WEEK 6: SOLAR ENERGY

During the day the sun has different positions. For low concentration systems (and low temperatures) tracking can be avoided (or limited to a few positions per year) if non-imaging optics are used. For higher concentrations, however, if the mirrors or lenses do not move, then the focus of the mirrors or lenses changes (but also in these cases non-imaging optics provides the widest acceptance angles for a given concentration). Therefore, it seems unavoidable that there needs to be a tracking system that follows the position of the sun (for solar photovoltaic a solar tracker is only optional).

The tracking system increases the cost and complexity. With this in mind, different designs can be distinguished in how they concentrate the light and track the position of the sun.

Thermal Radiation

Thermal radiation is a form of energy emission and transmission that depends entirely on the temperature characteristics of the emissive surface. Thermal radiation is in fact an electromagnetic wave that travels at the speed of light (*C* = 300,000 km/s in a vacuum). This speed is related to the wavelength (λ) and frequency (v of the radiation as given by the equation:

$$C = \lambda \nu \quad \textbf{(eq.1)}$$

When a beam of thermal radiation is incident on the surface of a body, part of it is reflected away from the surface, part is absorbed by the body, and part is transmitted through the body. The various properties associated with this phenomenon are the fraction of radiation reflected, called *reflectivity* (ρ); the fraction of radiation absorbed, called *absorptivity* (α); and the fraction of radiation transmitted, called *transmissivity* (τ). The three quantities are related by the following equation:

$$\rho + \alpha + \tau = 1 \quad \textbf{(eq.2)}$$

The following equation is used to express the dependence of these properties on the wavelength:

$$\rho_\lambda + \alpha_\lambda + \tau_\lambda = 1 \quad \textbf{(eq. 3)}$$

where ρ_λ = Spectral reflectivity; α_λ = Spectral absorptivity; τ_λ = Spectral transmissivity

If a body absorbs all the impinging thermal radiation such that $\tau = 0$, $\rho = 0$, and $\alpha = 1$, regardless of the spectral character or directional preference of the incident radiation, it is called a *blackbody*.

A blackbody is not only a perfect absorber, it is also characterized by an upper limit to the emission of thermal radiation. The energy emitted by a blackbody is a function of its temperature and is not evenly distributed over all wavelengths. The rate of energy emission per unit area at a particular wavelength is termed the *monochromatic emissive power*. Max Planck was the first to derive a functional relation for the monochromatic emissive power of a blackbody in terms of temperature and wavelength. This was done by using the quantum theory, and the resulting equation, called *Planck's equation for blackbody radiation*, is given by

$$E_{b\lambda} = \frac{C_1}{\lambda^5\left(e^{C_2/\lambda T} - 1\right)} \quad \textbf{(eq. 4)}$$

where

$E_{b\lambda}$ = monochromatic emissive power of a blackbody (W/m^2-μm).

T = temperature of the body (K).

λ = wavelength (μm).

C_1 = constant = 3.74×10^8 W-$\mu m^4/m^2$.

C_2 = constant = 1.44×10^4 μm-K.

By differentiating Eq. 4 and equating to 0, the wavelength corresponding to the maximum of the distribution can be obtained and is equal to $\lambda_{max}T = 2897.8$ μm-K. This is known as *Wien's displacement law*. Figure 1 shows the spectral radiation distribution for blackbody radiation at three temperature sources. The curves have been obtained by using the Planck's equation.

The total emissive power, E_b, and the monochromatic emissive power, $E_{b\lambda}$, of a blackbody are related by

$$E_b = \int_0^{\infty} E_{b\lambda}\, d\lambda \quad \textbf{(eq. 5)}$$

Substituting Eq. (4) into Eq. (5) and performing the integration results in the Stefan-Boltzmann law:

$$E_b = \sigma T^4 \quad \textbf{(eq. 6)}$$

where α = the Stefan-Boltzmann constant = 5.6697 x 10^{-8} W/m^2-K^4.

In many cases, it is necessary to know the amount of radiation emitted by a blackbody in a specific wavelength band $\lambda_1 \rightarrow \lambda_2$. We get;

$$E_b(\lambda_1 T \rightarrow \lambda_2 T) = \int_{\lambda_1 T}^{\lambda_2 T} \frac{E_{b\lambda}}{T}\, d\lambda T \quad \textbf{(eq. 7)}$$

which results in $E_b(0 \rightarrow \lambda_1 T)$ - $E_b(0 \rightarrow \lambda_2 T)$. Table 2.4 presents a tabulation of $E_b(0 \rightarrow \lambda T)$ as a fraction of the total emissive power, $Eb = \sigma T^4$, for various values of λT.

A blackbody is also a perfect diffuse emitter, so its intensity of radiation, I_b, is a constant in all directions, given by

$$E_b = \pi I_b \quad \textbf{(eq. 8)}$$

Real surfaces emit less energy than corresponding blackbodies. The ratio of the total emissive power, E, of a real surface to the total emissive power, E_b, of a blackbody, both at the same temperature, is called the *emissivity* (ε) of a real surface; that is;

$$\varepsilon = \frac{E}{E_b} \quad \textbf{(eq. 9)}$$

To express the dependence on wavelength, the monochromatic or spectral emissivity, ε_λ, is defined as the ratio of the monochromatic emissive power, E_λ, of a real surface to the monochromatic emissive power, $E_{b\lambda}$, of a blackbody, both at the same wavelength and temperature:

$$\varepsilon_\lambda = \frac{E_\lambda}{E_{b\lambda}} \quad \textbf{(eq. 10)}$$

Kirchoff's law of radiation states that, for any surface in thermal equilibrium, monochromatic emissivity is equal to monochromatic absorptivity:

$$\varepsilon_\lambda(T) = \alpha_\lambda(T) \quad \textbf{(eq. 11)}$$

Equation (11) can be generalized as

$$\varepsilon(T) = \alpha(T) \quad \textbf{(eq. 12)}$$

Similar to Eq. (2.37) for a real surface, the radiant energy leaving the surface includes its original emission and any reflected rays. The rate of total radiant energy leaving a surface per unit surface area is called the *radiosity* (*J*), given by

$$J = \varepsilon E_b + \rho H \quad \textbf{(eq. 13)}$$

where

Eb = blackbody emissive power per unit surface area (W/m2).

H = irradiation incident on the surface per unit surface area (W/m2).

ε = emissivity of the surface.

ρ = reflectivity of the surface.

A real surface is both a diffuse emitter and a diffuse reflector and hence, it has diffuse radiosity; i.e., the intensity of radiation from this surface (*I*) is constant in all directions. Therefore, the following equation is used for a real surface:

$$J = \pi \times I \quad \textbf{(eq. 14)}$$

Photovoltaic (PV) Cells

PVs or *solar cells* convert sunlight directly into electricity. When photons strike certain semiconductor materials, such as silicon, they dislodge electrons, which causes a potential difference to form between the specially treated front surface of the solar cells and the back surface. In order to increase the voltage, individual cells are combined in a panel form. The most advanced photon utilization technology is the solar cell to which the PV effects of semiconductors are applied.

Solar cells are the standard-bearer of the new energy technologies because of their great potential. Their successful development is dependent on cost reduction of the power-generating systems that include SCs.

Photovoltaic cells consist of a junction between two thin layers (positive, p, and negative, n) of dissimilar semiconducting materials. When a valance electron of an atom absorbs a photon of light, the energy of the electron is increased by the amount of energy of the photon. If the energy of the photon is equal to or more than the band gap of the semiconductor, the electron with the excess energy will jump into the conduction band where it can move freely. Figure 1. Shows the PV device schematically. These solar cell contains a junction of a p-type and an n-type semiconductor (a p-n junction).

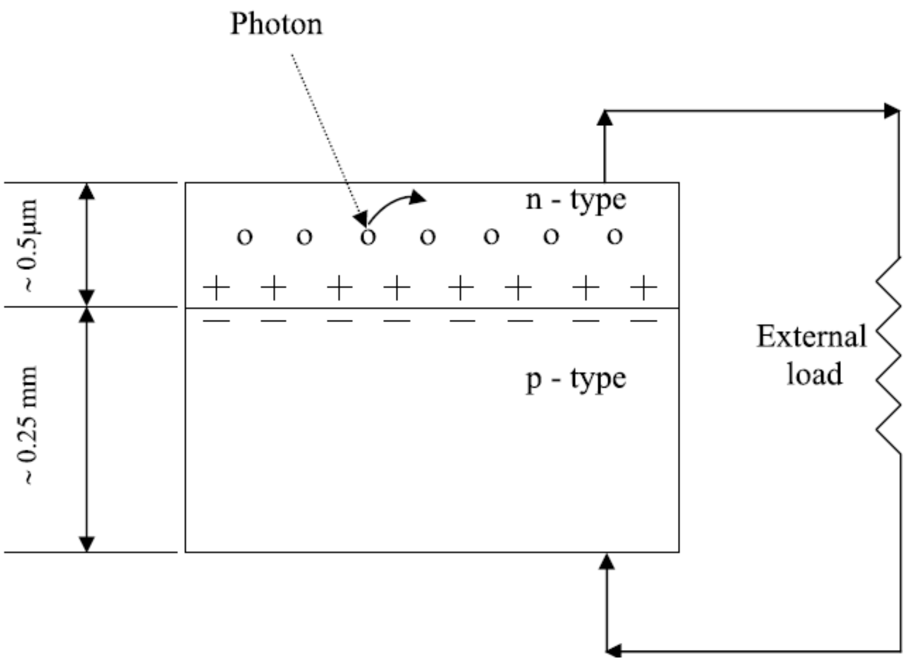

Figure 1. Simple PV cell and resistive load

The thickness of the n-type layer in a typical crystalline silicon cell is about 0.5 μm, whereas that of the p-type layer is about 0.25 mm. Thermal radiation is in fact an electromagnetic wave that travels at the speed of light (*C* = 300,000 km/s in a vacuum). This speed is related to the wavelength (λ) and frequency (v) of the radiation as given by the equation:

$$C = \lambda \nu \quad \textbf{(Eq. 1)}$$

The energy contained in a photon, *Ep*, is given by

$$E_p = h\nu \quad \textbf{(Eq. 2)}$$

where

h = Planck's constant, = 6.625 x 10^{-34} J-s.

v = frequency (s^{-1}).

Combining Eq. 1 with Eq. 2, we get

$$E_p = \frac{hC}{\lambda} \quad \textbf{(Eq. 3)}$$

Silicon has a band gab of 1.11 eV (1 eV = 1.6 x 10^{-19} J); therefore, by using Eq. 3, it can be found that photons with wavelength of 1.12 μm or less are useful in creating electron-hole pairs and thus electricity. The number of photons, n_p, incident on a cell can be estimated from the intensity of light, I_p:

$$n_p = \frac{I_p}{E_p} \quad \textbf{(Eq. 4)}$$

When solar energy (photons) hits the solar cell, electrons are knocked loose from the atoms in the semiconductor material, creating electron-hole pairs. If electrical conductors are attached to the positive and negative sides, forming an electrical circuit, the electrons are captured in the form of electric current, called *photocurrent*, I_{ph}.

During darkness the solar cell is not active and works as a diode, i.e., a p-n junction that does not produce any current or voltage. If, however, it is connected to an external, large voltage supply, it generates a current, called the *diode* or *dark current*, I_D. A solar cell is usually represented by an electrical equivalent one-diode model, shown in Figure 2.

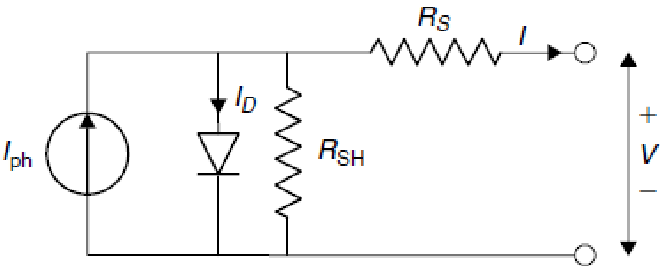

Figure 2. Single solar cell model.

As shown in Figure 2, the model contains a current source, I_{ph}, one diode, and a series resistance *RS*, which represents the resistance inside each cell. The diode has also an internal shunt resistance, as shown in Figure 2. The net current is the difference between the photocurrent, I_{ph}, and the normal diode current, I_D, given by

$$I = I_{ph} - I_D = I_{ph} - I_o\left\{\exp\left[\frac{e(V + IR_S)}{kT_C}\right] - 1\right\} - \frac{V + IR_S}{R_{SH}} \quad \textbf{(Eq. 5)}$$

It should be noted that the shunt resistance is usually much bigger than a load resistance, whereas the series resistance is much smaller than a load resistance, so that less power is dissipated internally within the cell. Therefore, by ignoring these two resistances, the net current is the difference between the photocurrent, I_{ph}, and the normal diode current, I_D, given by

$$I = I_{ph} - I_D = I_{ph} - I_o\left[\exp\left(\frac{eV}{kT_C}\right) - 1\right] \quad \textbf{(Eq. 6)}$$

where

k = Boltzmann's gas constant, = 1.381 x 10^{-23} J/K.

T_C = absolute temperature of the cell (K).

e = electronic charge, = 1.602 x 10^{-19} J/V.

V = voltage imposed across the cell (V).

I_o = dark saturation current, which depends strongly on temperature (A).

Figure 3 shows the *I*-*V* characteristic curve of a solar sell for a certain irradiance (G_t) at a fixed cell temperature, T_C. The current from a PV cell depends on the external voltage applied and the amount of sunlight on the cell. When the cell is short-circuited, the current is at maximum (short-circuit current, I_{sc}), and the voltage across the cell is 0. When the PV cell circuit is open, with the leads not making a circuit, the voltage is at its maximum (open-circuit voltage, V_{oc}), and the current is 0. In either case, at open circuit or short circuit, the power (current times voltage) is 0. Between open circuit and short circuit, the power output is greater than 0.

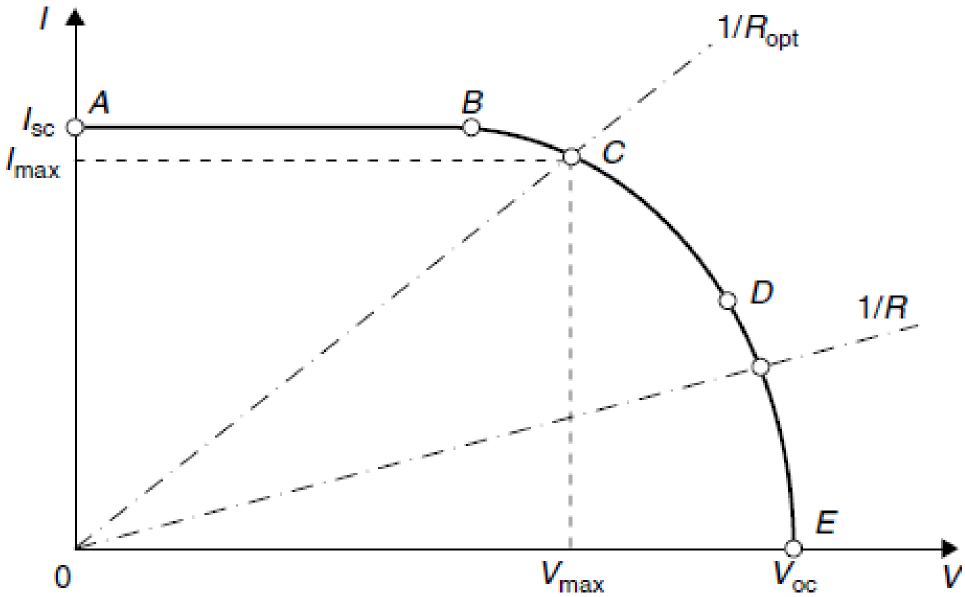

Figure 3. Representative current-voltage curve for photovoltaic cells.

The load characteristic is a straight line with a slope 1/*V* = 1/*R*. If the load resistance is small, the cell operates in the region *AB* of the curve, where the cell behaves as a constant current source, almost equal to the short-circuit current. On the other hand, if the load resistance is large, the cell operates on the region *DE* of the curve, where the cell behaves more as a constant voltage source, almost equal to the open circuit voltage. The power can be calculated by the product of the current and voltage. If this exercise is performed and plotted on the same axes, then Figure 4 can be obtained.

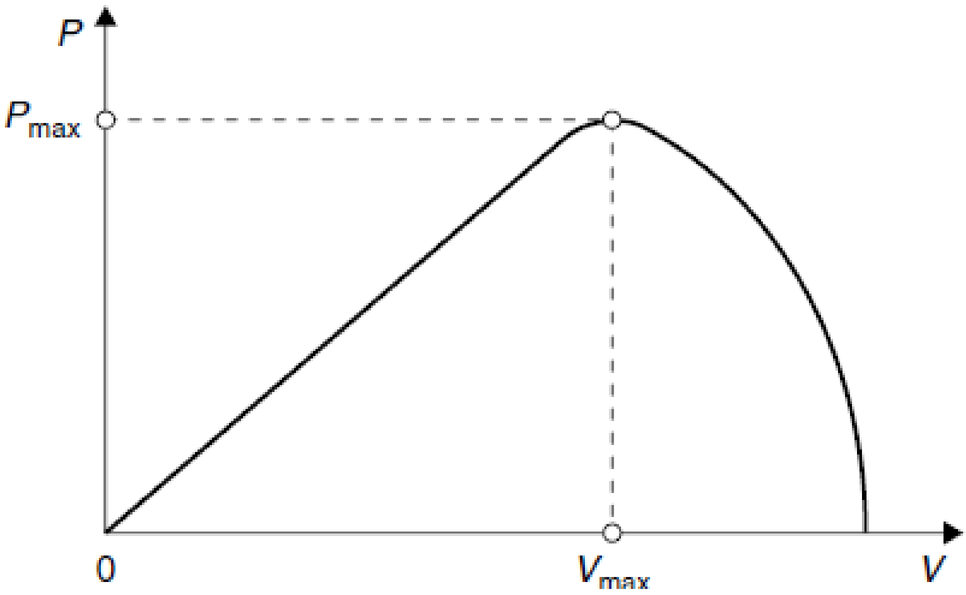

Figure 4. Representative power-voltage curve for photovoltaic cells.

The maximum power passes from a maximum power point (point *C* on Figure 3), at which point the load resistance is optimum, R_{opt}, and the power dissipated in the resistive load is maximum and given by

$$P_{max} = I_{max} V_{max} \quad \textbf{(Eq. 7)}$$

Point *C* on Figure 3 is also called the *maximum power point*, which is the operating point P_{max}, I_{max}, V_{max} at which the output power is maximized. Given P_{max}, an additional parameter, called the *fill factor*, FF, can be calculated such that

$$P_{max} = I_{sc} V_{oc} \mathrm{FF} \quad \textbf{(Eq. 8)}$$

Or

$$\mathrm{FF} = \frac{P_{max}}{I_{sc} V_{oc}} = \frac{I_{max} V_{max}}{I_{sc} V_{oc}} \quad \textbf{(Eq. 9)}$$

The fill factor is a measure of the real *I-V* characteristic. For good cells, its value is greater than 0.7. The fill factor decreases as the cell temperature increases.

Thus, by illuminating and loading a PV cell so that the voltage equals the PV cell's *V*max, the output power is maximized. The cell can be loaded using resistive loads, electronic loads, or batteries. Typical parameters of a single-crystal solar cell are current density I_{sc} = 32 mA/cm^2, V_{oc} = 0.58 V, V_{max} = 0.47 V, FF = 0.72, and P_{max} = 2273 mW.

Other fundamental parameters that can be obtained from Figure 3 are the short-circuit current and the open circuit voltage. The short-circuit current, I_{sc}, is the higher value of the current generated by the cell and is obtained under short-circuit conditions, i.e., $V = 0$, and is equal to I_{ph}. The open circuit voltage corresponds to the voltage drop across the diode when it is traversed by the photocurrent, I_{ph}, which is equal to I_D, when the generated current is $I = 0$.

Efficiency is another measure of PV cells that is sometimes reported. *Efficiency* is defined as the maximum electrical power output divided by the incident light power. Another parameter of interest is the maximum efficiency, which is the ratio between the maximum power and the incident light power, given by

$$\eta_{max} = \frac{P_{max}}{P_{in}} = \frac{I_{max} V_{max}}{A G_t} \quad \textbf{(Eq. 10)}$$

where A = cell area (m^2).

References:

Sotaris A. Kalogirou, Solar Energy Engineering – Processes and Systems, Second Edition, Academic Press, 2013.

Zekai Şen, Solar Energy Fundamentals and Modelling Techniques, First Edition, Springer, 2008