CHAPTER – V

5. Irradiance Dependence on Performance of Dye Sensitized and V-Grooved Silicon Solar Cells

Abstract

Irradiance intensity holds great influence for cell performance. A relative normalized irradiance-dependent efficiency of photovoltaic modules is recommended as an objective means of quantifying their behaviour under variable irradiance conditions. It allows users to decouple the irradiance-dependent behaviour of photovoltaic modules from their temperature dependence. This criterion is shown to have a broad applicability in diagnostics by manufacturers and users of photovoltaic module’s data sheets. A recommendation is made for the following study to require that the measured power-irradiance, power-temperature matrix according to the new standard could be incorporated. With the increase in temperature the rate of photon generation increases thus reverse saturation current increases rapidly and these results on reduction in band gap. Hence this leads to marginal changes in current but major changes in voltage.
5. 1. Introduction

Solar energy is most readily available source of energy. It is Non-polluting and maintenance free. To make best use of the solar PV systems the output is maximized either by mechanically tracking the Sun and orienting the panel in such a direction so as to receive the maximum solar irradiance or by electrically tracking the maximum power point under changing condition of insolation and temperature. The overall performance of solar cell varies with varying Irradiance and Temperature. With the change in the time of the day the power received from the Sun by the PV panel changes. Not only this both irradiance and temperature affect solar cell efficiency as well as corresponding Fill factor also changes. This paper gives an idea about how the solar cell performance changes with the change in above mentioned factors in reality and the result is shown by conducting a number of experiments.

The voltage and current both being a function of the light falling on the cell, there exists a complex relationship between insolation (sunlight) and output power. Solar cells capture slow-moving low energy electrons. These effects are saturated and cause a fixed energy loss under bright light condition. However, on an overcast day i.e. at lower insolation levels these mechanisms show an increasing percentage of the total power being generated. Too much insolation causes saturation of cells, and the number of free electrons or their mobility decreases greatly. For an example in
case of silicon the holes left by the photoelectrons neutralizes taking some time, and in this time these absorb a photoelectron from another atom inside the cell. This causes maximum as well as minimum production rates.

5.2 Irradiance

It is seen that the maximum irradiance is measured in the plane of 45°, but the amount of irradiance in the 0° tilted plane exceeds that in the morning and afternoon. The irradiance measured in the vertical plane is markedly lower than seen for the other planes. It is seen that the temperature distribution doesn’t follow the irradiance completely. The peak for maximum irradiance and maximum module temperature is found at the same time, but the module temperature decreases less in the afternoon, due to the higher ambient temperature. The relation between incidence angle and measured irradiance is seen that the lowest incidence angle is found at solar noon, where the irradiance is also at its maximum for all planes.

A qualitative measure for the module performance is found in the energy production $\Delta E_{\text{max}}$. $\Delta E_{\text{max}}$ is determined as the power output from the module over a time interval when operated in maximum power point. The relation between $\Delta E_{\text{max}}$, $P_{\text{max}}$ and time $\Delta t$ is given by $P_{\text{max}} = (\Delta E_{\text{max}}/\Delta t)$, $\Delta E_{\text{max}}$ is determined by integrating $P_{\text{max}}$ with respect to $\Delta t$ and is given per active module area. The produced energy $\Delta E_{\text{max}}$ for the modules on July 1st as well as
measured irradiance in the planes data where incidence angle on the module has been below 90°.

It is evident that the Si solar V-grooved module has the highest energy production of approx. 200 kJ/m² for the specific day. \( \Delta E_{\text{max}} \) for the DSSC is slightly higher than that of the other and amount for respectively approx. 130 kJ/m² and 120 kJ/m² on a daily basis. The 90° tilted DSSC module has the lowest energy production just exceeding 50 kJ/m². The energy production for the tested DSSC modules is markedly lower than seen for the silicon panel, resulting in an energy production for the DSSC 0° and DSC\( 45^\circ \) accounting for approx. 65% and 60% of the energy produced by the with microlens used module. The vertical DSSC module performs 25% of the 45° tilted silicon module and around 40% of the horizontal or 45° tilted DSSC module.

An analysis of measurements performed for a period from June 16th to July 9th has been carried out. The objective of the measurements was to create a base for comparison of the silicon- and DSSC module with respect to performance under realistic conditions. The complete data set was used to gain an overall understanding of the dependencies between electrical performance and external parameters that the modules were subjected to under open-air conditions. As the data set included results from all weather conditions data filtering was performed. Hereby the dependencies between irradiance level to \( I_{\text{sc}} \), \( V_{\text{oc}} \), FF, \( P_{\text{max}} \) and
conversion efficiency was identified. Linearity in irradiance level and measured $I_{sc}$ was seen for both the tested DSSC and silicon modules. The generated $V_{oc}$ for the silicon module was seen to be influenced by irradiance level which showed a logarithmic decreasing $V_{oc}$ for lowered light levels. The Fill Factor was seen to decrease for both the silicon and the DSSC modules for increasing irradiance, most pronounced for the DSSC modules. The best fit to $P_{max}$ as function of $G$ for all modules was seen to be linear. By regarding the conversion efficiency a tendency of increased efficiency for decreasing irradiance is seen for the DSSC. This is not the case for the silicon module, which exhibits higher efficiency at higher light levels. By evaluating results from one sunny day, a qualitative analysis of energy production was performed. Further a more specific analysis of performance dependency with respect to irradiance and module temperature could be performed. The results showed that the top-glass of the modules hold great importance for performance as the reflection of light is increased for increasing incidence angles. The decrease in $[I_{sc} / G]$ seen for the modules which was expected to be constant is contributed to the increased reflectance at the glass surface. The additional $I_{sc}$-contribution for the DSSC which was seen in the laboratory.

5.3 Investigational Work

The effect of module temperature on $V_{oc}$ for the silicon module was seen to result in a decrease of $V_{oc}$ for high module
temperatures. The tendency was not noticeable for the DSSCs. The Fill Factor for the DSSC was seen to benefit under low light conditions, resulting in a relative FF scaled to solar noon $T_s=12.00$ reaching up to 1.30 under low irradiance. The efficiency for the DSSCs was seen to increase when moving away from solar noon, and the additional gain in efficiency was up to 10% when scaled to efficiency at $T_s=12.00$ due to better performance under low light levels. The Silicon module showed highest conversion efficiency in the morning which is attributed to the temperature influence on $V_{oc}$. The produced energy of the modules when operated in maximum power point for one sunny day has been determined and a markedly larger energy production for the silicon module per active area is seen. The performance of the DSC$0^\circ$ and DSSC$45^\circ$ is comparable and accounts for more than 60% of energy per active area from the silicon module. The other positioned vertical module is the module with the lowest energy production due to the relatively low irradiance in the vertical plane.

5.4 Determination of Glass Transmittance

Theoretical transmittance of float glass the transmittance of float glass was determined in a simplified manner, as assumptions were made about the absorbance being neglective and only reflectance between the air-glass surface was considered. By determining the transmittance of glass with and without TCO-glass experimentally a good measure for the actual light transmittance
through the glass would be available. As the measurements are only possible for an air-glass-air setup, the refraction of light would still differ from the actual situation, as a module consists of more layers (for the DSSC: TiO₂, electrolyte, back glass). The results of the transmittance-measurements can be used to correct the results for a lower limit of available light entering the cell.

![Graph](image)

**Figure: Distribution of irradiance from solar tracker**

In order to clarify that the day was sunny, the distribution of solar irradiance is looked upon. A sunny day is characterized by a very low amount of diffuse irradiance, since not much irradiance is scattered by to clouds with Solar Irradiation. The distribution of solar irradiance on July 1st has been obtained from a solar tracker and the measured irradiance cannot be compared to the other measurements of irradiance in the setup, as the pyranometer in the setup is fixed facing south. From the distribution, the amount
of diffuse irradiance is below 100 W/m² the entire day, so the day is assumed to be a sunny day with clear sky.

5.5 Solar Tracker

A solar tracker is a device that orients a payload toward the sun. Payloads can be photovoltaic panels, reflectors, lenses or other optical devices. In flat-panel photovoltaic (PV) applications, trackers are used to minimize the angle of incidence between the incoming sunlight and a photovoltaic panel. This increases the amount of energy produced from a fixed amount of installed power generating capacity. In standard photovoltaic applications, it is estimated that trackers are used in at least 85% of commercial installations greater than 1MW from 2009 to 2012. In concentrated photovoltaic (CPV) and concentrated solar thermal (CSP) applications, trackers are used to enable the optical components in the CPV and CSP systems. The optics in concentrated solar applications accepts the direct component of sunlight light and therefore must be oriented appropriately to collect energy. Tracking systems are found in all concentrator applications because such systems do not produce energy unless pointed at the sun.

5.6 I-V Characteristics Study:

I-V Characteristics is a curve between current and voltage. The curve shows an inverse relation. The area under the I-V curve is the maximum power that a panel would produce operating at
maximum current and maximum voltage. The area decreases with increase in solar cell voltage due to its increase in temperature. Due to fluctuations in environmental conditions, temperature change and irradiance level the IV curve would change and thus maximum power point might also change. Thus the MPPT algorithm keeps on tracking the knee point.

![IV-curve of a solar cell both under irradiated and dark conditions. The shaded area shows the maximum power operating region.](image)

The above figure shows two characteristics i.e. Dark and Irradiated characteristics. When the PN junction is illuminated the characteristics get modified in shape and shift downwards as the photon generated component gets added with the reverse leakage current. The maximum power point can be obtained by plotting the hyperbola defined by $V^*I_\text{c}= \text{constant}$ such that it is tangential to the I-V characteristics. The voltage and current corresponding to this
point are peak point voltage and peak point current. There is one point on the curve that will produce maximum electrical power under incident illumination level. Operating at any other point other then maximum power point will mean that cell will produce maximum thermal power and less electrical power [2].

5.7 Solar Cell Efficiency

It is the ratio of the electrical output of a solar cell to the incident energy in the form of sunlight. The energy conversion efficiency (\(\eta\)) of a solar cell is the percentage of the solar energy to which the cell is exposed that is converted into electrical energy [3]. This is calculated by dividing a cell’s power output (in watts) at its maximum power point (\(P_m\)) by the input light (\(E\), in W/m\(^2\)) and the surface area of the solar cell (\(A_c\) in m\(^2\)).

\[
\eta = \frac{P_m}{E \times A_c}
\]

(5.1)

By convention, solar cell efficiencies are measured under standard test conditions (STC) unless stated otherwise. STC specifies a temperature of 25 °C and an irradiance of 1000 W/m\(^2\) with an air mass 1.5 (AM1.5) spectrum. These conditions correspond to a clear day with sunlight incident upon a sun-facing 37°-tilted surface with the sun at an angle of 41.81° above the horizon [4, 5]. This represents solar noon near the spring and autumn equinoxes in the continental United States with surface of the cell aimed directly at the sun. Under these test conditions a solar cell of 20%
efficiency with a 100 cm\(^2\) (0.01 m\(^2\)) surface area would produce 2.0 watts of power.

The efficiency of the solar cells used in a photovoltaic system, in combination with latitude and climate, determines the annual energy output of the system. For example, a solar panel with 20\% efficiency and an area of 1 m\(^2\) will produce 200 watts of power at STC, but it can produce more when the sun is high in the sky and will produce less in cloudy conditions and when the sun is low in the sky. In central Colorado, which receives daily insolation of 2200 Wh/m\(^2\) [6, 7], such a panel can be expected to produce 440 kWh of energy per year. However, in Michigan, which receives only 1400 kWh/m\(^2\)/yr [8, 9], annual energy yield will drop to 280 kWh for the same panel. At more northerly European latitudes, yields are significantly lower: 175kWh annual energy yield in southern England [10,11].

Several factors affect a cell's conversion efficiency value, including its reflectance efficiency, thermodynamic efficiency, charge carrier separation efficiency, and conduction efficiency values [12,13]. Because these parameters can be difficult to measure directly, other parameters are measured instead, including quantum efficiency, \(V_{oc}\) ratio, and fill factor. Reflectance losses are accounted for by the quantum efficiency value, as they affect "external quantum efficiency." Recombination losses are accounted for by the quantum efficiency, \(V_{oc}\) ratio, and fill factor.
values. Resistive losses are predominantly accounted for by the fill factor value, but also contribute to the quantum efficiency and $V_{oc}$ ratio values.

5.8 Maximum Power Point

A solar cell may operate over a wide range of voltages (V) and currents (I). By increasing the resistive load on an irradiated cell continuously from zero (a short circuit) to a very high value (an open circuit) one can determine the maximum power point, the point that maximizes $V \times I$; that is, the load for which the cell can deliver maximum electrical power at that level of irradiation. (The output power is zero in both the short circuit and open circuit extremes).

A high quality, monocrystalline silicon solar cell, at 25 °C cell temperature, may produce 0.60 volts open-circuit ($V_{oc}$). The cell temperature in full sunlight, even with 25 °C air temperature, will probably be close to 45 °C, reducing the open-circuit voltage to 0.55 volts per cell. The voltage drops modestly, with this type of cell, until the short-circuit current is approached ($I_{sc}$). Maximum power (with 45 °C cell temperature) is typically produced with 75% to 80% of the open-circuit voltage (0.43 volts in this case) and 90% of the short-circuit current. This output can be up to 70% of the $V_{oc} \times I_{sc}$ product. The short-circuit current ($I_{sc}$) from a cell is nearly proportional to the illumination, while the open-circuit voltage ($V_{oc}$) may drop only 10% with a 80% drop in illumination.
Lower-quality cells have a more rapid drop in voltage with increasing current and could produce only 1/2 $V_{oc}$ at 1/2 $I_{sc}$. The usable power output could thus drop from 70% of the $V_{oc} \times I_{sc}$ product to 50% or even as little as 25%. Vendors who rate their solar cell "power" only as $V_{oc} \times I_{sc}$, without giving load curves, can be seriously distorting their actual performance.

The maximum power point of a photovoltaic varies with incident illumination. For example, accumulation of dust on photovoltaic panels reduces the maximum power point [14, 15]. For systems large enough to justify the extra expense, a maximum power point tracker tracks the instantaneous power by continually measuring the voltage and current (and hence, power transfer), and uses this information to dynamically adjust the load so the maximum power is always transferred, regardless of the variation in lighting.

5.9 Fill Factor

Another defining term in the overall behavior of a solar cell is the fill factor (FF). This is the available power at the maximum power point ($P_m$) divided by the open circuit voltage ($V_{oc}$) and the short circuit current ($I_{sc}$):

The maximum power point

$$P_m = \eta \times A_c \times E = V_{oc} \times I_{sc} \times (FF)$$
The efficiency

\[ \eta = \frac{V_{oc} \times I_{sc} \times (FF)}{A \times E} \]  

(5.3)

The fill factor is directly affected by the values of the cell’s series and shunt resistances. Increasing the shunt resistance \( R_{sh} \) and decreasing the series resistance \( R_s \) lead to a higher fill factor, thus resulting in greater efficiency, and bringing the cell’s output power closer to its theoretical maximum [16-20].

Energy conversion efficiency is measured by dividing the electrical power produced by the cell by the light power falling on the cell. Many factors influence the electrical power output, including spectral distribution, spatial distribution of power, temperature, and resistive load applied to the cell. IEC standard 61215 is used to compare the performance of cells and is designed around terrestrial, temperate conditions, using its standard temperature and conditions (STC): irradiance of 1 kW/m², a spectral distribution close to solar radiation through AM (airmass) of 1.5 and a cell temperature 25 °C. The resistive load is varied until the peak or maximum power point (MPP) is achieved. The power at this point is recorded as Watt-peak \( (W_p) \). The same standard is used for measuring the power and efficiency of PV modules [21].

Air mass has an effect on power output. In space, where there is no atmosphere, the spectrum of the sun is relatively
unfiltered. However, on earth, with air filtering the incoming light, the solar spectrum changes. To account for the spectral differences, a system was devised to calculate this filtering effect. Simply, the filtering effect ranges from Air Mass 0 (AM0) in space, to approximately Air Mass 1.5 on Earth. Multiplying the spectral differences by the quantum efficiency of the solar cell in question will yield the efficiency of the device. For example, a silicon solar cell in space might have an efficiency of 14% at AM0, but have an efficiency of 16% on earth at AM 1.5. Terrestrial efficiencies typically are greater than space efficiencies. Note, however, that the incident photons in space have considerably more energy, so the solar cell might produce considerably more power in space, despite the lower efficiency as indicated by reduced percentage of the total incident energy captured [22].

The fill factor is denoted as FF, is a parameter that helps in characterizing the non-linear electrical nature of the solar cell. Fill factor is defined as the ratio of the maximum power from the solar cell to the product of $V_{oc}$ and $I_{sc}$, and it gives an idea about the power that a cell can produce with an optimal load under given conditions, $P = (FF).(V_{oc}).(I_{sc})$. Fill factor is also an indicator of quality of cell. With FF approaching towards unity the quality of cell gets better. Fill Factor can be improved in many ways.

Irradiance intensity holds great influence for cell performance. With respect to irradiance dependency, the DSSC and
silicon cells are each other’s opposite. The experimental results have seen for the DSSCs favor at low irradiance. This is mainly due to a loss reduction in the cell under low irradiance where the number of recombination’s and the charge transfer resistance is low. This amounts in a relative high Fill Factor for the DSSCs at low irradiance. A direct proportionality between $I_{sc}$ and irradiance is identified. Since the $V_{oc}$ dependence is seen to be very weak and a dominant decay is only seen under low light levels, the conversion efficiency for the DSSC is influenced by the Fill Factor-dependence of irradiance level. The silicon cells are seen to perform best under high illumination. A direct proportionality between $I_{sc}$ and irradiance $G$ is identified and the $V_{oc}$ dependence of $G$ follows theory with a logarithmic decrease at low light levels. This drop in $V_{oc}$ is more pronounced for the silicon than seen for the DSSCs and since the Fill Factor is seen to be almost independent of $G$, the $V_{oc}$ dependence holds greatest influence for the conversion efficiency. The tendencies identified are very coherent for the measurements and is evaluated to be the performance parameter to influence on cell performance the most.

Understanding solar radiation data and the amount of solar energy intercepts specific area are essential for modeling solar energy system and covering the demand. Therefore, precise knowledge of historical global solar radiation at a location of study
is required. The following is data retrieved from Meteorological Station Data.

Table 5.1: Performance parameters of various DSSC cells at G = 1000 W/m²

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Type of DSSC</th>
<th>I_{sc} (A)</th>
<th>V_{oc} (V)</th>
<th>FF (%)</th>
<th>P_{max} (W)</th>
<th>η (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>DSSC-1</td>
<td>0.85</td>
<td>4.6</td>
<td>55.5</td>
<td>2.25</td>
<td>4.18</td>
</tr>
<tr>
<td>2</td>
<td>DSSC-2</td>
<td>0.88</td>
<td>4.6</td>
<td>62.0</td>
<td>2.55</td>
<td>4.83</td>
</tr>
<tr>
<td>3</td>
<td>DSSC-3</td>
<td>0.86</td>
<td>4.7</td>
<td>63.4</td>
<td>2.52</td>
<td>4.86</td>
</tr>
<tr>
<td>4</td>
<td>DSSC-4</td>
<td>0.87</td>
<td>4.5</td>
<td>59.4</td>
<td>2.33</td>
<td>4.48</td>
</tr>
<tr>
<td>5</td>
<td>DSSC-5</td>
<td>0.85</td>
<td>4.6</td>
<td>55.5</td>
<td>2.25</td>
<td>4.18</td>
</tr>
<tr>
<td>6</td>
<td>DSSC-6</td>
<td>0.88</td>
<td>4.6</td>
<td>62.0</td>
<td>2.55</td>
<td>4.87</td>
</tr>
<tr>
<td>7</td>
<td>DSSC-7</td>
<td>0.86</td>
<td>4.7</td>
<td>63.4</td>
<td>2.52</td>
<td>4.88</td>
</tr>
<tr>
<td>8</td>
<td>DSSC-8</td>
<td>0.87</td>
<td>4.5</td>
<td>59.4</td>
<td>2.33</td>
<td>4.48</td>
</tr>
<tr>
<td>9</td>
<td>DSSC-9</td>
<td>0.87</td>
<td>4.5</td>
<td>59.4</td>
<td>2.33</td>
<td>4.48</td>
</tr>
<tr>
<td>10</td>
<td>DSSC-10</td>
<td>0.85</td>
<td>4.6</td>
<td>55.5</td>
<td>2.25</td>
<td>4.18</td>
</tr>
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</table>

Table 5.2: Performance parameters for various silicon cells at G = 1000 W/m²

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Type of Si</th>
<th>I_{sc} (mA)</th>
<th>V_{oc} (mV)</th>
<th>FF (%)</th>
<th>P_{max} (mW)</th>
<th>η (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Si-1</td>
<td>279</td>
<td>525</td>
<td>67.5</td>
<td>99.3</td>
<td>9.6</td>
</tr>
<tr>
<td>2</td>
<td>Si-2</td>
<td>166</td>
<td>525</td>
<td>72.1</td>
<td>63.0</td>
<td>7.6</td>
</tr>
<tr>
<td>3</td>
<td>Si-3</td>
<td>300</td>
<td>581</td>
<td>65.1</td>
<td>113</td>
<td>14</td>
</tr>
<tr>
<td>4</td>
<td>Si-4</td>
<td>209</td>
<td>544</td>
<td>66.9</td>
<td>87.1</td>
<td>8.9</td>
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<tr>
<td>5</td>
<td>Si-5</td>
<td>254</td>
<td>561</td>
<td>71.8</td>
<td>95.4</td>
<td>9.1</td>
</tr>
<tr>
<td>6</td>
<td>Si-6</td>
<td>279</td>
<td>525</td>
<td>67.5</td>
<td>99.3</td>
<td>9.6</td>
</tr>
<tr>
<td>7</td>
<td>Si-7</td>
<td>166</td>
<td>525</td>
<td>72.1</td>
<td>63.0</td>
<td>7.6</td>
</tr>
<tr>
<td>8</td>
<td>Si-8</td>
<td>300</td>
<td>581</td>
<td>65.1</td>
<td>113</td>
<td>14</td>
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<tr>
<td>9</td>
<td>Si-9</td>
<td>279</td>
<td>525</td>
<td>67.5</td>
<td>99.3</td>
<td>9.6</td>
</tr>
<tr>
<td>10</td>
<td>Si-10</td>
<td>254</td>
<td>561</td>
<td>71.8</td>
<td>95.4</td>
<td>9.1</td>
</tr>
</tbody>
</table>
5.10 Effect of Irradiance and Temperature

The term Irradiance is defined as the measure of power density of sunlight received at a location on the earth and is measured in watt per metre square, whereas irradiation is the measure of energy density of sunlight. The term Irradiance and Irradiation are related to solar components. As the solar insolation keeps on changing throughout the day similarly I-V and P-V characteristics varies. With the increasing solar irradiance both the open circuit voltage and the short circuit current increases and hence the maximum power point varies. Temperature plays another major factor in determining the solar cell efficiency. As the temperature increases the rate of photon generation increases thus reverse saturation current increases rapidly and this reduces the band gap. Hence this leads to marginal changes in current but major changes in voltage. The cell voltage reduces by 2.2 mV per degree rise of temperature. Temperature acts like a negative factor affecting solar cell performance. Therefore solar cells give their full performance on cold and sunny days rather on hot and sunny weather. Now-a-days Solar panels are made of non-silicon cells as they are temperature insensitive. Thus the temperature remains close to room temperature.
Table 5.3: Horizontal Irradiation data for South India/Salem

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Month</th>
<th>KWh/m²/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>January</td>
<td>4.94</td>
</tr>
<tr>
<td>2.</td>
<td>February</td>
<td>5.87</td>
</tr>
<tr>
<td>3.</td>
<td>March</td>
<td>6.65</td>
</tr>
<tr>
<td>4.</td>
<td>April</td>
<td>6.73</td>
</tr>
<tr>
<td>5.</td>
<td>May</td>
<td>6.13</td>
</tr>
<tr>
<td>6.</td>
<td>June</td>
<td>5.25</td>
</tr>
<tr>
<td>7.</td>
<td>July</td>
<td>4.74</td>
</tr>
<tr>
<td>8.</td>
<td>August</td>
<td>4.80</td>
</tr>
<tr>
<td>9.</td>
<td>September</td>
<td>5.01</td>
</tr>
<tr>
<td>10.</td>
<td>October</td>
<td>4.43</td>
</tr>
<tr>
<td>11.</td>
<td>November</td>
<td>4.07</td>
</tr>
<tr>
<td>12.</td>
<td>December</td>
<td>4.27</td>
</tr>
<tr>
<td></td>
<td>Annual</td>
<td>5.24</td>
</tr>
</tbody>
</table>

5.11 Effect of Light Intensity

Changing the light intensity incident on a solar cell changes all solar cell parameters, including the short-circuit current, the open-circuit voltage, the FF, the efficiency and the impact of series and shunt resistances. The light intensity on a solar cell is called the number of suns, where 1 sun corresponds to standard illumination at AM1.5, or 1 kW/m². For example a system with 10 kW/m² incident on the solar cell would be operating at 10 suns, or at 10X. A PV module designed to operate under 1 sun conditions is called a "flat plate" module while those using concentrated sunlight are called "concentrators".
(a) Calculation of \( V_{oc}(G) \) Expression

\( V_{oc} \) is expected to show a logarithmical increase for increasing irradiation intensity \( G \), given by the relation

\[
V_{oc} = \frac{n k T}{q} \ln \left( \frac{I_s}{I_0} + 1 \right)
\]

(5.4)
as \( I_s \) is directly proportional with \( G \). All properties except irradiation intensity \( G \) is assumed constant (\( n, k, T, q, I_0 \)), and as \( I_s = I_{sc} \) is simplified to

\[
V_{oc} = c \ln \left( \frac{I_{sc} + 1}{I_0} \right)
\]

(5.5)
c and \( I_0 \) are unknown constants. With two corresponding data sets \((I_1; V_1)\) and \((I_2; V_2)\) from the measurements performed at different irradiation intensity the constants \( c \) and \( I_0 \) are to be numerically determined. As

\[
I_0 = \left| \frac{I_0}{\left( e^{\frac{1}{c}} - 1 \right)} \right| \Rightarrow I_0 = \left| \frac{I_1}{\left( e^{\frac{1}{c}} - 1 \right)} \right| \Rightarrow I_0 = \left| \frac{I_2}{\left( e^{\frac{1}{c}} - 1 \right)} \right| \Rightarrow 0 = \left| \frac{I_0}{\left( e^{\frac{1}{c}} - 1 \right)} \right| \Rightarrow I_0 \approx \left| \frac{I_1}{\left( e^{\frac{1}{c}} - 1 \right)} \right| \Rightarrow I_0 \approx \left| \frac{I_2}{\left( e^{\frac{1}{c}} - 1 \right)} \right|
\]

(5.6)
is solved with regards to \( c \) by performing bisection by iterating \( c \) to the point where the equation changes sign.

For the three silicon cells as well as the average for the DSSCs, \( c \) has been determined by three different data sets in order to see which gives the best fit in the end. With the determined \( c \), \( I_0 \) is determined. \( I_0 \) is determined for the whole measurement set.
which range from 70 W/m² to 1000 W/m² and the average $I_0$ is then used in the final equation for Voc. The experimental results as well as the theoretical expression for $V_{oc}$ which has been fitted from the experimental data are shown in $(V_{oc}; I_{sc})$ - graphs. Only the best fit is shown. The constants and determined expression are given in Table 5.4.

Table 5.4: Expression for $V_{oc}$ as function of $I_{sc}$

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Types of Cell</th>
<th>$c$ [mV]</th>
<th>$I_0$ [mA]x10⁻⁷</th>
<th>Expression for $V_{oc}$[mV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>DSSC-1 (Cocinia Indica)</td>
<td>38.75</td>
<td>6.80</td>
<td>$V_{oc} (I_{sc}) = 38.15mV \cdot \ln \left( \frac{I_{sc}}{6.80 \times 10^{-7} \text{mA}} + 1 \right)$</td>
</tr>
<tr>
<td>2</td>
<td>DSSC-2 (Eclipta Alba)</td>
<td>39.71</td>
<td>6.81</td>
<td>$V_{oc} (I_{sc}) = 39.71mV \cdot \ln \left( \frac{I_{sc}}{6.81 \times 10^{-7} \text{mA}} + 1 \right)$</td>
</tr>
<tr>
<td>3</td>
<td>DSSC-3 (Solanum Melongena Dye)</td>
<td>40.57</td>
<td>6.70</td>
<td>$V_{oc} (I_{sc}) = 40.57mV \cdot \ln \left( \frac{I_{sc}}{6.70 \times 10^{-7} \text{mA}} + 1 \right)$</td>
</tr>
<tr>
<td>4</td>
<td>Flat Type Silicon Solar Cell</td>
<td>45.66</td>
<td>1.79</td>
<td>$V_{oc} (I_{sc}) = 45.66mV \cdot \ln \left( \frac{I_{sc}}{1.79 \times 10^{-7} \text{mA}} + 1 \right)$</td>
</tr>
<tr>
<td>5</td>
<td>V-grooved Si-Cell without Microlens</td>
<td>37.79</td>
<td>1.61</td>
<td>$V_{oc} (I_{sc}) = 37.79mV \cdot \ln \left( \frac{I_{sc}}{1.61 \times 10^{-7} \text{mA}} + 1 \right)$</td>
</tr>
<tr>
<td>6</td>
<td>V-grooved Si-Cell with Microlens</td>
<td>84.09</td>
<td>2.49</td>
<td>$V_{oc} (I_{sc}) = 84.09mV \cdot \ln \left( \frac{I_{sc}}{2.49 \times 10^{-7} \text{mA}} + 1 \right)$</td>
</tr>
</tbody>
</table>

5.12 Concentrators

A concentrator is a solar cell designed to operate under illumination greater than 1 sun. The incident sunlight is focused or
guided by optical elements such that a high intensity light beam shines on a small solar cell. Concentrators have several potential advantages, including a higher efficiency potential than a one-sun solar cell and the possibility of lower cost. The short-circuit current from a solar cell depends linearly on light intensity, such that a device operating under 10 suns would have 10 times the short-circuit current as the same device under one sun operation. However, this effect does not provide an efficiency increase, since the incident power also increases linearly with concentration. Instead, the efficiency benefits arise from the logarithmic dependence of the open-circuit voltage on short circuit. Therefore, under concentration, $V_{oc}$ increases logarithmically with light intensity, as shown in the equation below;

$$V_{oc} = \frac{n_k T}{q} \ln \left( \frac{X(I_{sc})}{I_0} \right) = \frac{n_k T}{q} \left[ \ln \left( \frac{I_{sc}}{I_0} \right) + \ln X \right] = V_{oc} + \frac{n_k T}{q} \ln X$$

(5.7)

where X is the concentration of sunlight. From the equation above, a doubling of the light intensity ($X=2$) causes an 18 mV rise in $V_{oc}$. The cost of a concentrating PV system may be lower than a corresponding flat-plate PV system since only a small area of solar cells is needed.

The efficiency benefits of concentration may be reduced by increased losses in series resistance as the short-circuit current increases and also by the increased temperature operation of the solar cell. As losses due to short-circuit current depend on the
square of the current, power loss due to series resistance increases as the square of the concentration.

5.13 Low Light Intensity

Solar cells experience daily variations in light intensity, with the incident power from the sun varying between 0 and 1 kW/m². At low light levels, the effect of the shunt resistance becomes increasingly important. As the light intensity decreases, the bias point and current through the solar cell also decreases, and the equivalent resistance of the solar cell may begin to approach the shunt resistance. When these two resistances are similar, the fraction of the total current flowing through the shunt resistance increases, thereby increasing the fractional power loss due to shunt resistance. Consequently, under cloudy conditions, a solar cell with a high shunt resistance retains a greater fraction of its original power than a solar cell with a low shunt resistance [22].

5.14 Effect of Temperature

Like all other semiconductor devices, solar cells are sensitive to temperature. Increases in temperature reduce the band gap of a semiconductor, thereby effecting most of the semiconductor material parameters. The decrease in the band gap of a semiconductor with increasing temperature can be viewed as increasing the energy of the electrons in the material. Lower energy is therefore needed to break the bond. In the bond model of a semiconductor band gap, reduction in the bond energy also
reduces the band gap. Therefore increasing the temperature reduces the band gap.

In a solar cell, the parameter most affected by an increase in temperature is the open-circuit voltage. The impact of increasing temperature is shown in the figure below [23].

The open-circuit voltage decreases with temperature because of the temperature dependence of $I_0$. The equation for $I_0$ from one side of a p-n junction is given by;

$$I_0 = qA \frac{Dn_i^2}{LN_D}$$

(5.8)

where: $q$ is the electronic charge; $D$ is the diffusivity of the minority carrier given for silicon as a function of doping in the silicon materials parameters; $L$ is the diffusion length of the minority carrier; $N_D$ is the doping; and $n_i$ is the intrinsic carrier concentration given for silicon.

In the above equation, many of the parameters have some temperature dependence, but the most significant effect is due to the intrinsic carrier concentration, $n_i$. The intrinsic carrier concentration depends on the band gap energy (with lower band gaps giving a higher intrinsic carrier concentration), and on the energy which the carriers have (with higher temperatures giving higher intrinsic carrier concentrations). The equation for the intrinsic carrier concentration is;
\[ n_i^2 = 4 \left( \frac{2 \pi k T}{h^2} \right)^3 \left( m_e^* m_h^* \right)^{3/2} \exp \left( -\frac{E_{GO}}{kT} \right) = B T^3 \exp \left( -\frac{E_{GO}}{kT} \right) \] (6.9)

where: \( T \) is the temperature; \( h \) and \( k \) are constants; \( m_e \) and \( m_h \) are the effective masses of electrons and holes respectively; \( E_{GO} \) is the band gap linearly extrapolated to absolute zero; and \( B \) is a constant which is essentially independent of temperature.

Substituting these equations back into the expression for \( I_0 \), and assuming that the temperature dependencies of the other parameters can be neglected, gives;

\[ I_o = qA \frac{B T^3 \exp \left( -\frac{E_{GO}}{kT} \right)}{ln(N_F)} \approx B' T^\gamma \exp \left( -\frac{E_{GO}}{kT} \right) \] (5.10)

where \( B' \) is a temperature independent constant. A constant, \( \gamma \), is used instead of the number 3 to incorporate the possible temperature dependencies of the other material parameters. For silicon solar cells near room temperature, \( I_0 \) approximately doubles for every 10 °C increase in temperature.

The impact of \( I_0 \) on the open-circuit voltage can be calculated by substituting the equation for \( I_0 \) into the equation for \( V_{oc} \) as shown below;

\[ V_{oc} = \frac{kT}{q} \ln \left( \frac{I_{sc} - I_0}{I_c} \right) = \frac{kT}{q} \ln \frac{I_{sc}}{I_c} - \frac{kT}{q} \ln \left[ B' T^\gamma \exp \left( -\frac{qV_{GO}}{kT} \right) \right] \]

\[ = \frac{kT}{q} \left( \ln I_{sc} - \ln B' - \gamma \ln T + \frac{qV_{GO}}{kT} \right) \] (5.11)
where $E_{G0} = qV_{G0}$. Assuming that $dV_{oc}/dT$ does not depend on $dI_{sc}/dT$, $dV_{oc}/dT$ can be found as;

$$\frac{dV_{oc}}{dT} = \frac{V_{oc} - V_{G0} + \gamma \frac{kT}{q}}{T} \approx -2.2 \text{ mV/°C for Si}$$

(5.12)

The above equation shows that the temperature sensitivity of a solar cell depends on the open circuit voltage of the solar cell, with higher voltage solar cells being less affected by temperature.

For silicon, $E_{G0}$ is 1.2, and using $\gamma$ as 3 gives a reduction in the open-circuit voltage of about 2.2 mV/°C;

$$\frac{dV_{oc}}{dT} = \frac{V_{G0} - V_{oc} + \gamma \frac{kT}{q}}{T} \approx -2.2 \text{ mV/°C for Si}$$

(5.13)

The short-circuit current, $I_{sc}$, increases slightly with temperature, since the band gap energy, $E_{G0}$, decreases and more photons have enough energy to create e-h pairs. However, this is a small effect and the temperature dependence of the short-circuit current from a silicon solar cell is;

$$I_{sc} \frac{dI_{sc}}{dT} \approx 0.0006 \text{ per °C for Si}$$

(5.14)

The temperature dependency FF for silicon is approximated by the following equation;

$$\frac{1}{FF} \frac{dFF}{dT} \approx \left( \frac{1}{V_{oc}} \frac{dV_{oc}}{dT} - \frac{1}{T} \right) \approx -0.0015 \text{ per °C for Si}$$

(5.15)

The effect of temperature on the maximum power output, $P_{m}$, is;
\[
P_{M_{var}} = \frac{1}{P_{M}} \frac{dP_{M}}{dT} = \frac{1}{V_{DC}} \frac{dV_{DC}}{dT} + \frac{1}{FF} \frac{dFF}{dT} + \frac{1}{I_{SC}} \frac{dI_{SC}}{dT}
\]  

(5.12)

\[
\frac{1}{P_{M}} \frac{dP_{M}}{dT} \approx -(0.004 \text{ to } 0.005) \text{ per } ^\circ \text{C for Si}
\]  

(5.13)

Table 5.4: I-V Characteristics results of various Irradiance with Illuminance Intensity for different types of cells

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Cell Type</th>
<th>Irradiance (W/cm²)</th>
<th>Illuminance (Lux) x10⁴</th>
<th>(I_{sc}) (mA/cm²)</th>
<th>(V_{oc}) (mV)</th>
<th>(ff) (%)</th>
<th>(\eta) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>DSSC-1 (Cocinia Indica)</td>
<td>40</td>
<td>9.96</td>
<td>5.71</td>
<td>680</td>
<td>60.1</td>
<td>2.33</td>
</tr>
<tr>
<td></td>
<td></td>
<td>60</td>
<td>14.94</td>
<td>5.98</td>
<td>687</td>
<td>50.3</td>
<td>2.40</td>
</tr>
<tr>
<td></td>
<td></td>
<td>80</td>
<td>19.92</td>
<td>6.46</td>
<td>693</td>
<td>54.0</td>
<td>3.31</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100</td>
<td>24.9</td>
<td>6.81</td>
<td>700</td>
<td>78.6</td>
<td>5.00</td>
</tr>
<tr>
<td>2.</td>
<td>DSSC-2 (Eclipta Alba)</td>
<td>40</td>
<td>9.96</td>
<td>5.71</td>
<td>681</td>
<td>60.1</td>
<td>2.33</td>
</tr>
<tr>
<td></td>
<td></td>
<td>60</td>
<td>14.94</td>
<td>6.41</td>
<td>692</td>
<td>55.9</td>
<td>2.58</td>
</tr>
<tr>
<td></td>
<td></td>
<td>80</td>
<td>19.92</td>
<td>7.54</td>
<td>714</td>
<td>60.9</td>
<td>3.08</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100</td>
<td>24.9</td>
<td>9.82</td>
<td>720</td>
<td>71.6</td>
<td>5.02</td>
</tr>
<tr>
<td>3.</td>
<td>DSSC-3 (Solanum Melongena Dye)</td>
<td>40</td>
<td>9.96</td>
<td>5.70</td>
<td>670</td>
<td>61.3</td>
<td>2.34</td>
</tr>
<tr>
<td></td>
<td></td>
<td>60</td>
<td>14.94</td>
<td>8.60</td>
<td>690</td>
<td>56.3</td>
<td>3.48</td>
</tr>
<tr>
<td></td>
<td></td>
<td>80</td>
<td>19.92</td>
<td>9.87</td>
<td>707</td>
<td>57.1</td>
<td>2.68</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100</td>
<td>24.9</td>
<td>9.99</td>
<td>720</td>
<td>64.8</td>
<td>4.69</td>
</tr>
<tr>
<td>4.</td>
<td>Flat type silicon solar cell</td>
<td>40</td>
<td>9.96</td>
<td>37.7</td>
<td>675</td>
<td>77.7</td>
<td>19.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>60</td>
<td>14.94</td>
<td>37.7</td>
<td>671</td>
<td>80.7</td>
<td>20.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>80</td>
<td>19.92</td>
<td>32.7</td>
<td>667</td>
<td>80.2</td>
<td>17.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100</td>
<td>24.9</td>
<td>32.2</td>
<td>677</td>
<td>81.2</td>
<td>17.8</td>
</tr>
<tr>
<td>5.</td>
<td>V-grooved Si-cell without Microlens</td>
<td>40</td>
<td>9.96</td>
<td>37.9</td>
<td>632</td>
<td>78.7</td>
<td>18.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>60</td>
<td>14.94</td>
<td>37.8</td>
<td>629</td>
<td>77.7</td>
<td>18.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>80</td>
<td>19.92</td>
<td>37.7</td>
<td>628</td>
<td>77.6</td>
<td>18.4</td>
</tr>
<tr>
<td>6.</td>
<td>V-grooved Si-cell with Microlens</td>
<td>40</td>
<td>9.96</td>
<td>38.7</td>
<td>629</td>
<td>77.9</td>
<td>18.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>60</td>
<td>14.94</td>
<td>38.6</td>
<td>624</td>
<td>77.8</td>
<td>18.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>80</td>
<td>19.92</td>
<td>38.5</td>
<td>622</td>
<td>77.7</td>
<td>18.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100</td>
<td>24.9</td>
<td>38.4</td>
<td>621</td>
<td>77.6</td>
<td>18.5</td>
</tr>
</tbody>
</table>

(Note: Photon values are in \(\mu\)moles/m²/s. For other conversions, divide lux by 10.764 to obtain foot candles, or multiply foot candles times 0.0929 to obtain lux)
Conversion table as follows:

<table>
<thead>
<tr>
<th>Radiation Source</th>
<th>Photons To W/m²</th>
<th>W/m² To Photons</th>
<th>Lux To Photons</th>
<th>Photons To F.C.</th>
<th>F.C. To Photons</th>
<th>W/m² To Lux</th>
<th>Lux To W/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sunlight</td>
<td>0.219</td>
<td>4.57</td>
<td>54</td>
<td>0.019</td>
<td>5.02</td>
<td>0.199</td>
<td>0.249</td>
</tr>
</tbody>
</table>

Most semiconductor modelling is done at 300 K since it is close to room temperature and a convenient number. However, solar cells are typically measured almost 2 degrees lower at 25 °C (298.15 K). In most cases the difference is insignificant (only 4 mV of $V_{oc}$) and both are referred to as room temperature. Occasionally, the modelled results need to be adjusted to correlate with the measured results. The following data are Intrinsic Carrier Concentration Temperature, $T = 298$ K, Intrinsic Carrier Concentration, $n_i = 8.9 \times 10^9$ cm$^{-3}$, At 300 K, $n_i = 1.01 \times 10^{10}$ cm$^{-3}$ and $kT/q = 25.852$ mV, At 25 °C (298.15 K), $n_i = 8.6 \times 10^9$ cm$^{-3}$ and $kT/q = 25.693$ mV.

5.15 Experimental Set up & Testing for Irradiance

The test was performed in the Laser Optics and Solar Cells Laboratory at Department of Physics, Periyar University, Salem, Tamilnadu, India, and as shown in figure 5.2. The set up consist of a Xenon lamp as light source, a water filter to imitate the atmosphere, a mirror to bend the beam, a diffusing plate to distribute the illumination to the test area and fans to avoid heating cells. The panel is fixed on a wood frame with 45° tilt angle.
so that the panel surface is normal to the irradiation. In order to determine the temperature of cell, three thermo couples were used in the set up, placed one in level with the backside of the cell, one on the front side of the cell and one on the front side of the cell.

The irradiation intensity at the test area is measured by a standard pyranometer. The spectral distribution of Xenon lamp compared to solar irradiance at 1000 W/m², A.M1.5 [24]. The peak of intensity for the Xenon Lamp is found around 550 nm, whereas the solar energy spectral distribution peaks at 450 nm. The intensity is changed by varying the distance between the light source and front glass of the cell and therefore it can be estimated that the spectral distribution of the light is comparable for each distance. The test set up has been created with the focus to develop a set up, where all other parameters that can influence the cell performance other than irradiance intensity is kept constant such as humidity and ambient temperature. The ambient and the temperature on the backside of the cells during testing are monitored. The typical variation in cell temperature was below 5°C, so it is assumed reasonable to estimate constant cell temperature.
The lux meter is for measuring brightness in lux, fc or cd/m². The lux meter is sometimes equipped with internal memory or a data logger to record the measurements. The measurement of light intensity with the lux meter is becoming more important in the workplace where protective screens are needed. The technique of measuring environmental conditions, to which the measurement of light belongs, also occupies a lead position in a scale of importance. The lux meter with data logger is highly regarded especially due to its cosine correction of the angle of incident light. This lux meter has a memory to store measured values, and software to analyse readings.

The intensity of illumination – illuminance – is measured by a lux-meter. A common luxmeter consists of the measuring device itself and a sensor. The sensor is made of selenium or silicon
photocells. Special attention should also be paid to another part of a luxmeter – the cosine adapter. It depicts a cosine adapter by Harting-Helweig and one by Reeb-Tosberg. A photocell without a cosine adapter would produce measurement error proportional to the angle of incidence of the light [25].

5.16 Results and Discussion

In this work, detailed experimental results showing the solar module’s characteristics; \( V_{oc}, J_{sc}, FF \) and \( \eta \) were affected by AM; irradiance as well as module temperatures have been presented. The DSSM’s \( V_{oc}, J_{sc}, FF \) and \( \eta \) improved as AM increased. This shows that the DSSC performs well under diffuse radiation. This is not true for V-grooved Si solar cells. This finding is very helpful to solar electricity practitioners during PV sizing. If AM at a particular location is usually high, choosing DSSCs over V-grooved Si would guarantee better results for the client. The DSSC’s good performance under diffuse radiation shows the DSSC does not have to follow the north-south orientation rule. This means that DSSCs can be used as windows or walls in buildings irrespective of their orientations.

The orientation-dependence of V-grooved Si solar cells does not allow for this flexibility hence limiting innovation in the design of Net Zero Energy buildings. The improved performance of the DSSC between 12.00 hours and 18.00 hours as compared to 06.30 hours to 20.00 hours when V-grooved Si solar cells perform well
shows that the two technologies (DSSM and a-Si) can be jointly used in the design of Net Zero Energy buildings. Better results for the DSSC at lower as compared to higher irradiance intensities makes it ideal for use in electronic consumer goods like laptops, calculators, etc, which by nature, are mainly used indoors. The attribute also makes the DSSC useful in complimenting a-Si solar modules, especially in Building Integrated Photovoltaics (BIPV) in areas known to have fluctuations in irradiance intensity.

The DSSC showed an overall benefit from a combination of high irradiance and elevated temperatures. V-grooved Si solar cells are also reported to perform well at high irradiance levels and at high temperatures. Irradiance intensity holds great influence for cell performance. With respect to irradiance dependency, the DSC and silicon cells are each other's opposite.

The experimental results have seen for the DSSCs favor low irradiance where the highest conversion efficiency is identified for both in-lab and outdoor results. This is mainly due to a loss reduction in the cell under low irradiance where the number of recombination and the charge transfer resistance is low. This amounts in a relative high Fill Factor for the DSSCs at low irradiance. A direct proportionality between $I_{sc}$ and irradiance is identified. Since the $V_{oc}$-dependence is seen to be very weak and a dominant decay is only seen under low light levels, the conversion efficiency for the DSSC is influenced by the Fill Factor-dependence
of irradiance level. The silicon cells are seen to perform best under high illumination. A direct proportionality between $I_{sc}$ and irradiance $G$ is identified and the $V_{oc}$-dependence of $G$ follows theory with a logarithmic decrease at low light levels. This drop in $V_{oc}$ is more pronounced for the silicon than seen for the DSSCs and since the Fill Factor is seen to be almost independent of $G$, the $V_{oc}$-dependence holds greatest influence for the conversion efficiency.

The V-grooved silicon cell exhibits low efficiency at lowered irradiance which is increased at high illumination. The silicon has a negative temperature coefficient resulting in a lowering of efficiency when the operating temperature is high which will occur at strong irradiance. Therefore the parameters investigated are all seen to interact and work against each other benefit.

5. 17 Conclusion

The performance of a DSSC has been investigated under different air mass (AM), irradiance intensity and temperature conditions at Salem, South India. The good response of the DSSC to short wavelength radiation made it perform well at increased AM values as compared to what is reported of V-grooved silicon cell. The DSSC performed better compared to what is reported of V-grooved silicon cells under irradiance and temperature dependence. The results are useful in PV sizing, especially in the area of Building Integrated Photovoltaics (BIPV) at Salem and other parts of South India.
The experimental work was performed both in DSSC and V-Grooved silicon solar cells, so a comparison in results and tendencies seen for the different test-environments could be analyzed. Different types of both DSSC- and silicon cells were used in the investigational work, depending on place of testing. Therefore only the general tendencies seen are pointed out, as it is difficult to give a quantitative measure due to difference in cells.
5.18 Reference


14. "Silicon Solar Cells with Screen-Printed Front Side Metallization Exceeding 19% Efficiency".


