptions on the solar cell used in the simulation:

1. Short-circuit current, Isc: 6.40 A
2. Open-circuit voltage, Voc: .6 V
3. Number of series cells: 36
4. Device simulation temperature: 30 ^oC

To verify the accuracy of the designed model, a parallel run with an existing renewable solar energy facility was undertaken with the following configurations:

1. Short-circuit current, Isc: 6.40A
2. Open-circuit voltage, Voc: .6 V
3. Number of series cells: 36
4. Solar module orientation: 200^o SW
5. Solar module angle: 45^o

Table 3 shows the converted amount of solar irradiance using the developed computer software model and the actual results generated from the actual solar panel setup using 36 cells polycrystalline.

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Table 3: Results on the Parallel Run between the Developed Model and the Actual Set-up

Time	Irradiance W/m²	Voltage (V)		Current (A)		Power (W)	
		Model	Actual	Model	Actual	Model	Actual
April 18, 2020							
8:00	260	15.68	14.9	1.568	1.5	24.58	23.14
9:00	308	17.09	17.1	1.709	1.6	29.21	28.34
10:00	289	16.62	16.5	1.662	1.7	27.62	26.98
11:00	380	18.87	18.7	1.827	1.7	33.39	29.36
12:00	324	17.42	17.3	1.742	1.7	30.36	28.87
1:00	318	17.39	17.3	1.73	1.7	29.95	28.43
2:00	310	17.14	16.9	1.714	1.6	29.37	28.12
3:00	280	16.36	16.2	1.636	1.5	26.77	25.13
4:00	0	0	0	0	0.0	0	0
5:00	0	0	0	0	0.0	0	0
Time	**Irradiance W/m²**	**Voltage (V)**		**Current (A)**		**Power (W)**	
		Model	**Actual**	**Model**	**Actual**	**Model**	**Actual**
April 19, 2020							
8:00	220	13.82	12.9	1.382	1.3	19.1	18.23
9:00	287	16.56	16.4	1.656	1.5	27.44	26.45
10:00	268	15.97	15.9	1.597	1.5	25.5	24.35
11:00	400	18.5	18.4	1.85	1.7	34.22	33.18
12:00	387	18.35	18.2	1.835	1.7	33.69	32.78
1:00	396	18.46	18.3	1.846	1.7	34.06	33.24
2:00	347	17.82	17.8	1.782	1.6	31.75	30.28
3:00	212	13.38	13.2	1.338	1.3	17.9	16.46
4:00	0	0	0	0	0.0	0	0
5:00	0	0	0	0	0.0	0	0
Time	**Irradiance W/m²**	**Voltage (V)**		**Current (A)**		**Power (W)**	
		Model	**Actual**	**Model**	**Actual**	**Model**	**Actual**
April 25, 2020							
8:00	156	9.96	9.9	0.996	0.9	9.93	8.99
9:00	147	9.39	9.3	0.939	0.9	8.83	7.79
10:00	265	15.86	15.8	1.586	1.5	25.16	24.98
11:00	279	16.33	16.2	1.633	1.6	26.67	25.97
12:00	267	15.93	14.9	1.593	1.5	15.93	15.86
1:00	230	14.35	14.3	1.435	1.4	20.58	20.47
2:00	217	13.66	12.9	1.366	1.3	18.65	17.94
3:00	118	7.54	7.4	0.754	0.7	5.69	5.59
4:00	0	0	0	0	0.0	0	0
5:00	0	0	0	0	0.0	0	0
Time	**Irradiance**	**Voltage (V)**		**Current (A)**		**Power (W)**	

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	W/m^2	Model	Actual	Model	Actual	Model	Actual
April 26, 2020							
8:00	260	15.68	15.6	1.568	1.5	24.58	23.49
9:00	287	16.56	16.4	1.656	1.6	27.44	26.37
10:00	320	17.35	17.3	1.735	1.7	30.09	29.86
11:00	396	18.46	18.4	1.846	1.8	34.06	33.89
12:00	387	18.35	18.4	1.835	1.8	33.69	33.58
1:00	378	18.25	17.9	1.825	1.8	33.3	33.28
2:00	367	18.11	17.9	1.811	1.8	32.79	31.76
3:00	225	14.09	13.8	1.409	1.4	19.85	18.78
4:00	0	0	0	0	0.0	0	0
5:00	0	0	0	0	0.0	0	0
Time	**Irradiance W/m^2**	**Voltage (V)**		**Current (A)**		**Power (W)**	
		Model	**Actual**	**Model**	**Actual**	**Model**	**Actual**
May 2, 2020							
8:00	267	15.93	15.9	1.593	1.5	25.39	24.47
9:00	273	16.14	15.9	1.614	1.6	26.05	25.92
10:00	286	16.54	16.5	1.654	1.6	27.35	26.94
11:00	379	18.26	18.2	1.826	1.8	33.34	32.28
12:00	326	17.46	17.4	1.746	1.7	30.49	29.38
1:00	318	17.3	17.4	1.73	1.7	29.95	29.38
2:00	297	16.83	16.8	1.683	1.6	28.33	27.27
3:00	283	16.45	16.4	1.645	1.6	27.06	26.95
4:00	0	0	0	0	0.0	0	0
5:00	0	0	0	0	0.0	0	0

The data shows that, during the parallel run between the model and an existing renewable solar facility, the model readings are not stable compared to the actual facility readings. However, the model results revealed a very promising outcome as acceptable variation found between the model and the actual facility readings. The voltage readings showed a variance of fewer than 1 volts or even lower. The current readings revealed that all the readings from the model and the actual facility had differences of less than 0.5 amperes. In terms of power output, a very visible difference in results between the model and the actual facility was noticeable. However, the model results are still within the power allowance range of ±5%, an acceptable range that solar models take.

Table 4: The Difference in the Results on the Parallel Run Between the Developed Model and the Actual Set-Up

Indicators		Mean	Std. Dev.	Mean Difference (*After-Before*)	T
Voltage	Model	**16.11**	2.51	0.18	0.32
	Actual	**15.92**	2.56		(0.75)
Current	Model	**1.61**	0.25	0.07	1.24
	Actual	**1.54**	0.25		(0.22)
Power	Model	**26.25**	7.14	0.89	0.56 (0.58)
	Actual	**25.36**	7.05		

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NOTE: Figures in parentheses are p-values. P-values less than the 0.05 level of significance indicate a significant difference between the indicators of the model and actual set up.

There is no significant difference in the results on the parallel run between the developed model and the actual set-up. This further implies that the readings for the voltage, current, and power of the model and the real set up are just the same. It shows that the developed model would be an excellent predictive model to measure solar irradiance and convert the output into voltage, current, and power.

Evaluation of the Computer Software Model

After constructing the model, the documentation and testing phase performed to correct the errors and adjusting the mathematical formula. During the computer software model operation, recommendations noted and implemented to enhance the best performance and functionality of the model. Based on the evaluation given by the team of five (5) IT Experts using the Prototype/Model Demonstration and Evaluation Form from Rochester Institute of Technology. In getting the Interpretation of the Accumulated Grade per attribute, the researcher used the modal, which was the most frequently occurring score or value.

Table 5: Evaluation of the developed Computer Software Model

Attribute Being Evaluated	Grade (MODE)	Interpretation	Remarks
Functionality?: Does the prototype/model have all the functionality required to meet the team's deliverables	A	93-96	Superior
Performance ?: Does the performance of the prototype/model meet the team's deliverables	A	93-96	Superior
Robustness?: Can the prototype/model operate repeatedly without adjustments or repair	A -	90-93	Below Superior
Workmanship?: Does the prototype/model fabrication show quality workmanship	A -	90-93	Below Superior
Overall?: Grade Recommendation	A	93-96	Superior

Legend: F <60 D- 60-<63 D 63-<66 D+ 66-<69 C- 70-<73 C 73-<76 C+ 76-<79 B- 80-<83 B 83-<86 B+ 86-<89 A- 90-<93 A 93-<96 A+ >96

The result revealed that the majority of the evaluators responded that the robustness and workmanship of the developed computer software model were below superior. However, most of them answered that the functionality and the overall performance of the said model were superior.

IV. Conclusions

Currently, feasibility studies on the economical operations of renewable solar energy are questionable because current generations are only based on estimates and assumptions. Measuring solar irradiance as the basis in providing data to make important decisions on investments before the installation of a renewable solar energy facility, was most probably the best method. Therefore, based on the results the computer software model revealed a very promising outcome as acceptable variation was found between the model and the actual facility readings and turns out to be a good predictive model in measuring solar irradiance and converting the electricity into volts, current, and power.

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