Difference between the maximum empirical and field measured peak Watt values of thermal power system under highly sufficient solar conditions

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Abstract. Mono-Crystalline solar cell module is experimentally conducted in Khartoum, Sudan to study the difference between maximum empirical value of peak Watt and maximum value of thermal power produced in field under highly sufficient solar conditions. Field measurements are recorded for incident solar radiation, produced voltage, current and temperature at several time intervals during sun shine period. The thermal power system has been calculated using fundamental principles of heat transfer. The study shows that solar power for considered module could not attain the empirical peak power irrespective to maximum value of direct incident solar radiation and maximum temperature gained. A loss of about 6\% of power can be considered as the difference between field measurements and the manufacturer's indicated empirical value. Solar cell exhibits 94\% efficiency in comparison with manufacturer's provided data, and is 31\% more efficient in thermal energy production than in electrical power extraction for hot-dry climate conditions.

1. Introduction

The climatic conditions in Sudan are favorable for utilization of solar energy, as reviewed in figure 1. Sudan is exposed to solar incident of more than world's average radiation. Such potential is highly favorable in both thermal and photovoltaic energy extraction. This leads to receive many more hours of bright sunshine during the course of the year within the continent of the Earth. However, this will draw the attention to explain how the photovoltaic principle works to transform sunlight directly into electricity, what sort of hardware does the job, how the source is hitched to the load, and how to go through designing an appropriate system to specific needs. But before it has been immersed in the details of fascinating the power technology, it needs to be paused and consider how truly revolutionary begin to use photovoltaic devices to grow accustomed to their presence in our lives. This attitude could be happened in the respect of concept that should reflect on how marvelous it to be able to get electricity directly from the sun. It is worth mentioning that, Sudan as geographically located in the Sahara desert, with less cloud cover and a better solar angle, one could ideally obtain closer to 8.3 kWh/m\textsuperscript{2}/day provided the nearly ever present wind would not blow sand onto the units. The area of

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the Sahara desert is over 9 million km². 90,600 km², or about 1%, could generate as much electricity as all of the world's power plants combined.

Figure 1. World Solar Map

2. Theory
Principally, the output of a photovoltaic module or array is directly proportional to the amount of sunlight it receives, in terms of both intensity and duration. Seasonal and daily variations in available sunlight are a function of the earth’s rotation and its angle of tilt toward the sun. In simplest terms, this explains why sunlight becomes more abundant towards noon and tapers off in the afternoon and why it falls upon a given area with less intensity during hourly time of the day. Thus, for solar radiation to be most direct there are optimum tilt angles at which collecting devices (either photovoltaic or thermal) ought to be placed.

Due to the incident solar radiation on module surface area, an amount of heat transfer exists between exposed surface area and photo voltage cells. The rate of steady state heat transfer in a radial direction through a homogeneous material plane wall of Mono-crystalline cell is defined by the following equation of heat transfer fundamental:

\[ Q = (T_{sr} - T_i) \sum \frac{A}{R} \]  

Where:
- \( Q \) = Amount of heat transfer, W
- \( T_i \) = Temperature following the cell uniform thickness wall, °C
- \( A \) = Radiated cell surface area, \( \text{m}^2 \)
- \( R \) = Thermal resistance of cell material, \( \text{m}^2.\text{°C/W} \)
- \( T_{sr} \) = Incident solar air temperature, °C

Value of \( T_{sr} \) during maximum value of radiation is calculated by:

\[ T_{sr} = T_{amb} + (\alpha I / h_o) \]  

Where:
- \( T_{amb} \) = Ambient air temperature, °C
- \( \alpha \) = Solar absorptivity of outside film surface, dimensionless value. (For Mono-crystalline silicon, \( \alpha = 0.5 \))
- \( I \) = Incident solar radiation, W/m²
\( h_o = \) Convective film coefficient of outside surface, \( \text{W/ m}^2\text{.}\text{°C} \). (For direct Incident solar radiation this value depends on wind velocity, and is equal to 22.7\( \text{W/ m}^2\text{.}\text{°C} \) at wind velocity of 3.4 \( \text{m/s} \))

Thermal resistance of cell material can be found through:

\[
R = \frac{\Delta x}{k} \tag{3}
\]

Where:

\( \Delta x = \) Cell Thickness, \( \text{m} \)

\( k = \) Thermal conductivity, \( \text{W/ m.}\text{°C} \)

Electrical power produced is measured via:

\[
P = (I \times V) \tag{4}
\]

Where:

\( I = \) Current, \( \text{A} \)

\( V = \) Voltage, \( \text{V} \)

### 3. Results and analysis

This study was conducted in Khartoum, Sudan (Latitude: 15° 35' 53" North) for a photovoltaic module directed to incident solar radiation during the month of June, which is considered as the mostly hottest month during the year as averaged for 40 years based on the Metrological Climatic Data of the country.

A crystalline solar cell produced by RAGGIE Manufacturer (Model: RGM-130W ISO9001 CE) having the following technical specifications: maximum Peak Power (P\(_{\text{max}}\)=130W), Voltage (V\(_{\text{mp}}\)=17.5 V), Current (I\(_{\text{mp}}\)=7.42 A), surface area (1.495m x 0.670m), cell thickness (2.5cm), and thermal conductivity (149 W/m.\text{°C}) was used to conduct the experimental data. The cell is directed towards the sun and exposed to the North direction by an angle of 15°. Data is recorded at different time intervals during sun shine, and panel was considered as both solar cell and solar collector. Measurements of average interval values of both solar cell and collector are obtained in table 1, which indicates that for 11 hours of sun shine exposure total radiation received was measured to be 7,003Whr/m\(^2\) and the average voltage, current and surface temperature were 12.05V, 1.89A and 44.45\( \text{°C} \) respectively.

| Time Interval, O’clock | Radiation (Whr/m\(^2\)) | Voltage (V) | Current (A) | Temperature (°C) |
|------------------------|--------------------------|-------------|-------------|------------------|
| 07                     | 146.75                   | 11.45       | 0.42        | 25.65            |
| 08                     | 381.50                   | 11.66       | 1.17        | 33.33            |
| 09                     | 603.50                   | 11.85       | 1.94        | 42.23            |
| 10                     | 775.25                   | 11.99       | 2.53        | 47.90            |
| 11                     | 883.00                   | 12.10       | 2.96        | 52.90            |
| 12                     | 931.00                   | 12.17       | 3.13        | 53.98            |
| 01                     | 903.50                   | 12.23       | 3.06        | 54.03            |
| 02                     | 817.50                   | 12.26       | 2.78        | 53.00            |
| 03                     | 692.25                   | 12.27       | 2.33        | 50.23            |
| 04                     | 493.50                   | 12.24       | 1.50        | 45.70            |
| 05                     | 285.00                   | 12.19       | 0.74        | 40.05            |
| 06                     | 090.25                   | 12.13       | 0.18        | 34.45            |

Figure 1 shows the relationships of voltage and current in accordance to the hourly change of incident solar radiation. It clearly shows that for the herein considered module voltage increases as the incident solar radiation increases until it reaches its maximum value and dramatically falls with the
decreased amount of solar radiation. While current exhibits a relatively similar behavior as it falls smoothly with the decrease of incident solar radiation.

![Figure 2](image1.png)

**Figure 2.** Voltage and current through time intervals of sun shine.

Figure 2 represents the relationships of direct incident solar radiation and temperature versus different time intervals. The figure indicates that, as the temperature increases along sun shine period the direct incident solar radiation proportionally increases and vice versa. However, temperature and radiation reach their maximum values at mid day hours, mainly at 12 and 1 O’clock PM.

![Figure 3](image2.png)

**Figure 3.** Incident solar radiation and temperature through sun shine time intervals.

Observation of incident radiation, voltage and current behaviors are illustrated in figure 3, as it clearly shows the direct relation between solar cell outputs and the amount of collected solar radiation.
As targeting for maximum thermal energy to be produced by the solar cell, maximum values of data mentioned in table 1 are substituted into equations (2) and (3). Solar air temperature and thermal resistance of cell material were found to be respectively equal to 74.5°C and 0.1678 m²°C/W. When substituting these values into equation (1) it gives an amount of heat transfer equal to 122.3 W. As for electricity production, using maximum values induced into equation (4), maximum electrical power produced is 38.4 W, which is found to be 31% of thermal potential extracted power from the solar cell.

The difference in Watts between the thermal power produced by solar cell and peak power of the same solar module measured empirically by the manufacturer was found to be equal to 7.6 W, which indicates solar cell efficiency of 94.1%.

Figure 5 compares between thermal and electrical power outputs as functions of both time intervals and solar radiation. Solar radiation is demonstrated in a curve as a function of time, while power values are represented as a variation of bubble size. The figure indicates that potential thermal power delivered is greater than extracted electrical power at all values of incident solar radiation.

**Figure 4.** Voltage and current change with incident solar radiation.
Figure 5. Thermal and electrical power produced with incident solar radiation.

4. Conclusion
Solar power for such module could not attain peak value of its power irrespective to the maximum value of direct incident solar radiation and maximum temperature attained. A loss of about 6% can be considered as the difference between the field measurements to be obtained at maximum value and that indicated by the manufacturer for empirical maximum value. These losses encountered on the system may be caused due to many factors which related to in accuracy of the measurements, instruments and devices error, in appropriate inclination of module and other circumstances. Whereas over 68% of incident solar energy is dissipated into losses for electricity extraction when compared to thermal energy gained.

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