

PHOTOVOLTAIC SYSTEM DEPLOYMENT OPTIMIZATION

by

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A thesis submitted to the Faculty of the University of Delaware in partial fulfillment of the requirements for the degree of Master of Science in Electrical and Computer Engineering

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ABSTRACT

In the last decade, global warming, due to emissions from combustion of fossil fuels, has become a universal environmental concern. Energy choices have direct impacts on our health, environment, and economy. Among the renewable energy technologies, photovoltaic (PV) is considered to be a very promising choice with significant potential. Current approaches on improving solar panel's performance include 1. Developments in optimizing semiconductor behaviors, such as, multilayer cells, new materials for solar cells that enhance solar cell performance; 2. Methods to increase sun light absorbing and centralizing such as solar tracking; and 3. As solar cell performs better at lower temperature, efforts have been made on solar panel cooling.

The approach proposed in this paper relates to the concept of solar cell cooling. By tilting the solar cell at an angle to the sun, the heating of the solar cell decreases due to reduced solar irradiance, while the cooling of the solar cell by thermal radiation and convection remains the same, and thus the solar cell will be cooler and more efficient. Of course, with such a tilted deployment, more solar cells have to be used for the same deployment area. Thus, this thesis concerns itself with how to gain the maximum energy from certain amount of deployment area by optimizing the geometry of the PV installation. Traditionally, solar cells are placed perpendicular to the solar radiation to gather the maximum incident light per cell, yet it is not known whether solar panel functions the best when facing direct sunlight as the efficiency of solar cells goes down when cell operating temperature is increased by receiving solar

radiation. Changing the incident light angle could possibly increase the electricity created by a certain area of incident light but will increase the number of solar cells required. Crystalline silicon solar cell price has fallen dramatically in the past decades from \$76.67/Watts in 1977 to an estimated \$0.74/Watts in 2013 and is predicted to continue to decrease rapidly in the future. At the same time, the one-time installation fee of a PV system remains very high. Therefore, as the solar panel price becomes minimal compared to the installation cost, and as most households have limited space for solar installation, it is worth looking into the solar cells deployment that result in the largest electricity generation from a fixed size area used for solar cells placement during one installation.

The behavior of solar cells at different tilt angles between the incident light has been theoretically and experimentally studied. Experimental results and simulations suggested a power output gain of at most 3% can be achieved by deploying the solar cell at a certain angle away from sun light for the modules tested under normal weather condition. In summary, this project has explored an alternative passive cooling method that could possibly increase the PV power output from a fixed area of solar panels placed on a limited space, but is proved to be not very practical.

Chapter 1

INTRODUCTION

Nowadays, 86.7% of the world's energy use can be sourced back to fossil fuels [1]. It has always been a concern for human whether this massive exploitation of fossil fuel is leading to the exhaustion of conventional fuel resources in the near future. There are other disadvantages of a fossil fuel based energy structure. One of them being its direct correlation to global warming. Global warming, due to emissions from combustion of fossil fuels, has become a universal environmental concern in the past decade.

Energy choices have direct impacts on our health, environment, and economy. Renewable energy generally create much smaller environmental impact. Also as its name suggests, renewable energy provides reliable power supplies which will never deplete thus enhance energy security.

Among all the renewable energy technologies, photovoltaic (PV) is considered to be a very promising choice with significant potential. PV provides very clean energy with almost no environmental impact. Solar energy supply , the sunlight, is free and abundant. However, currently solar panels have a relatively low efficiency level compared not only to the efficiency of conventional fossil fuel but also when compared to the efficiency of other renewable energy system such as wind or hydro.

To increase the economic viability of solar cells the efficiency of PV modules must be increased while maintaining or reducing the production cost. Researchers have been working on improving solar cell efficiencies since early 1960s. Although

there are significant amount of research in this field, the general approaches on improving solar panel's performance can be categorized into 3 main areas:

1. Developments in optimizing semiconductor behaviors, such as, multilayer cells, band-structure improvement, new materials for solar cells that enhance solar cell performance; 2. Methods to increase sun light absorbing and centralizing such as concentrating solar cells, solar tracking, light trapping, spectrum optimization; and 3. As solar cell performs better at lower temperature, efforts have been made on solar panel cooling.

The approach proposed in this paper relates to the concept of solar cell cooling.

1.1 Solar Panel Deployment

It is a common known fact that a single solar cell produces the maximum power when being placed perpendicular to sunrays. Among all the mysteries behaviors of solar cell, this one seems very intuitive.

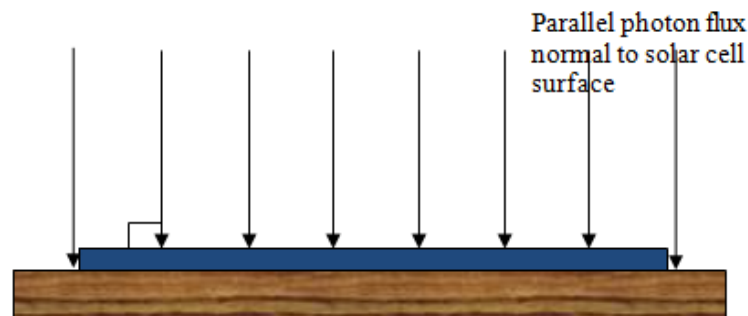


Figure 1.1 A solar panel placed normal to parallel photon flux.

Assume solar irradiance is 100% consist of parallel beam, this is not entirely true as the earth's atmosphere and other objects on earth introduce diffuse component

into the radiation, nonetheless parallel sunrays is a close estimation on a perfect sunny day. It can be easily comprehended that by placing solar cell normal to incoming photon flux the panel can receive the greatest amount of radiation per solar cell. And since solar panels convert light into electrical power, the highest power output can be produced when light intensity is the highest, it is always the optimum to place the solar panel normal to the incoming sunrays for 1 solar panel.

But what is the best deployment for multiple solar modules with limited space to place these modules?

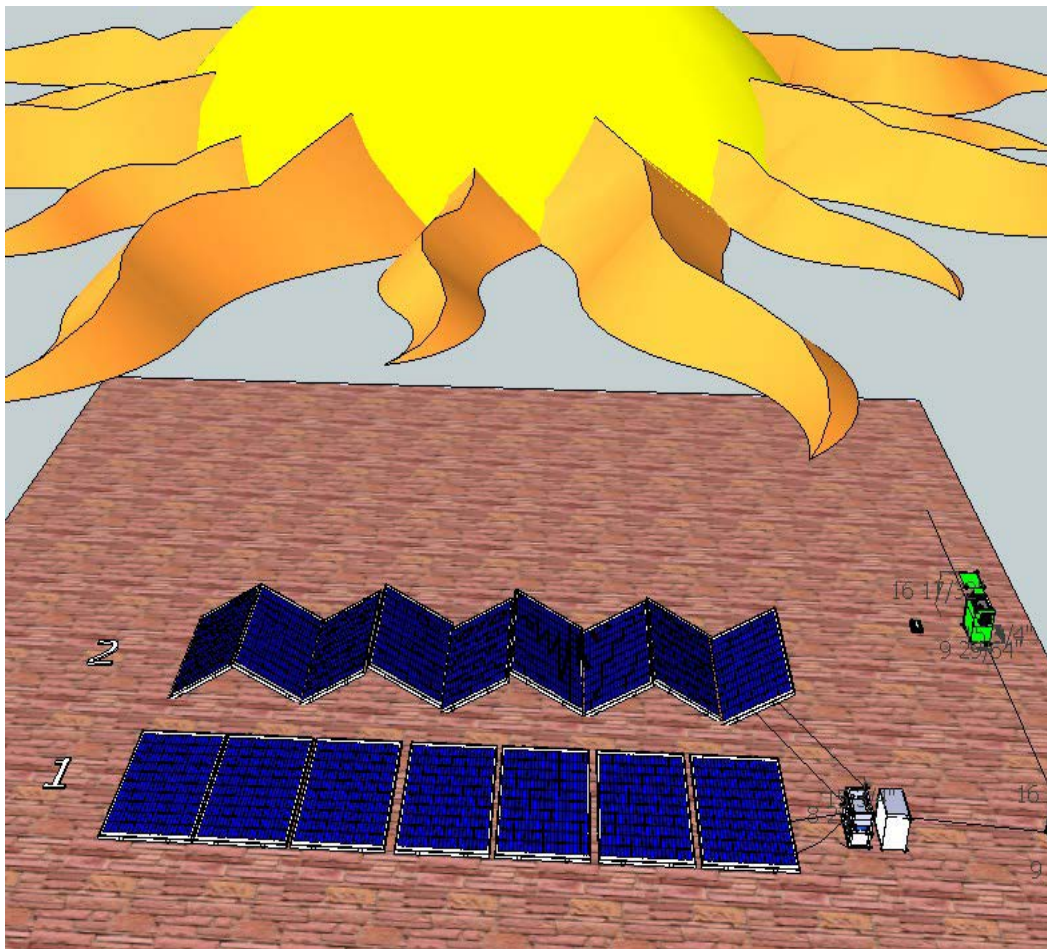


Figure 1.2 Flat solar array1 and tilted solar array2 placed on the surface normal to incoming sunrays.

In the figure above, assuming the sun is directly above the roof where solar arrays are mounted therefore the radiation is perpendicular to the roof surface. Modules in the solar array1 are laid flat on the surface of roof thus facing directly to the incoming sunlight; Modules in solar array2 is tilted away from the sun for an angle.

Zoom onto solar array2, the arrangement of solar cells look like:

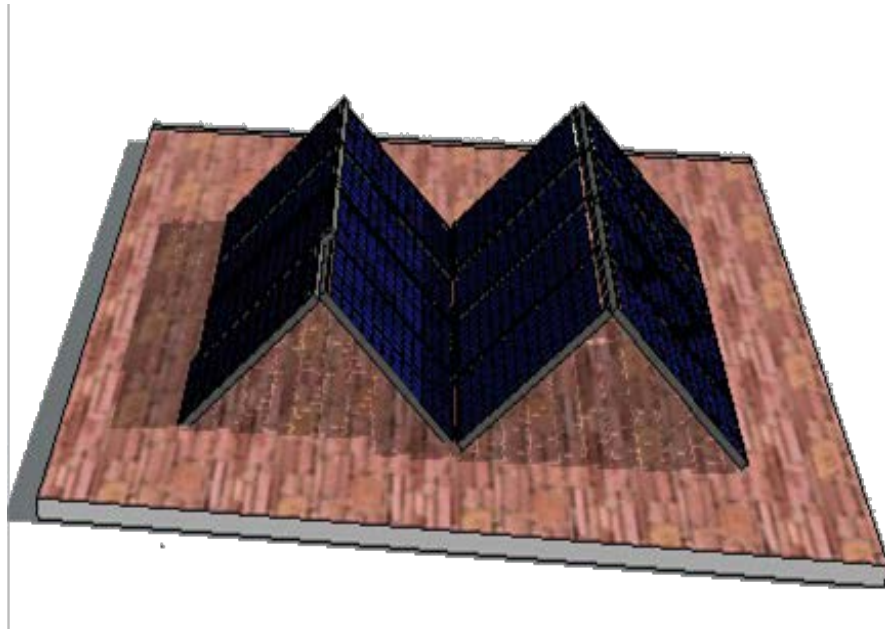


Figure 1.3 A zoom in to the tilted panel placement.

In figure 1.2, Solar array1 has 7 solar panels, solar array2 uses 9 panels. But they occupy the same space on the roof and in this specific case receive the same

amount of solar radiation of photon flux. If all the solar modules are identical, the question is, which of them can produce more electrical power: solar array1 or solar array2?

Traditionally, solar cells are placed perpendicular to the solar radiation to gather the maximum incident light per cell, yet it is not known whether solar panel functions the best when facing direct sunlight. Solar cell convert most of the photon energy into heat, as will later discussed in this paper, efficiency of solar cells goes down when cell operating temperature is increased by receiving solar radiation. The argument here is that by tilting the solar cell at an angle to the sun, the heating of the solar cell decreases due to reduced solar irradiance, while the cooling of the solar cell by thermal radiation and convection remains the same, and thus the solar cell will be cooler and more efficient.

Obviously, with such a tilted deployment, more solar cells have to be used for the same deployment area(as in the above case, 7 panels for solar array1 and 9 panels for solar array2). Crystalline silicon solar cell price has fallen dramatically in the past decades from \$76.67/Watts in 1977 to an estimated \$0.74/Watts in 2013 [2] and is predicted to continue to decrease rapidly in the future. At the same time, the one-time installation fee of a PV system remains very high. Therefore, as the solar panel price becomes minimal compared to the installation cost, and as most households have limited space for solar installation, it is worth looking into the solar cells deployment that result in the greatest electricity generation from a fixed size area used for solar cells placement during one installation. Thus, this thesis concerns itself with how to gain the maximum energy from certain amount of deployment area by optimizing the geometry of the PV installation.

Changing the placement of solar panel to solar irradiance greatly influence the performance of solar cell and changes most of the solar cell parameters. Compare with a solar cell placed perpendicular to the radiation, a tilted solar module like the one shown below:

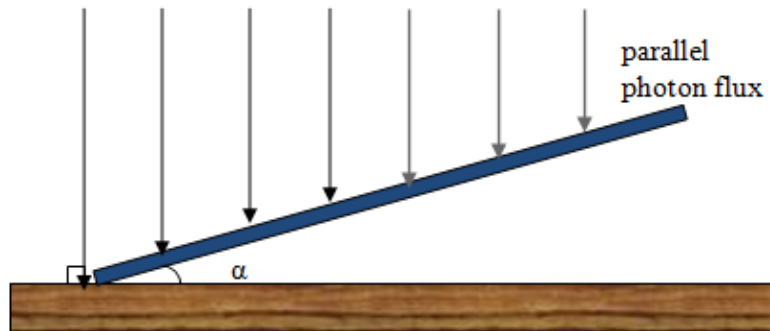


Figure 1.4 Parallel photon flux on a tilted solar panel.

The most affected parameters are light intensity on the solar surface, and, as has been briefly discussed, solar cell temperature.

In the next few chapters, the effect of light intensity and temperature change on the solar cell performance will be theoretically studied and experimentally tested. Other cooling methods for solar cell will also be discussed.

Chapter 2

SOLAR CELL TEMPERATURE DEPENDENCE

As a semiconductor device, solar cells share the same semiconductor properties with all other semiconductor devices, one of them is the sensitivity to temperature. Temperature affect most of the important parameters in solar cell that we are concerned of, such as the open-circuit voltage V_{oc} , short-circuit current I_{sc} , voltage at maximum power point V_{max} , current at maximum power point I_{max} and fill factor FF . The pronounced effect that the operating solar cell temperature has upon its electric generating performance is well documented. Commercial solar cells usually come with specification sheet that details it's nominal operating cell temperature($NOCT$) and the effect of operating temperature of a PV module has upon its power output.

The fundamental expression for solar cell power output is given by:

$$P_m = V_{max}I_{max} = V_{oc}I_{sc}FF \quad 2.1$$

P_m refers to the maximum power point on the solar cells' I-V curve, V_{max} and I_{max} refer to the corresponding I and V on the I-V curve that produce the maximum power output.

The above equation can also serve as a definition for the fill factor:

$$FF = \frac{P_m}{V_{oc}I_{sc}} \quad 2.2$$

Since operating temperature of a PV module affects all the parameters in the equation above, solar cells power output or efficiency can be viewed as a function of the operating temperature. The following discussion presents the effects temperature insert on each individual parameters.

2.1 Cell Operating Temperature

PV module are typically rated at standard test condition(STC), which is under irradiance on cell surface at 1000W/m^2 , solar spectrum of AM 1.5 and ambient temperature at 25°C . However in practice solar panel hardly works, if ever, under standard test condition when operating in the field. The performance of a solar panel therefore is always different from what one would expect from specification sheets. In order to determine the output of a solar panel, it is important to search for an approach that would accurately predict the operating temperature of a solar cell. So far many expressions have been developed for cell operating temperature T_c in correlation with the intrinsic properties of solar cell, ambient environment variables, such as the ambient temperature T_a , air circulation or wind speed that affect heat transfer, and solar irradiance.

One important parameter used to predict operating solar cell temperature is called nominal operating cell temperature or NOCT, NOCT is related to the intrinsic properties of the solar cell module and is determined from actual measurements of cell temperature at nominal terrestrial environment(NTE) described as follows [3]:

Irradiance on cell surface: 800W/m^2

Air temperature: 20°C

Average wind Velocity: 1m/s

Mounting: open rack, tilted normally to the solar noon sun.

Ross and Smokler [4] experimented the temperature rise at the back of the solar cell during operation(as the temperature at the back of solar cell is very close to the actual operating temperature of the solar cell) at a range of solar irradiance for solar cells with different NOCT,

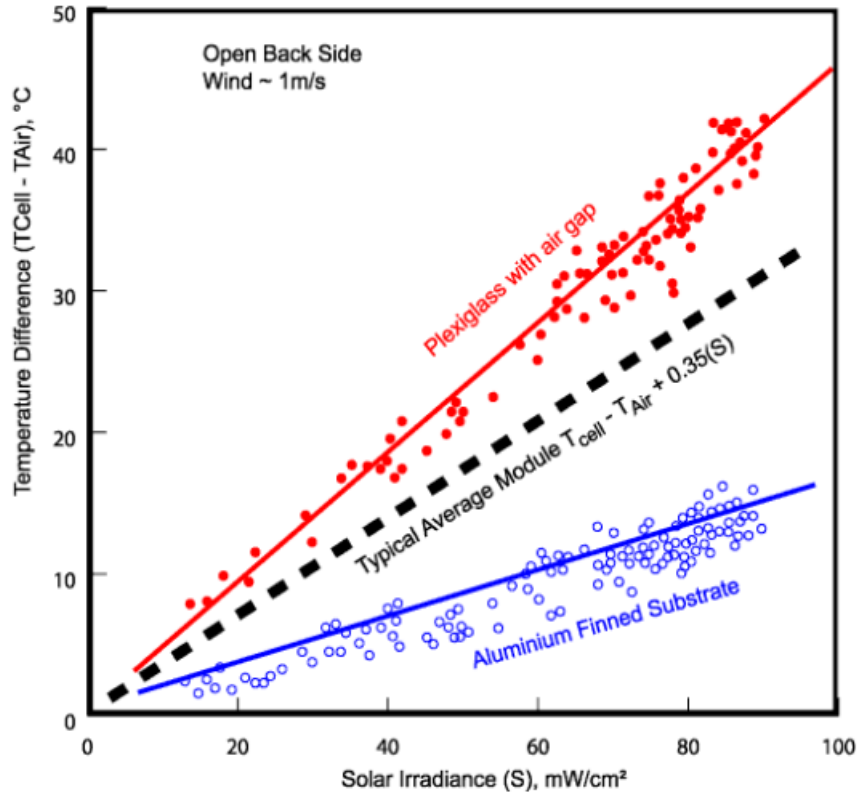


Figure 2.1 The relationship between solar irradiance and cell temperature rise [4].

The diagram shows the temperature rise is linear with solar irradiance, indicating that both conductive and convective losses are linear with incident solar insulation for a given wind speed. It also shows the temperature increasing rate is higher for module material with higher nominal operating cell temperature. An approximate expression for cell temperature is given by:

$$T_c = T_a + \frac{NOCT-20}{80} S \quad 2.3$$

Where S is the insulation in mW/cm², the above equation is valid for wind speed=1m/s. The real cell operating temperature will be lower than the calculated T_c when the wind velocity is higher and the cell temperature will be higher when wind is

stale. The best module operated at NOCT of 33°C and the worst at 58°C and the typical module at 48°C [5].

2.2 Temperature Dependency of Solar Cell

Temperature dependency of solar cell has been studied extensively and can be concluded by the diagram below:

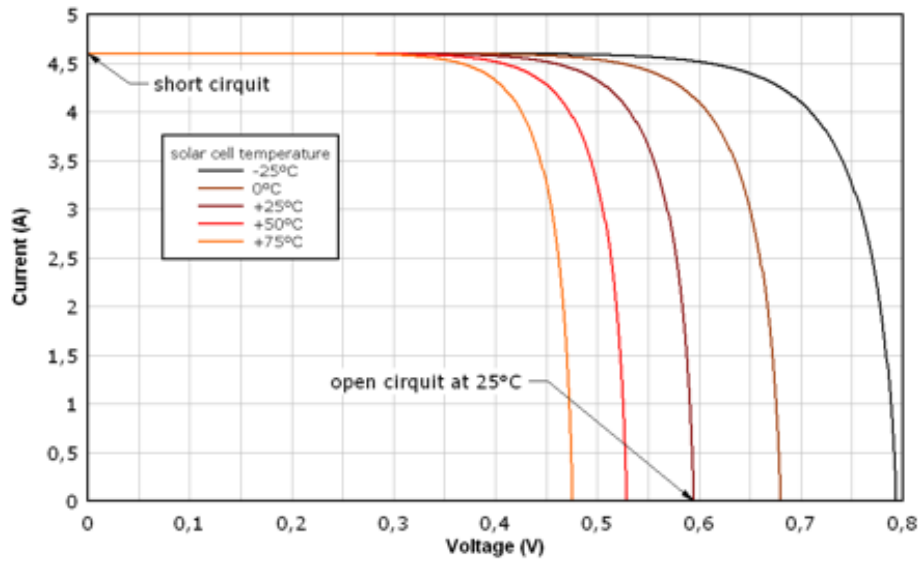


Figure 2.2 Solar cell I-V characteristic temperature dependency [6].

From the diagram above, one can observe a slight increase in I_{sc} with the increase of the temperature, while the parameter most affected by the increase in temperature is V_{oc} , which noticeably decreases with the temperature increase.

In general, the commonly used diode current expression is:

$$I = I_0(e^{\frac{qv}{nkT}} - 1) \quad 2.4$$

Where:

I is the net diode current flow;

n is the ideality factor ,the value for n is usually between 1 and 2, while for ideal diode, n=1;

I_0 is the dark saturation current;

V is the applied voltage across the diode;

q is electron charge constant;

k is the Boltzmann's constant;

T is the absolute temperature in Kelvin.

I_0 , the dark saturation current, measures the recombination in the diode ,it is a extremely important parameter of semiconductor diode and is also temperature dependent. The characteristics for this parameter can be described as:

$$I_0 = qA\left(\frac{D_n n_i^2}{L_n N_a} + \frac{D_p n_i^2}{L_p N_d}\right) \quad 2.5$$

Where:

A is the area of diode;

N_a and N_d are the doping density at N and P regions respectively;

D_n and D_p are diffusivity of the minority carriers;

L_n and L_p are the diffusion length;

n_i is the intrinsic carrier density.

Diffusivity, diffusion length and carrier density all have temperature dependence to some degree, among which the temperature dependency is the greatest

for n_i , the intrinsic carrier density, the expression for the intrinsic carrier density is given by:

$$n_i^2 = 4 \left(\frac{2\pi kT}{h^2} \right)^3 (m_e^* m_h^*)^{3/2} \exp \left(-\frac{E_{G0}}{kT} \right) \quad 2.6$$

Where:

T is the absolute temperature in Kelvin;

h and k are constants;

m_e^* and m_h^* are effective mass for electrons and holes;

E_{G0} is the band gap relative to absolute zero.

At a give condition where only temperature changes, we can extract all the parameters independent of temperature and use a constant to represent it, the expression for n_i becomes:

$$n_i^2 = CT^3 \exp \left(-\frac{E_{G0}}{kT} \right) \quad 2.7$$

Subsuming the equation for n_i back to dark saturation current expression, and assume all the other temperature dependent parameters can be considered temperature independent , we have:

$$I_0 = C'T^\gamma \exp \left(-\frac{E_{G0}}{kT} \right) \quad 2.8$$

Where:

C' is the new constant that represents temperature independent component;

γ is used instead of order 3 to incorporate time dependency of other parameters.

Experimental results show that for silicon solar cell near room temperature, I_0 approximately doubles for every 10°C increase in temperature [7].

2.2.1 Open-circuit Voltage Temperature Dependency

The open-circuit voltage V_{oc} for solar cell is:

$$V_{oc} = \frac{nkT}{q} \ln \left(\frac{I_L}{I_o} + 1 \right) \quad 2.9$$

Where:

I_L is the light current generated by solar irradiance.

Note from the equation that solar cell voltage is independent of the cell area.

As the light current is much greater than the dark saturation current, the term 1 is often time neglected and assume $n=1$ the equation for V_{oc} becomes:

$$\begin{aligned} V_{oc} &= \frac{nkT}{q} \ln \left(\frac{I_L}{I_o} \right) = \frac{kT}{q} (\ln I_L - \ln I_o) \\ &= \frac{kT}{q} \ln I_L - \frac{kT}{q} \ln [C'T^\gamma \exp \left(-\frac{E_{GO}}{kT} \right)] \end{aligned} \quad 2.10$$

Where E_{GO} can be represented by :

$$E_{GO} = qV_{GO} \quad 2.11$$

Therefore:

$$V_{oc} = \frac{kT}{q} (\ln I_{sc} - \ln C' - \gamma \ln T + \frac{qV_{GO}}{kT}) \quad 2.12$$

Assume I_L has no temperature dependent component, dV_{oc}/dT can be found as:

$$\frac{dV_{oc}}{dT} = \frac{V_{oc} - V_{GO}}{T} - \gamma \frac{k}{q} \quad 2.13$$

For silicon, $E_{GO}=1.2\text{ev}$ and using $\gamma=3$ the reduction of V_{oc} is about $2.2\text{mV}/^\circ\text{C}$ per solar cell, for a solar panel with N cells in series the open circuit voltage reduction is:

$$\frac{dV_{oc}}{dT} = -2.2\text{mV} \times N \quad 2.14$$

per module.

2.2.2 Short-circuit Current Temperature Dependency

In the discussion above we treated short-circuit current I_{sc} as constant due to its minimal dependency on temperature. For an ideal cell, the increase in the temperature reduce the band gap of semiconductor and increase the generation of electron and hole pairs by increased thermal energy. However, this small effect nearly cause no visible change to the performance of solar cell under common operating condition. For non ideal cell with series and shunt resistance. at lower solar irradiance level I_{sc} increase with temperature while at higher solar radiation I_{sc} decrease with temperature due to the increasing cell series resistance and transmission wire losses [8].

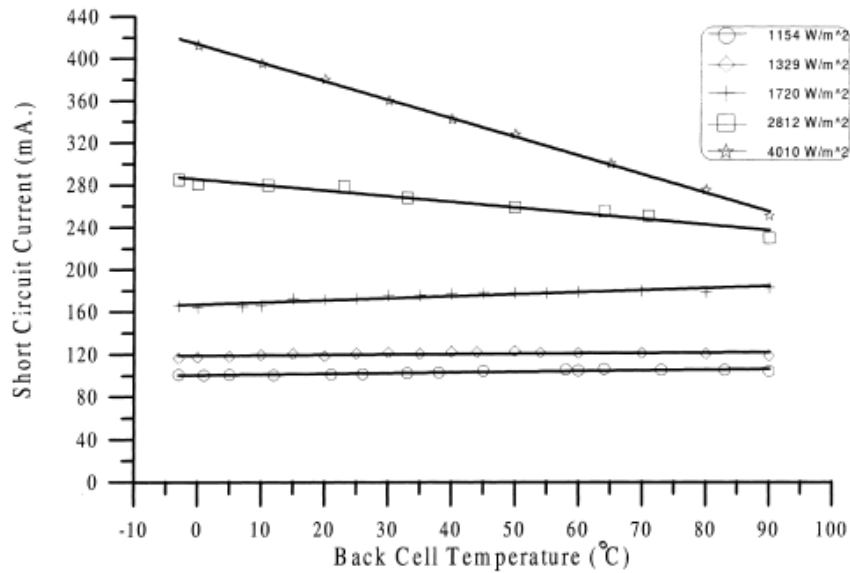


Figure 2.3 Variation of short-circuit current as a function of back cell temperature at different illuminations [9].

2.2.3 Fill Factor Temperature Dependency

As previously discussed in this chapter, Fill Factor(FF) is simply a ratio that measures the performance of solar cell and is defined as:

$$FF = \frac{P_m}{V_{oc} I_{sc}} = \frac{I_{max} V_{max}}{I_{sc} V_{oc}} \quad 2.15$$

Green [9] derived the following equation using the simple definition of fill factor given above, using only the ratio V_{max}/V_{oc} with a single variable r , as shown:

$$FF = r \left(\frac{e^{\frac{V_{oc}}{n}}}{e^{\frac{V_{oc}}{n}} - 1} \right) \left(\frac{\frac{r V_{oc}}{n}}{1 + \frac{r V_{oc}}{n}} \right) \quad 2.16$$

Assume for the special case when ideality=1, this equation can be approximated to be:

$$FF = \frac{V_{oc} - \ln(V_{oc} + 0.72)}{V_{oc} + 1} \quad 2.17$$

This approximation is an empirical expression independent of r first introduced by Green [9].

The temperature dependency of fill factor therefore can be approximated as below:

$$\frac{1}{FF} \frac{dFF}{dT} = \frac{(1-FF)}{FF} \left(\frac{1}{V_{oc}} \frac{dV_{oc}}{dT} - \frac{1}{T} \right) \quad 2.18$$

By removing the FF term on the right, this expression can be further simplified to:

$$\frac{1}{FF} \frac{dFF}{dT} = \frac{1}{V_{oc}} \frac{dV_{oc}}{dT} - \frac{1}{T} \quad 2.19$$

Using the previous result for open-circuit voltage, fill factor decreases -0.0015 per °C for silicon.

2.2.4 Power Temperature Dependence

There are many expressions derived for temperature dependence of the PV modules power output and efficiency, which is simply related to irradiance over power produced by the solar cell. Most of them assume linear form, differing only in the

numerical values of parameters simulating solar panel itself and operating environment [10].

The temperature coefficient for PV power output generally accepted by industry is $-0.5\% \text{ } ^\circ\text{C}^{-1}$ [11]. Which indicates for every 1°C solar cell temperature rise the power output and efficiency drop 0.5% . The diagram below shows the P-V characteristics for PV module at 0°C , 25°C , 50°C and 75°C respectively adopting this temperature coefficient.

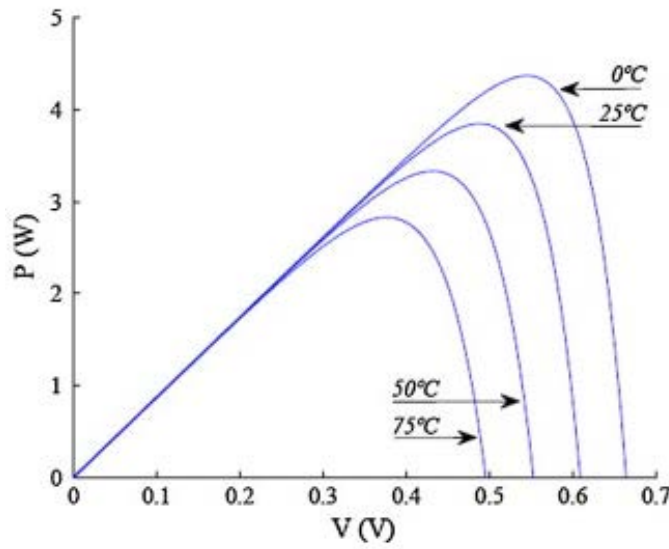


Figure 2.4 P-V characteristics for various module temperature [12].

In this study, V_{oc} , I_{sc} and FF under standard test condition (STC) are treated as known and are used to estimate solar cell performance under 1 sun (1000 W/m^2) and wind speed $= 1 \text{ m/s}$ at any cell operating temperature T , while T is derived from solar cell operating temperature equation discussed earlier in this chapter.

$$P_m = I_{sc-NOCT} \times (V_{oc-NOCT} - N \times 2.2mV/^{\circ}C \times (T_a + \frac{(NOCT-20^{\circ}C)}{80}S - 25^{\circ}C) \times (FF_{NOCT} - 0.0015/^{\circ}C \times (T_a + \frac{(NOCT-20^{\circ}C)}{80}S - 25^{\circ}C) \quad 2.19$$

Where:

$I_{sc-NOCT}$, $V_{oc-NOCT}$ is and FF_{NOCT} is the short-circuit current, open-circuit voltage and fill factor under standard test condition(STC);

N is the number of the solar cells in a module;

T_a is the ambient air temperature;

NOCT is the nominal operating cell temperature tested;

S is the isolation of the test condition.

2.3 Conclusions

The operating temperature of solar cell is a very important parameter that must be taken into account when designing and choosing solar cells. Theoretical and experimental results indicate that the power output of a PV module, thus the efficiency, have a approximate linear relationship with the temperature. The higher the temperature, the lower the efficiency of the solar cell. This approximate linear correlation changes with environment variation, solar cell material properties and whole solar cell system. All the discussions in this chapter is designated for crystalline silicon solar cell and poly-crystalline silicon solar cell. For other types of solar cell, even though they all have temperature dependency to some extent, the effects of temperature can be much different. For example, thin-film solar cell(TFSC) generally performs better at higher temperature and suffer less power loss due to high cell operating temperature.

Chapter 3

EFFECT OF LIGHT INTENSITY

3.1 Introduction

It is intuitive to think light intensity changes the behavior of a solar cell. As a start, solar cell cannot generate any current when there is no light present so it is reasonable to assume a strong correlation between light generated current and the light intensity. In fact, changing light intensity changes all PV parameters, including light generated current I_L , short-circuit current I_{sc} , open-circuit voltage V_{oc} , and even though not significantly, fill factor FF. It should be also noted that low light intensity magnify energy losses from series and shunt resistance in a real solar panel system. One may have such experience that on a cloudy or rainy day the solar system practically produces no power output. For residential flat plate solar cell, it is always most favorable to have strong, bright sun radiation. Strong radiation, as we have discussed in the last chapter, will increase the cell operating temperature thus cause some efficiency drop across the solar cell, solar cell produce much more power under strong irradiance that well compensate for this loss.

3.2 Effect of Light Intensity on Current Generation

In a cell with perfectly passivated surface and uniform generation, the equation for the short-circuit current can be approximated as:

$$I_{sc} = AqG(L_n + L_p) \quad 3.1$$

Where,

A is the area of the solar cell;

q is the electric charge;

G is the generation rate;

L_n, L_p is the electron and hole diffusion length respectively.

It is clear that current generation is strongly correlated to generation rate and diffusion length. We need look into the effect of light intensity on these 2 parameters respectively.

The definition of diffusion length is the average distance a carrier can move from point of generation until it recombines. It is an intrinsic property of certain type of semiconductor at certain temperature and it is not affected by external radiation.

Rewrite the light generating current equation:

$$I_L = CG \quad 3.2$$

Where C is a constant independent of light intensity.

The generation rate at certain distance into the semiconductor material is approximated to be:

$$G = \alpha N_0 e^{-\alpha x} \quad 3.3$$

Where:

α is the absorption coefficient;

x is the distance into the semiconductor material;

N_0 is the photon flux at the surface, which is proportional to light intensity.

Therefore, the total generation rate is the integration of the generation across the cell depth:

$$G_{tot} = \int_0^L G_{op}(x)dx = N_0 \int_0^L \alpha e^{-\alpha x} dx \quad 3.4$$

The light generated current therefore is:

$$I_L = C N_0 \int_0^L \alpha e^{-\alpha x} dx = C' N_0 \quad 3.5$$

Where C' is a constant independent of light intensity

It can be seen from the equation above that the light generating current is directly proportional to the photon flux, or light intensity.

Note that the term short-circuit current I_{sc} and light generated current I_L is interchangeable in this case since most time I_{sc} is equal to I_L . Unless with a very high series resistance ($> 10 \Omega \cdot \text{cm}^2$) I_{sc} is less than I_L and writing the solar cell equation with I_{sc} is incorrect [13].

In this thesis where we discuss light intensity on a tilted surface, transmission and reflection need to be taken into consideration. Light intensity will decrease faster on a tilted surface than $\cos\alpha$ due to increasing reflection for higher tilt angle.

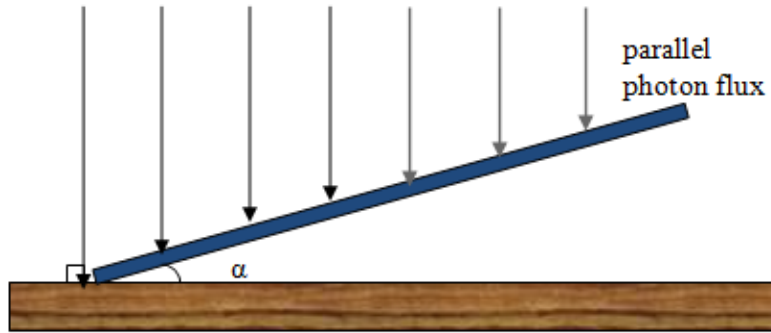


Figure 3.1 Parallel photon flux on a tilted surface

The vast majority of solar panels have front surface made of glass and are coated with anti-reflection surface. By nature, solar panels are made to absorb as much light as possible or in other word, the reflectance is minimized to produce the highest possible light current. For this reason, essentially all the light that passes through the front surface is trapped in the solar cell, the only reflection we are considering here is the reflection from the front surface of the module. Which is not different in nature when compared to other well studied reflections and transmissions on glass windows.

Reflection from this front surface can be calculated from the Fresnel Equations, which describe the behavior of light when moving between media of differing refractive indices. the equation that predict the reflection of light is called Fresnel reflection, and is a function of the index of refraction of the front surface of the module and of the angle at which the light is incident onto the module.

The polarization of the incident sun ray is a mix of s-polarized and p-polarized light depending on the time of the day. In a large range of angle, the reflection of p-polarized light is lower than s-polarized light. For a more conservative math model, it is assumed in this thesis that all sun ray is s-polarized.

The reflectance for s-polarized light is:

$$R_s = \left(\frac{n_1 \cos \alpha_i - n_2 \cos \alpha_t}{n_1 \cos \alpha_i + n_2 \cos \alpha_t} \right)^2 \quad 3.6$$

Where:

R_s is the reflectance for s-polarized light;

n_1 and n_2 is the index of refraction for 2 medium at the point of interface;

α_i is the incident angle, α_t is the transmission angle.

After applying Snell's law, the above equation becomes:

$$R_s = \left(\frac{n_1 \cos \alpha_i - n_2 \sqrt{1 - \left(\frac{n_1}{n_2} \sin \alpha_i\right)^2}}{n_1 \cos \alpha_i + n_2 \sqrt{1 - \left(\frac{n_1}{n_2} \sin \alpha_i\right)^2}} \right)^2 \quad 3.7$$

And the transmittance T therefore is:

$$T_s = 1 - R_s \quad 3.8$$

The great majority of solar modules are made with a front surface of “Solar Glass”. This is a tempered “soda-lime” float glass very similar to tempered window glass except that it has a much lower Iron (Fe) content. The lower Fe content makes solar glass much more transparent than regular window glass. Soda lime glass has an index of refraction of about 1.50-1.52 [14].

Majority of solar panels available on the market applies anti-reflection coating(ARC) on the front surface of solar panel to reduce reflection from bare glass.. Anti-reflection coatings on solar cells are similar to those used on other optical equipment such as camera lenses. Visually, solar panel with anti-reflection coating has a dark blue or pure black color due to little visible light reflection that can be observed by human eye. Refractive index of front surface of solar cell after ARC is usually around 1.2-1.3 [15].

Index refraction for air is 1.

Therefore, using $n_1=1, n_2(\text{ARC})=1.25, n_2'(\text{glass})=1.5$, the reflection percentage is plotted below assuming S-polarization.

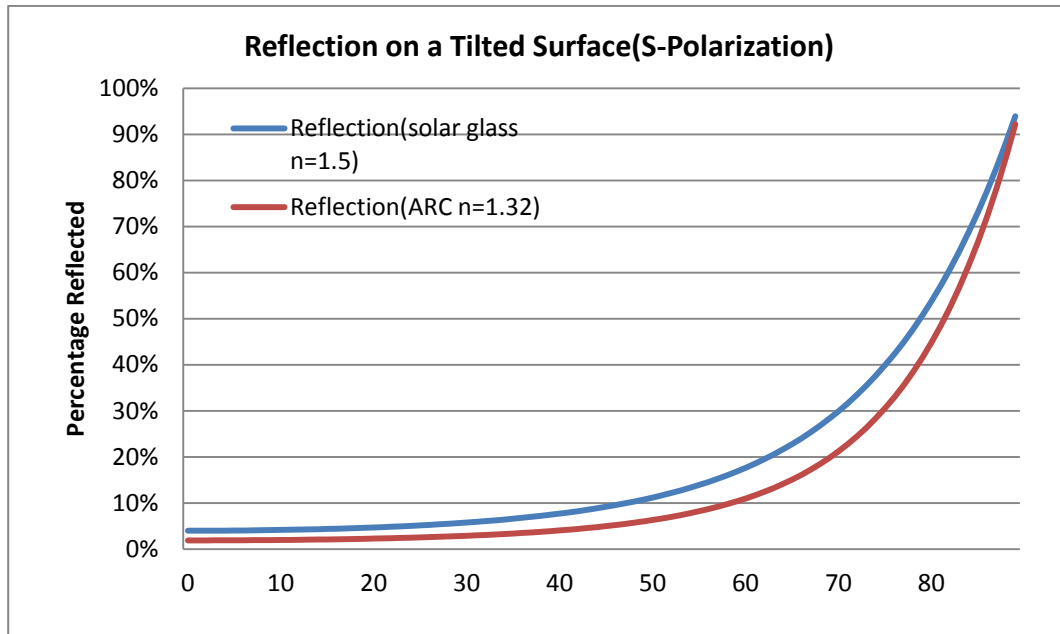


Figure 3.2 Reflection of S-polarization light on a tilted surface for solar glass and glass with ARC

Transmission on the tilted surface assuming s-polarization for sunrays is on the following page:

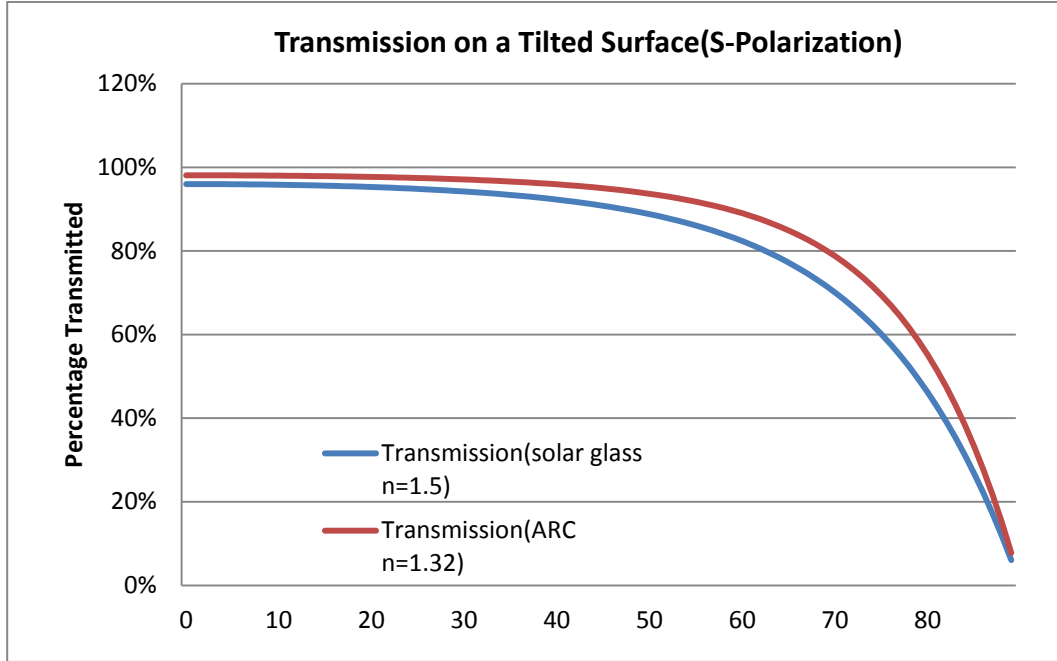


Figure 3.3 Transmission of S-polarization light on a tilted surface for solar glass and glass with ARC

Assuming same environmental and sun conditions, tilting a solar panel from a normal position relative to sunrays to an angle of α will result in a light generated current (for an ideal cell, $I_{sc}=I_L$):

$$I_L = C' N_0 \cos(\alpha) \left(1 - \left[\frac{n_1 \cos \alpha_i - n_2 \sqrt{1 - \left(\frac{n_1}{n_2} \sin \alpha_i \right)^2}}{n_1 \cos \alpha_i + n_2 \sqrt{1 - \left(\frac{n_1}{n_2} \sin \alpha_i \right)^2}} \right]^2 \right) \quad 3.9$$

Where N_0 is the photon flux at the surface of solar cell when the cell position is normal to solar irradiance.

3.3 Effect of Light Intensity on Open-circuit Voltage

As discussed in previous chapter, the expression for open-circuit voltage V_{oc} is given by:

$$V_{oc} = \frac{nkT}{q} \ln \left(\frac{I_L}{I_o} + 1 \right) \quad 3.10$$

Where I_o is the dark saturation current that is not light intensity dependent, the only light intensity dependent term is the light generated current which form a linear relationship with photon flux received by solar cell.

With X times light intensity at the surface, I_L becomes $X I_L$, new V_{oc} then becomes:

$$V'_{oc} = \frac{nkT}{q} \ln \left(\frac{XI_L}{I_o} + 1 \right) = V_{oc} + \frac{nkT}{q} \ln (X) \quad 3.11$$

Rearrange the equation:

$$V'_{oc} - V_{oc} = \frac{nkT}{q} \ln (X) \quad 3.12$$

Assuming same environmental condition and solar radiation, tilting a solar panel from a normal position to an angle of α will result in a open-circuit voltage change of:

$$V'_{oc} - V_{oc} = \frac{nkT}{q} \ln \left\{ \cos(\alpha) \left(1 - \left[\frac{n_1 \cos \alpha_i - n_2 \sqrt{1 - \left(\frac{n_1}{n_2} \sin \alpha_i \right)^2}}{n_1 \cos \alpha_i + n_2 \sqrt{1 - \left(\frac{n_1}{n_2} \sin \alpha_i \right)^2}} \right]^2 \right) \right\} \quad 3.13$$

Although it seems like changing of light intensity makes an influence on the open-circuit voltage, the influence is not as big on V_{oc} as the influence on the short-circuit current, for example, doubling of the light intensity cause a 18mV rise in V_{oc} , and consider most commercial solar cells have a V_{oc} over 0.6 V, this is only a 3% change. While for short-circuit current, a doubling of light intensity will double the amount of short-circuit current generated or a 100% change.

The other efficiency benefits of tilting away the solar panel (thus reducing the light intensity) are the lowering of cell operating temperature, decreasing the losses from series resistance as power loss from series resistance is proportional to the square of the current. As since there is a linear relationship between the light intensity and current produced, the power loss is therefore depends on the square of the light intensity.

3.4 Effect of Light Intensity on Fill Factor

Recall the empirical expression for fill factor proposed by Green [9] from last chapter:

$$FF = \frac{V_{oc} - \ln(V_{oc} + 0.72)}{V_{oc} + 1} \quad 3.14$$

With X times light intensity arriving at the surface, substitute the expression for V_{oc}' :

$$V_{oc}' = V_{oc} + \frac{nkT}{q} \ln(X) \quad 3.15$$

into the fill factor expression, the new FF becomes:

$$FF' = \frac{V_{oc} + \frac{nkT}{q} \ln(X) - \ln(V_{oc} + \frac{nkT}{q} \ln(X) + 0.72)}{V_{oc} + \frac{nkT}{q} \ln(X) + 1} \quad 3.16$$

For an average solar cell with V_{oc} roughly at 0.62V, doubling in the light intensity will increase the fill factor by 0.0026 or 1.2%. This is a very small effect and can be neglected unless the light intensity is extremely low on a very cloudy day or is extremely high for concentrated solar cell applications.

3.5 Conclusions

Light intensity changes all solar parameters, of which the light intensity is greatly affected. Doubling in light intensity would cause a 100% change in short-circuit current, 3% change in open-circuit voltage for a normal silicon based solar cell, and 1% in fill factor for a normal silicon solar cell. Transmission and reflection is also calculated for radiation on a tilted surface for the purpose of this research.

Chapter 4

IMPACT OF BOTH LIGHT INTENSITY AND TEMPERATURE ON A TILTED SURFACE

Assume linear form, adding up the impact of light and temperature on a tilted surface, the new V_{oc} on a surface tilted α degree away from perpendicular position to solar irradiance is:

$$V'_{oc} = V_{oc} + \frac{nkT}{q} \ln \left\{ \cos(\alpha) \left(1 - \left[\frac{n_1 \cos \alpha_i - n_2 \sqrt{1 - \left(\frac{n_1}{n_2} \sin \alpha_i \right)^2}}{n_1 \cos \alpha_i + n_2 \sqrt{1 - \left(\frac{n_1}{n_2} \sin \alpha_i \right)^2}} \right]^2 \right) \right\} - 0.0022 \times [T_{air} + P \frac{P \cos \alpha}{80} (NOCT - 20) - 25] \quad 4.1$$

Where:

V_{oc} is the open-circuit voltage under STC for the same module placing normal to incoming sun radiation;

n is the ideality factor between 1 and 2;

P is the light intensity on the module placing normal to incoming sun radiation;

$NOCT$ is the nominal operating cell temperature.

The ideality factor describes the recombination mechanism in a diode and it is a measure of how closely the diode follows the ideal diode equation. This thesis in several occasions assume ideality factor equals 1.

Short-circuit current is linear with light intensity while the impact of other factors is minimal. Ignore the effect of temperature, the short-circuit current on a tilted surface is:

$$I_{sc}' = I_{sc} \cos(\alpha) \left(1 - \left[\frac{n_1 \cos \alpha_i - n_2 \sqrt{1 - \left(\frac{n_1}{n_2} \sin \alpha_i\right)^2}}{n_1 \cos \alpha_i + n_2 \sqrt{1 - \left(\frac{n_1}{n_2} \sin \alpha_i\right)^2}} \right]^2 \right) \quad 4.2$$

Where I_{sc} is the short-circuit current under STC on the same module when the module is placed in perpendicular to the incoming radiation.

Fill factor is temperature dependent, while the effect of light intensity, as discussed in the previous chapter, is very small. The fill factor on a tilted surface is therefore:

$$FF' = FF - 0.0015 \times [T_{air} + P \frac{PCOS(\alpha)}{80} (NOCT - 20) - 25] \quad 4.3$$

Where FF is the fill factor under STC on the same module when the module is placed in perpendicular to the incoming radiation.

The power output per solar cell on a tilted surface is thus:

$$\begin{aligned} P' &= I_{sc}' V_{oc}' FF' \\ &= \left\{ V_{oc} + \frac{nkT}{q} \ln \left\{ \cos(\alpha) \left(1 - \left[\frac{n_1 \cos \alpha_i - n_2 \sqrt{1 - \left(\frac{n_1}{n_2} \sin \alpha_i\right)^2}}{n_1 \cos \alpha_i + n_2 \sqrt{1 - \left(\frac{n_1}{n_2} \sin \alpha_i\right)^2}} \right]^2 \right) \right\} \right\} - 0.0022 \times [T_{air} + \\ &P \frac{PCOS(\alpha)}{80} (NOCT - 20) - 25] \left\{ I_{sc} \cos(\alpha) \left(1 - \left[\frac{n_1 \cos \alpha_i - n_2 \sqrt{1 - \left(\frac{n_1}{n_2} \sin \alpha_i\right)^2}}{n_1 \cos \alpha_i + n_2 \sqrt{1 - \left(\frac{n_1}{n_2} \sin \alpha_i\right)^2}} \right]^2 \right) \right\} \left\{ FF - \right. \\ &0.0015 \times [T_{air} + P \frac{Pcos\alpha}{80} (NOCT - 20) - 25] \left. \right\} \quad 4.4 \end{aligned}$$

By putting into more solar modules to compensate for the $\cos(\alpha)$ decline of short-circuit current, the new power output after compensation is then:

$$P'' = I_{sc}' V_{oc}' FF' \frac{1}{\cos(\alpha)}$$

$$\begin{aligned}
&= \{V_{oc} + \frac{nkT}{q} \ln \{ \cos(\alpha) (1 - [\frac{n_1 \cos \alpha_i - n_2 \sqrt{1 - (\frac{n_1}{n_2} \sin \alpha_i)^2}}{n_1 \cos \alpha_i + n_2 \sqrt{1 - (\frac{n_1}{n_2} \sin \alpha_i)^2}})^2] \} - 0.0022 \times [T_{air} + \\
&P \frac{PCOS(\alpha)}{80} (NOCT - 20) - 25] \} \{ I_{sc} (1 - [\frac{n_1 \cos \alpha_i - n_2 \sqrt{1 - (\frac{n_1}{n_2} \sin \alpha_i)^2}}{n_1 \cos \alpha_i + n_2 \sqrt{1 - (\frac{n_1}{n_2} \sin \alpha_i)^2}})^2] \} \{ FF - 0.0015 \times \\
&[T_{air} + P \frac{P_{cos \alpha}}{80} (NOCT - 20) - 25] \} \quad 4.5
\end{aligned}$$

The Performance Ratio, defined as the ratio of power output from the tilted solar modules and modules placed in perpendicular to the incoming sunrays when receiving the same amount photon flux (and occupy the same space if the mounting surface is normal to incoming sunrays).

$$Performance\ Ratio = \frac{p' \frac{1}{\cos \alpha}}{p} = \frac{p''}{p}$$

$$\begin{aligned}
&= \{V_{oc} + \frac{nkT}{q} \ln \{ \cos(\alpha) (1 - [\frac{n_1 \cos \alpha_i - n_2 \sqrt{1 - (\frac{n_1}{n_2} \sin \alpha_i)^2}}{n_1 \cos \alpha_i + n_2 \sqrt{1 - (\frac{n_1}{n_2} \sin \alpha_i)^2}})^2] \} - 0.0022 \times [T_{air} + \\
&P \frac{PCOS(\alpha)}{80} (NOCT - 20) - 25] \} \{ I_{sc} (1 - [\frac{n_1 \cos \alpha_i - n_2 \sqrt{1 - (\frac{n_1}{n_2} \sin \alpha_i)^2}}{n_1 \cos \alpha_i + n_2 \sqrt{1 - (\frac{n_1}{n_2} \sin \alpha_i)^2}})^2] \} \{ FF - 0.0015 \times \\
&[T_{air} + P \frac{P_{cos \alpha}}{80} (NOCT - 20) - 25] \} / (V_{oc} I_{sc} FF) \quad 4.6
\end{aligned}$$

Chapter 5

SOLAR CELL COOLING

5.1 Introduction

As the efficiency of solar cell goes down linearly with temperature increase, overheating of solar cell becomes one of the major concern for solar cell industry because overheating reduces the power output from panels dramatically. This is especially true for hot summer days when the efficiency of the solar panel is supposed to be the highest due to sufficient solar radiation. There has been a significant amount of research going into cooling solar panel. Most of these research is focused on "active cooling" which utilize liquid or air or a combination of liquid and air to actively cooling the system. All the active cooling approaches require energy to accomplish, whether this energy come from solar module itself or from external energy supply. It is certainly much more favorable to extract energy from solar cell itself to supply the cooling energy need, especially if the energy gain from cooling can be sufficient or even has surplus for the cooling activity. Based on this concept, one popular branch of such research is to develop photovoltaic thermal hybrid solar collectors, short for PVT, sometimes known as hybrid PV/T system. PVT systems convert solar radiation into thermal and electrical energy, while it is conventional to convert electromagnetic radiation into electricity, such systems also use a solar thermal collector to captures the remaining energy and use it to remove heat from the PV module. There is also some research efforts put into what I like to call "passive cooling" technologies, which is analogues to the passive cooling approach used in building design that focuses heat

gain control and heat dissipation. This approach utilizes natural convection and conduction that don't rely on energy supply. One example would be a flexible mounted solar panel that could gain more benefit from air flow than the fixed mount solar panel.

5.2 Active Cooling

A photovoltaic thermal hybrid solar collector, or PVT panel, is a combination of PV and thermal collectors into one device that could produce electricity and useful heat simultaneously. Since rooftop PVT has better power output per surface area they become especially interesting for roof with limited space, like in most residential areas and commercial buildings.

A significant amount of research has been devoted into developing photovoltaic thermal hybrid solar collectors since 1970s [16]. There are 4 types of commercially available PVT collectors, they are PVT liquid collectors, PVT air collectors, PVT liquid and air collectors and PVT concentrators. So far there are various concepts of combined PV-thermal collectors been proposed and these concepts differ in their approaches to obtain the maximum yield and it is not easy to say whether the yield of a complicated design will be substantially higher than the yield of a simple design [17].

5.2.1 PVT Liquid Collector

This liquid-cooled design uses a working fluid, typically water or mineral oil and circulates working fluid in the conductive metal piping or plate attached to the back of solar cell in order to extract heat and cool down the solar module. In a closed loop system, this heat is either exhausted or transferred to a heat exchanger where it

flows to its application. In open-loop system, the heated is used before fluid returns to the PV cells [18]. A typical PVT liquid collector is shown in the diagram below where an electrical is used to move water through the solar cycle of a system by forced circulation [19].

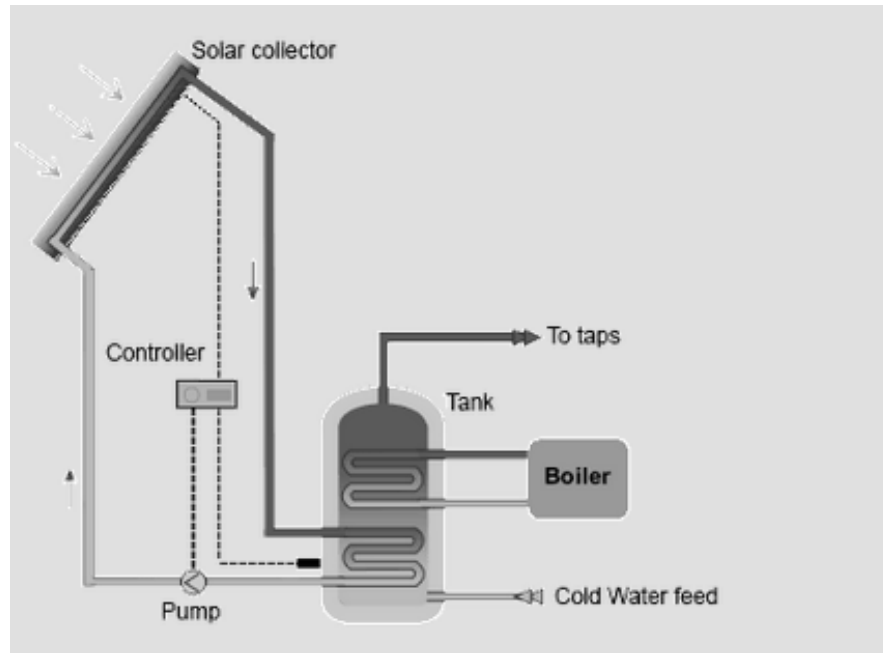


Figure 5.1 A typical PVT liquid collector is shown in the diagram below where an electrical is used to move water through the solar cycle of a system by forced circulation [19].

The first group that proposed a combined photovoltaic and thermal hybrid collectors system is Kern and Russel [20] and following them Florschuetz [21] used an extension of Hottel Whillier model to analysis the combined photovoltaic/thermal flat plate collectors. Bergene [22] proposed a detailed physical model of a hybrid photovoltaic/thermal system in 1995, they attributed values to the parameters and

showed that this liquid type PVT system has lots of potential concerning the general system efficiency gain, which is also confirmed by previous studies and experiments. Zolingen [23] proposed a 3D dynamical model for simulation of the thermal yield of liquid-cooled combined PV-thermal collector. Although there is no conclusive result for performance and cost effective of the combined system as optimized modifications for both electrical and thermal efficient operation must be considered. There are significant amount of aspects and cost analysis results are presented and many of them show promising results [24] [25] [26]. There are various commercial applications developed and many of them has achieved success in heat management and has proved to be cost-effective. Below is one application example that indirectly combined Hybrid PVT system with compressor heat pump [27].

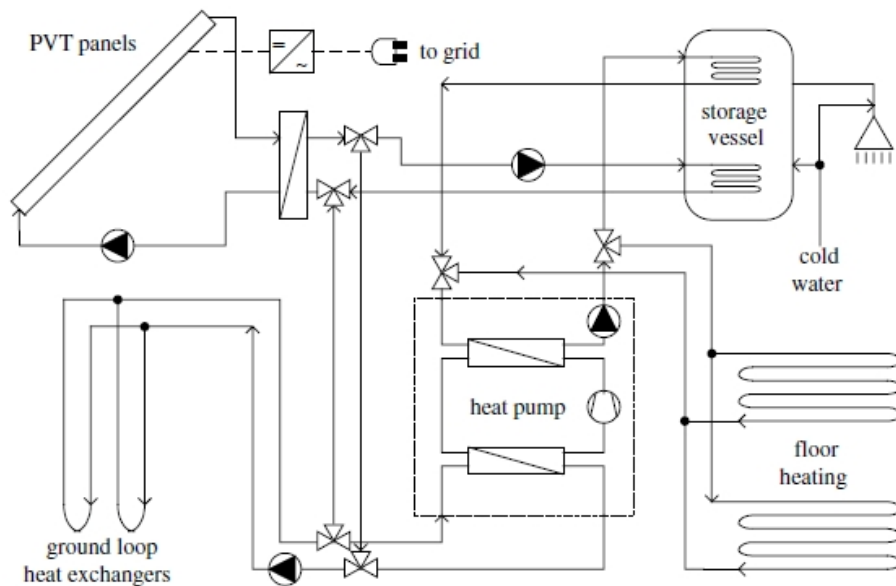


Figure 5.2 Hybrid PVT system combined with compressor heat pump [27].

5.2.2 Air Cooling

Air cooling presents a simple and cheap method for PV cooling, it is less popular than liquid based coolant because heat extraction by air circulation is usually less effective than heat extraction by water. Air extraction are limited in their thermal performance due to the low density, the small volumetric heat capacity and the small thermal conductivity of air [28]. According to an experiment conducted by Tang et al [29] , using air as a coolant was found to decrease the solar cells temperature by 4.7°C and increased the solar panel efficiency by 2.6% while the water coolant counterparts could decrease the cell temperature by 8°C and increased the solar panel efficiency by 3%.

However, the possibility of the utilization of heat for climatization makes PVT air collector attractive for building integration. Research in this field has led to the development of tetto integrale solarizzato(TIS). i.e. solar roof. The applications of the TIS has shown some commercial success and can be discussed by many researchers such as Niccolo [30].

Below is one example of PVT air collector building integration.

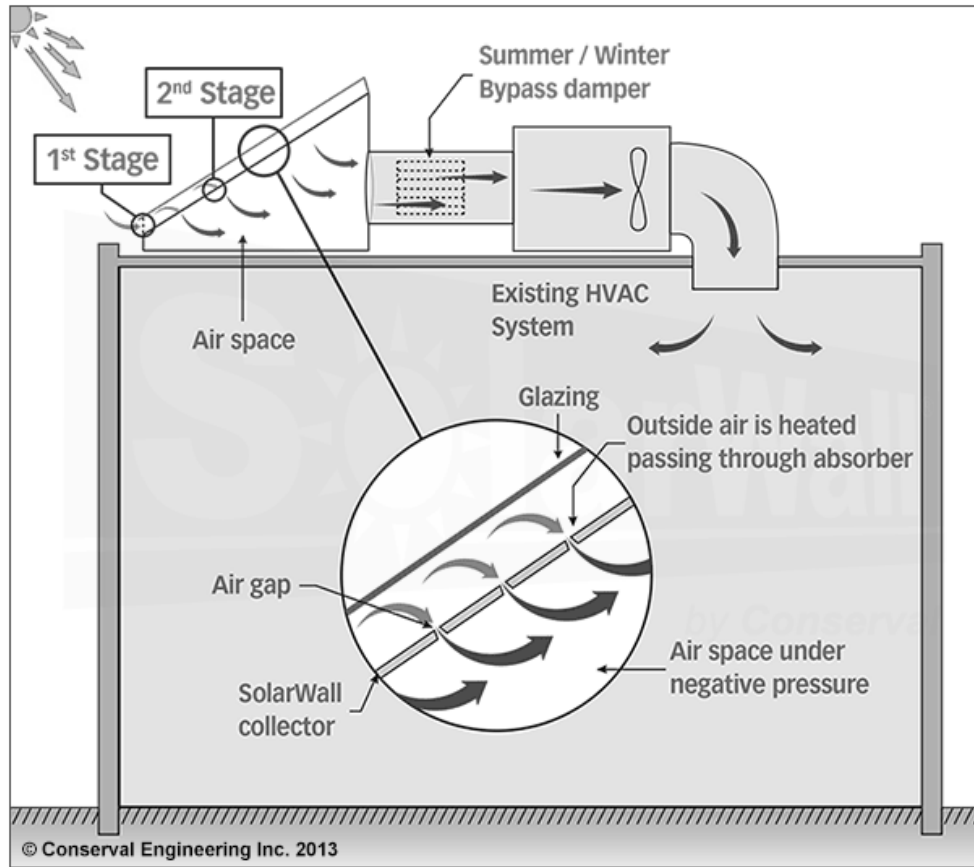


Figure 5.3 PVT air collector building integration [31].

The above system works in such a way that the solar heat produced is taken off and ducted into building through a damper to the HVAC. This could reduce, or may even eliminate, the conventional heating load during the day.(solar wall). Of course one can imagine one of the side effect in an application like this is that the PV waste heat in summer could increase of undesirable heat transfer to the building thus increasing cooling load.

Generally speaking, hybrid PVT system with air heat extraction mainly serve as an alternative and cost effective solution to building integrated PV system. And cost for installation and maintenance is low [32].

5.2.3 Other Hybrid PVT Collectors

Both PVT water collectors and PVT air collected has been proved to be potentially cost-effective and have shown some commercial success. There are also many other approaches to extract waste heat and achieve the best yield. One of them being the combination of water and/or air type collectors, this is also studied extensively and some of the applications have been commercialized to this date. Among them a comparative study for combined system is carried by Zondag et al [17]. He and the fellow researchers investigated sheet-and-tube, free flow, channel and 2 absorber type PVT collector. The result indicated an efficiency of over 50% can be achieved from the combined PVT collector.

By far we have discussed hybrid system for flat panels. Compared to flat panels, the cooling for concentrated PV is an even greater concern. Long time exposure under excess temperature not only result in energy loss but can also cause long term irreversible damage to the concentrators and shorten it's useful life by a significant amount [33]. A solar cooling system, preferably active cooling system due to its greater cooling capacity, is needed for concentrated solar applications. A cooling system for concentrated solar cell needs to be more accurate and better balanced. The over-temperature control needs to be addressed with more delicacy as there the potential to overheat the PV components in the receiver if the thermal supply is not balanced by demand. The first prototype of the hybrid CPV-T ANU-Chromasun micro-concentrator has been installed at The Australian National University at

Canberra, Australia in 2012 [34]. The results of electrical and thermal performance of the micro-concentrator system, including instantaneous and full-day monitoring, show that the combined efficiency of the system can exceed 70%. Over the span of a day, the average electrical efficiency was 8% and the average thermal efficiency was 50%. Another study is carried out by Cheknane et al [35] on the experimental studying that used water and acetone circulating in the copper heat pipe to examine the effect of cooling on concentrator silicon based solar cells. Result come from this study promised a reasonable costs for such high efficiency cells working up to 500 suns. However there should be more work done in this field to consider not only efficiency improvement but also take into account the cost related issue that is much better demonstrated on the researches on flat panels. Nonetheless, there is little doubt for PVT system on a concentrated solar module to be cost effect as the area that requires cooling in concentrated solar is significantly smaller than it's flat panel counterpart and the power out of the concentrated solar panel can greatly benefit from extracting excess heat.

The schematic of the PV-thermal CHAPS hybrid concentrator is shown below:

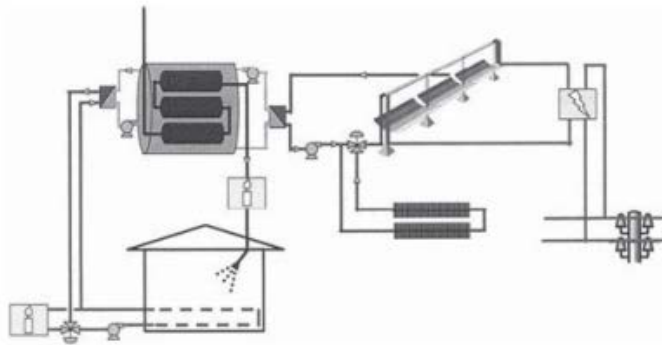


Figure 5.4: Schematic of the PV-thermal CHAPS hybrid concentrator [34].



Figure 5.5 ANU-Chromasun microconcentrator system installed at ANU [34].

5.3 Passive Cooling

"passive cooling" technologies, which is analogous to the passive cooling approach used in building design that focuses heat gain control and heat dissipation. This approach in general utilizes and maximizes natural convection and conduction. Passive cooling doesn't use energy generated by the solar panel and doesn't rely on external power supply.

Studies on passive cooling are less organized and structural. Although all the approaches are based on a single purpose that is to maximize natural heat convection and conduction to get rid of excess heat. One focus is to develop material that better conduct heat to help the back of the solar cell give away excess heat. IBM proposed a solution that is to place an ultrathin layer of liquid metal, a compound of gallium and indium, on the surface. This material is believed to benefit from both the high thermal conductivity of metal and at the meanwhile can be made to be extremely thin, around 10 micrometers due to its liquid properties. Guha and his colleagues have

demonstrated that they can focus the equivalent of 2,300 times the sun's natural energy on a one-centimeter-square photovoltaic chip. Without cooling, this would melt steel. With the liquid metal and water-cooling system, the IBM photovoltaic material remains at 85 °C [36].

More studies on passive cooling has been carried on maximizing air flow below on the solar cell surface. This could either be done by architectural deployment that encourage air flow or utilize local natural resources that absorbs or dissipate heat. Sendhil et al [37] have studied the effect of cooling fins, a passive cooling arrangement for solar cell. The thermal model results that maximum of four numbers of uniform fins of 5 mm height and 1 mm thickness can be effectively used to reduce the solar cell temperature. Another example of passive cooling of solar cells is proposed by Ashwin et al [38], his group conducted theoretical and experimental analysis on the cooling of flat plate solar panels using natural convection induced by the chimney effect. They designed a Solar Cooling Chimney(SCC). Results of a theoretical analysis and preliminary experimental investigations have helped to validate the concept. The proposed SCC can provide a sustainable and passive method for cooling solar photovoltaic in solar power plants.

The system diagram is shown below:

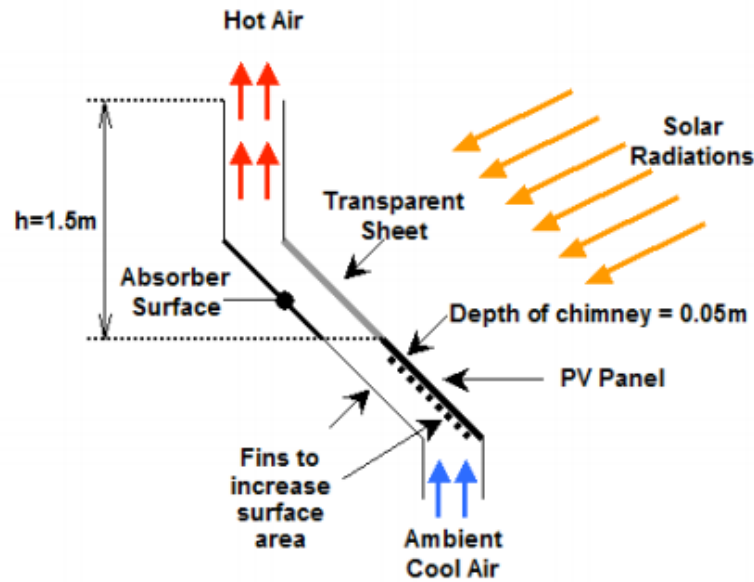


Figure 5.6 A cross-section of the passive cooling chimney diagram [38].

5.4 Conclusions

Overheating can greatly compromise solar cells performance, therefore it is necessary to explore various cooling methods to reach the most cost-effective solution. Although there has been a significant amount of studies and experimental results that demonstrated the great efficiency gain and a good economy potential. Cooling integrated PV system has not gained the popularity one would expect by now. One of the many reasons for lack of public interest is the complexity of such system and the maintenance issues that incur. Most of the customers for residential flat plate solar panels don't want to be bothered with a more complicated installation process, a time-consuming daily operation and the uncertainties of the system in exchange for an average 4-8 % energy gain. Some people may be skeptical of the cost efficiency of

such system. Therefore, we believe a simpler, much more understandable cooling approach can be better received by the common home PV costumers.

Chapter 6

RESULTS AND DISCUSSIONS

6.1 Experimental Set-up and Procedure

3 Instapark 10W high-efficiency mono-crystalline solar panels were used for the testing. 2 panels closer in performance were chosen, one as experimental and the other one as control. Both panels have open-circuit voltage of 22V and short-circuit current of 0.61A, under standard test condition(STC).

All 3 Instapark solar panels were mounted onto a steel pipe with flexible pipe gate hinges as shown in the picture below. The stop hinges allow each individual panel to be rotated around the pipe axis with a single hand and can be stopped at any angle when no force is applied. This arrangement also assures only 1 panel is rotated without interfering position of the others.

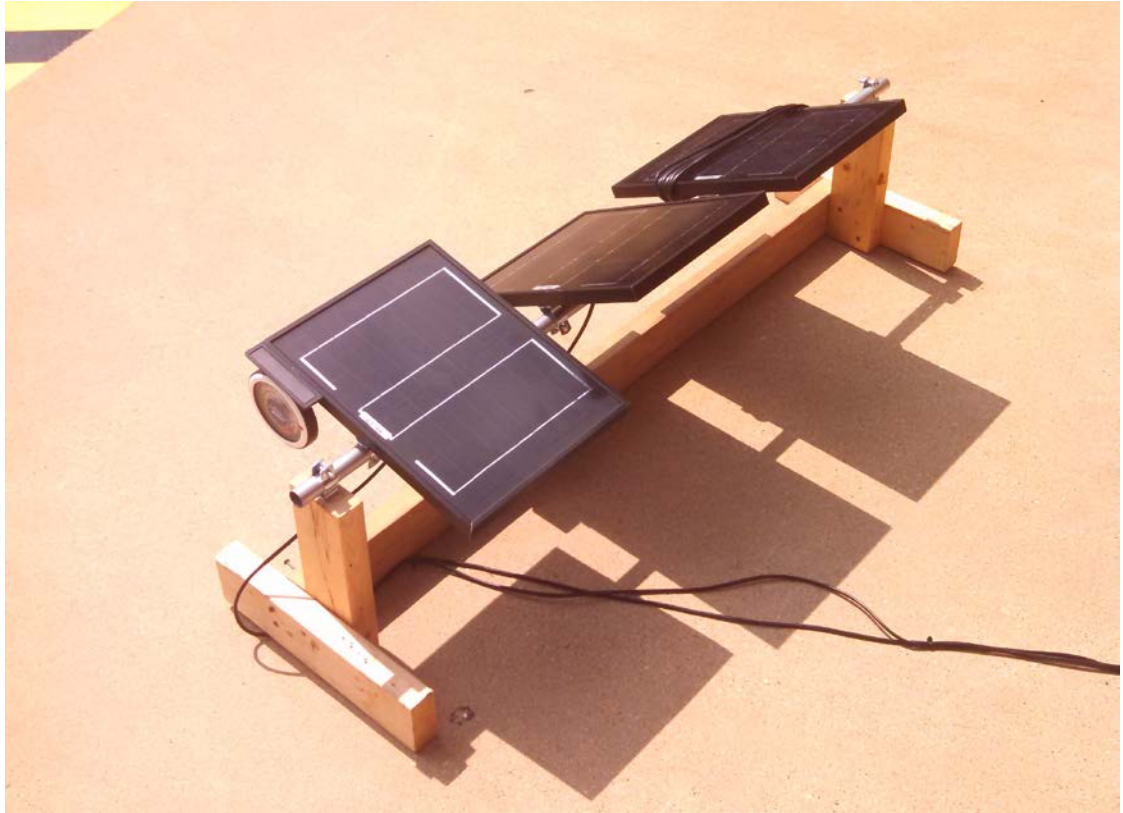


Figure 6.1 Flexible solar panel mounting that allows panel to rotate around pipe axis.

The angle of the control panel is measured by Empire magnetic polycast protractor, the angle of the experimental panel is measured by AccuRemote digital electronic magnetic angle protractor. The protractors are placed on the side of the solar panel facing down so that they wouldn't cast shade on the panels. The altitude angle and azimuth angle in Newark, DE at the starting time of the test is found on Sundesign [39] to make sure both panels are placed perpendicular to the incoming sunrays at the start of the test. The experimental solar panel1 is tilted from 0° to 60° away from the sun, with a increment of $2-3^{\circ}$ within 30° and a increment of 5° from

30° to 60°. The interval of each measurement is exactly 120 seconds, so that the experimental solar panel can achieve thermo equilibrium. Also, with accurate control of time at each measurement, the exact location of sun can be traced at the time of each measurement and thus can be taken into account when processing data.



Figure 6.2 Empire magnetic polycast protractor used to measure tilting angle

All testing were done between 11:00am and 1:00 pm when the sun movement relative to earth is the smallest. Testing were only carried on perfect sunny day when there is no visible cloud in the sky to result in significant change in the solar condition throughout the testing period.

Power output from experimental panel and control panel is measured with 2 Keithley 2400 SourceMeter, 4-wire sense was used for both panels to eliminate the effect of contact resistance and the resistance of the cable. The solar irradiance is

estimated using solar flux meter and hourly data from Delaware Environmental Observing System [40].



Figure 6.3 Keithley 2400 SourceMeters and PC for data collection.

Python code was written so that a PC can directly commands 2 Keithley SourceMeters to sweep both solar panels for a range of voltage and reads the corresponding current value and generate I-V curves for the solar panels. Note there are other existing software i.e. LabView that works in a similar manner but cannot command 2 SourceMeters to do sweeping at the same time. The python code we wrote

commands the SourceMeters to sweep the solar panel from 0-21V taking 100 samples on the way. Each sweep takes around 12 seconds to generate I-V curves for both experimental and control on one diagraph and automatically save the I-V curve as csv file in the folder. Another python function is written so that the code can extract all the useful parameters from folder where the csv files were saved. Those parameters include V_{oc} , I_{sc} , V_{mp} (voltage at maximum power point), I_{mp} (current at maximum power point), Power, FF, $n \cdot t$ (the product of ideality factor and temperature, this product is extracted by fitting the data with ideal diode equation but cannot be easily separated), series and shunt resistance of the solar cell(also extracted when curve fitting the data with ideal diode equation with series and shunt resistance).

There is one major limitation for the Keithley 2400 SourceMeter, and this limitation is that the source meter can only be used for low power application. For the current setting in this test, the maximum voltage output from the SourceMeter cannot exceed 21V. In many occasions, the solar panels tested has a open-circuit voltage higher than 21V, such as the measurement below:

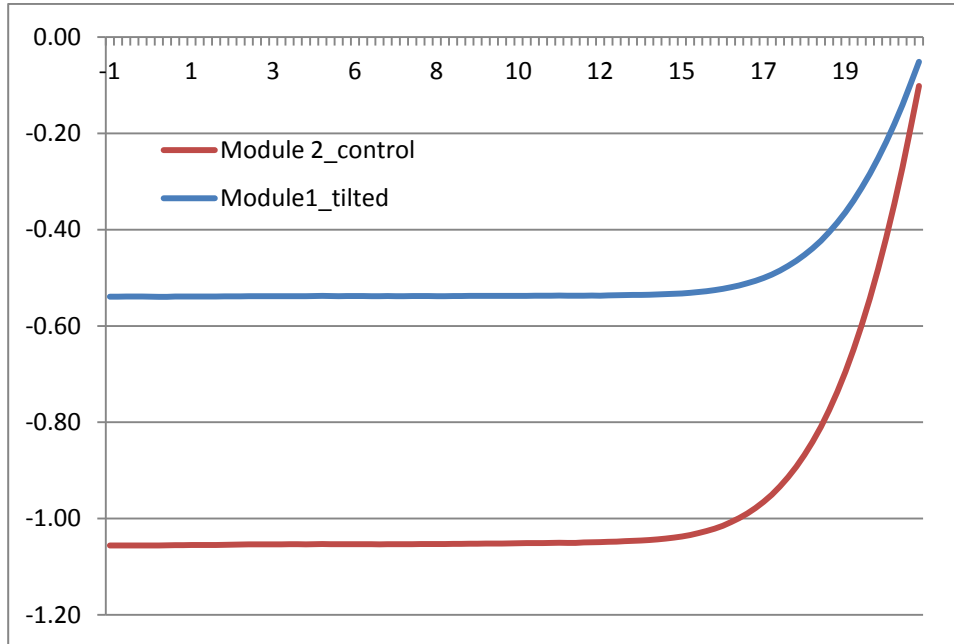


Figure 6.4 I-V curves of both solar modules at on measurement.

The current didn't reach 0 when the voltage limitation was achieved at 21V, so there was no sufficient data to determine V_{oc} (V_{oc} is the corresponding voltage value when current is 0). We therefore used curve optimizer in Pylab to fit the data with diode curve to predict the open-circuit voltage.

6.2 Results

At ambient temperature 28.3°C , light intensity $1180\text{W}/\text{m}^2$. The theoretical and experimental power performance ratio of tilted solar panels verses perpendicular placed solar panels that receive same amount of photon flux is shown below:

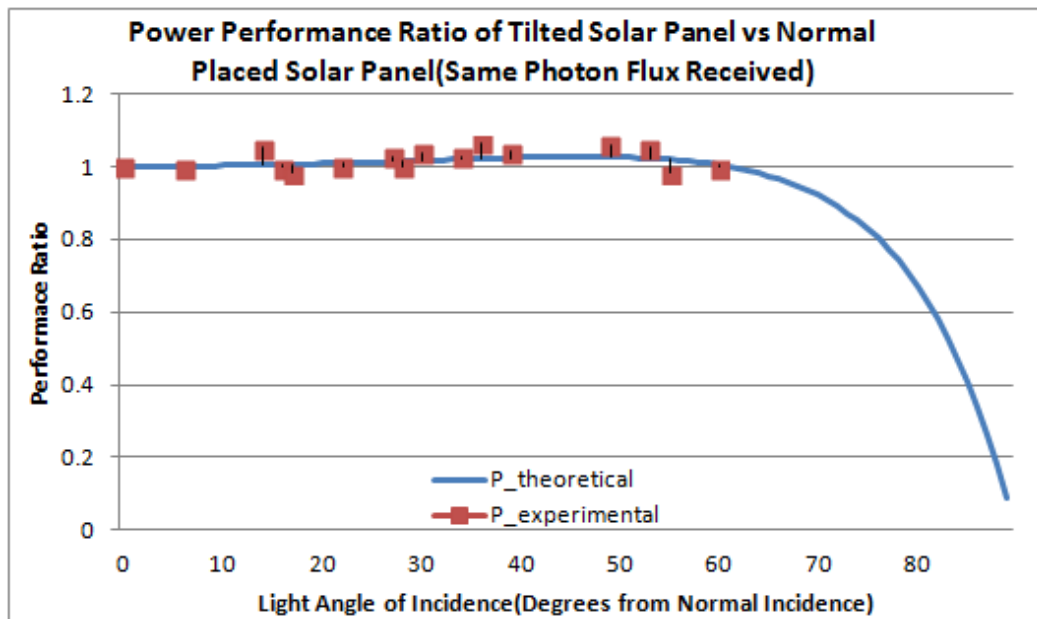


Figure 6.5 Power performance ratio of tilted solar panel verses normal placed solar panel(same photon flux received).

The theoretical and experimental performance ratio of Voc is:

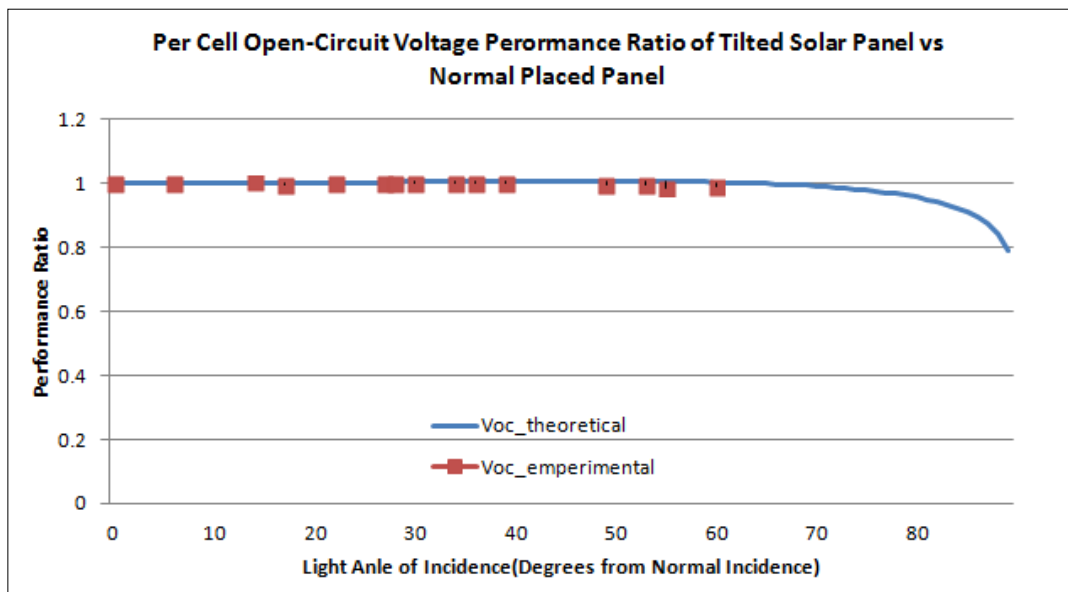


Figure 6.6 Per cell open-circuit voltage performance ratio of tilted solar panel verses normal placed panel.

The short-circuit current per cell tilted verses not tilted:

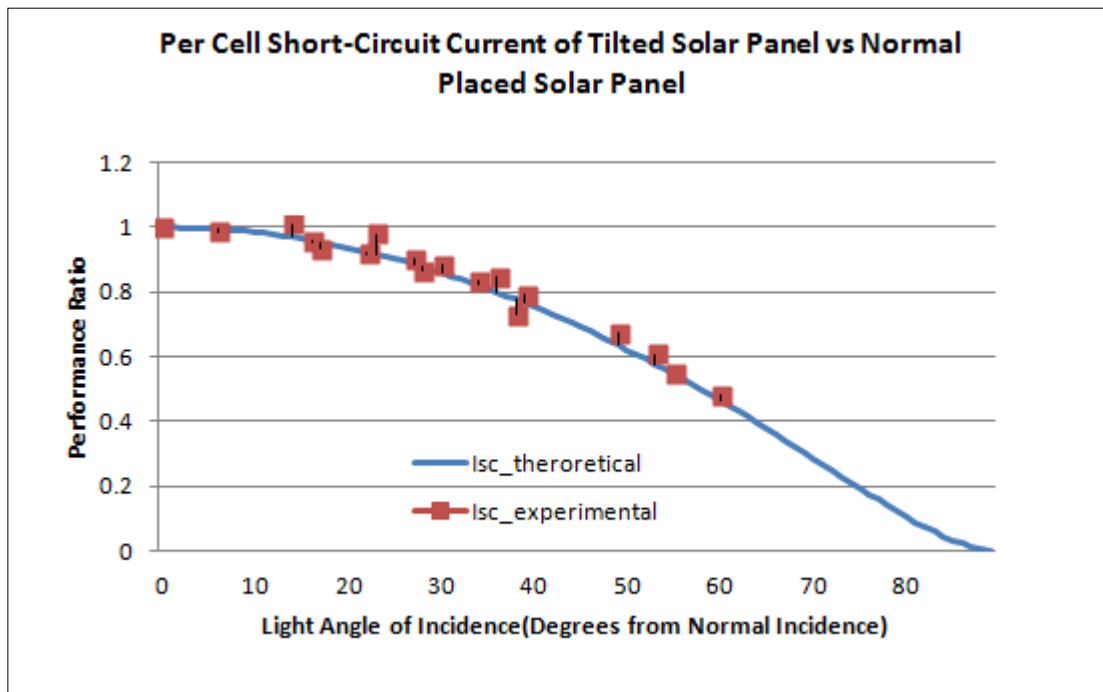


Figure 6.7 Per cell short-circuit current of tilted solar panel verses normal placed solar panel.

And last, the performance ratio of fill factor tilted verses not tilted:

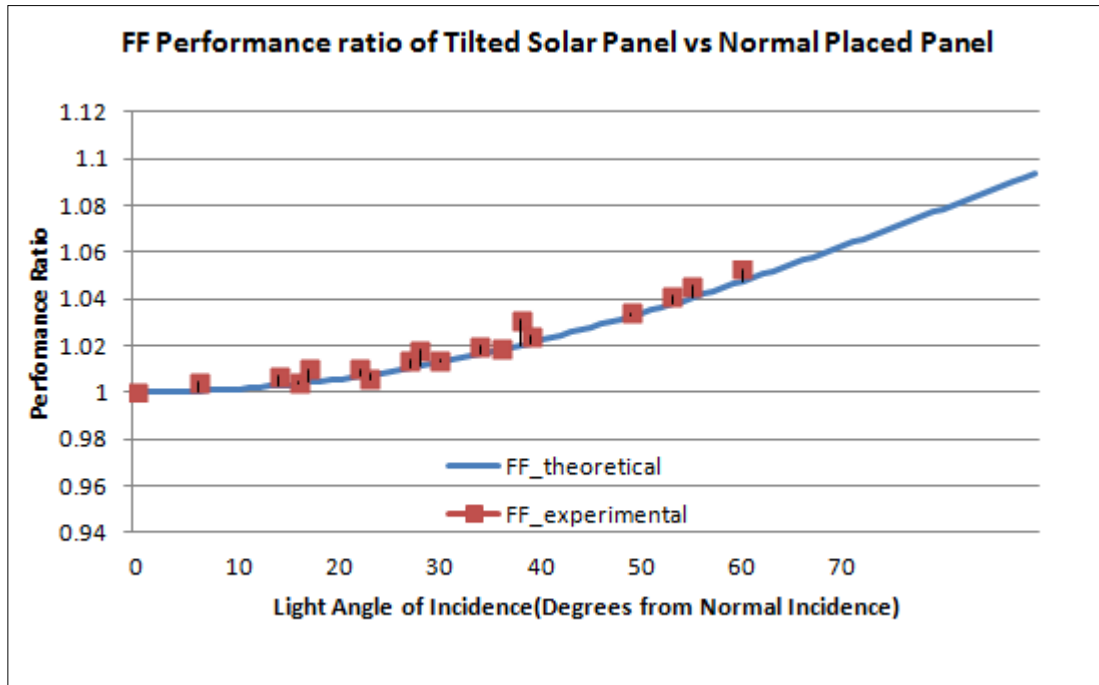


Figure 6.8 Fill factor performance ratio of tilted solar panel verses normal placed panel.

6.3 Discussions

The ideality factor, deduced from the product of n and t , ranges from 1.4-1.6 during the test, therefore an average of $n=1.5$ was used to construct theoretical model. The theoretical model for each solar parameter predicts the experimental data quite well. For the test condition specified in this chapter, the power output performance ratio of the tilted solar array is slightly higher than the normal placed solar array when the tilting angle is below 60° , but the change is barely noticeable. The performance ratio of open-circuit voltage, effected by both temperature and light intensity, stays roughly at 1 across a big range of tilting angle, meaning the efficiency gain from the cooling of the solar cell is offset by the decrease of V_{oc} induced by decreasing light

intensity. Short-circuit current follows the product of transmission and cosine curve quite well.

It is clear from the theoretical model that the performance ratio is the highest during summer time when the solar irradiance is very high and temperature is high so that the effect of cooling outweigh the effect of light intensity drop. A prediction for performance ratio is shown below for June 2014 at 12:00pm and January 2014 at 12:00pm, the temperature and light intensity used is the monthly summary at noon from DEOS database [40].

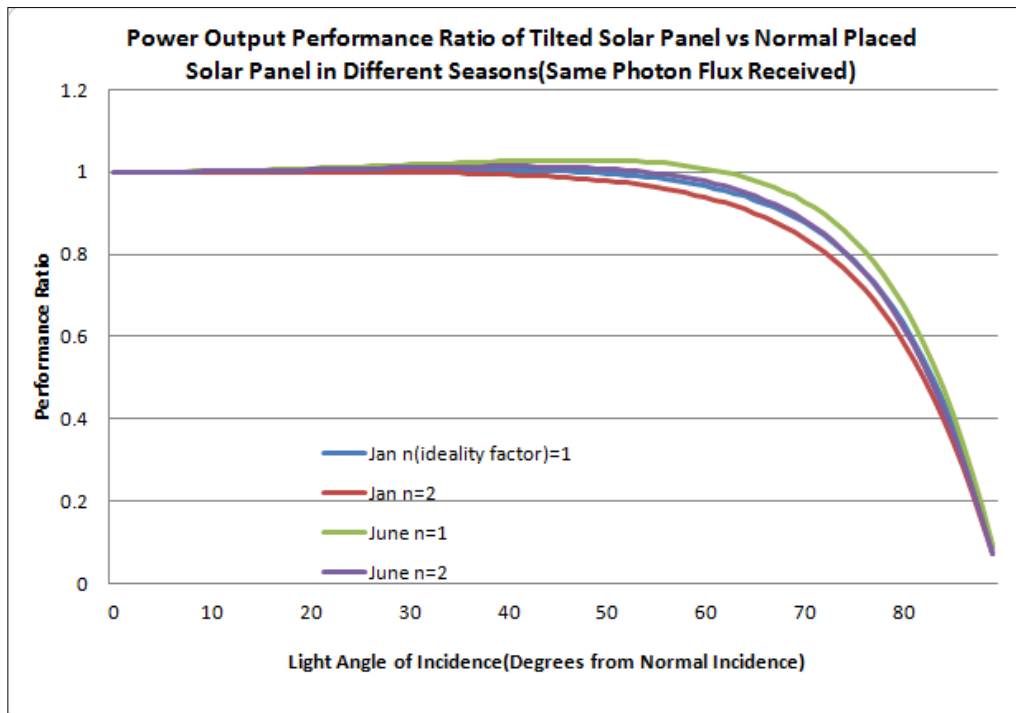


Figure 6.9 Power output performance ratio of tilted solar panel verses normal placed solar panel in different seasons(same photon flux received).

Zoom in to the shoulder of the diagram, the best performance ratio is 1.029 in June when the light intensity is 1100W/m^2 and temperature is at 30°C and $n=1$. The tilting angle for the best performance ratio is 51° . In other word, 3% power boost is achieved by using 60% more panels under the best scenario. And under worst case scenario, in January when the light intensity is 721W/m^2 and temperature 1.3°C at noon, the highest performance ratio is 1.0003, or a 0.03% increase.

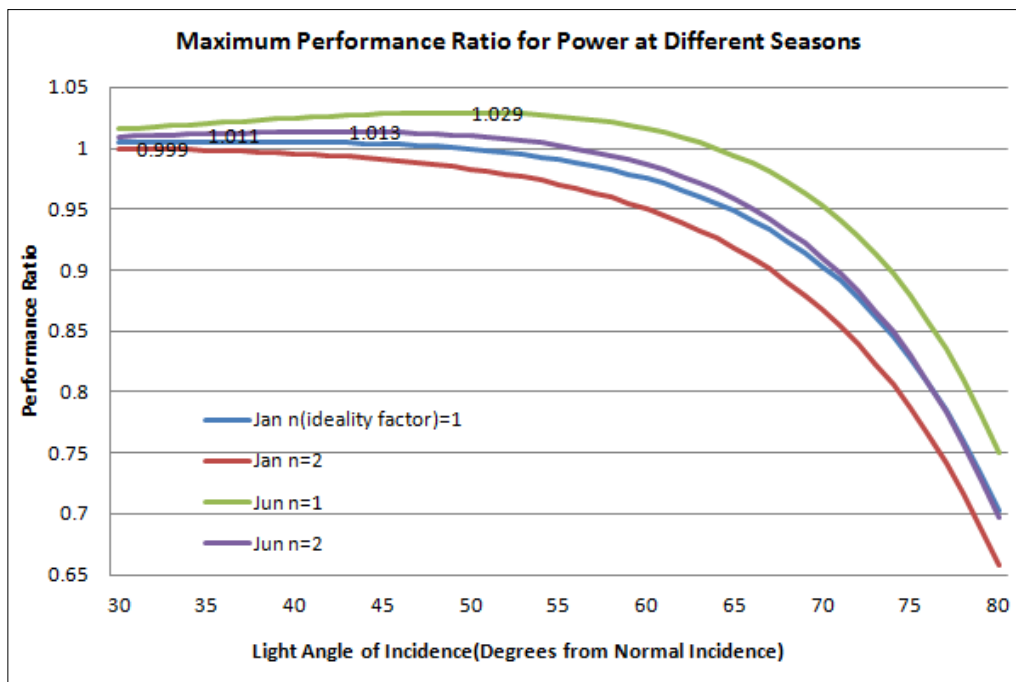


Figure 6.10 Shoulder part of power output performance ratio of tilted solar panel verses normal placed solar panel in different seasons(same photon flux received).

Chapter 7

CONCLUSIONS

The behavior of solar cells at different tilt angles between the incident light has been theoretically and experimentally studied. Experimental results and simulations suggested a power output gain of at most 3% can be achieved by deploying the solar cell at a certain angle away from sun light for the modules tested under normal weather condition. And this deployment could potentially cause efficiency decrease in low light and low temperature environment.

In summary, this project has explored an alternative passive cooling method that could possibly increase the PV power output from a fixed area of solar panels placed on a limited space, but is proved to be not very practical.

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