

Study of the operating temperature of a PV module

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Abstract

Solar photovoltaic (PV) systems generate electric power by absorbing electromagnetic energy. They have an efficiency of about 10-15%, and are heated by the remainder of energy. These heat losses increase with higher incoming irradiance. The issue of the phenomenon is that the module temperature directly influences the module's performances as the electric output power and the efficiency goes down as the module temperature rises. By studying the encapsulation scheme and the thermal modeling of a PV module, the heat transfer processes in the system can be understood and to know which parameters make the module temperature vary. Finally, as the expression of the temperature is difficult to establish, a simplified formula has been used in order to calculate the performances of a given module under different environmental conditions.

Key words: PV modules, heat transfer, heat losses, operating temperature, NOCT.

Introduction

Solar PV systems are power-generating devices that use a renewable source, the sunlight, to generate electricity. This process occurs owing to the cell material's properties: PV modules are made of silicon wafers which generate electricity

under sunlight. However, most of the time, heat is released as well. The aim of this report is to understand the influence of temperature on a PV module performances and the influence of environmental factors on the operating temperature. Hence, the report consists in two main parts. In the first part, general points about PV cells physics will be discussed in order to get a clear picture of the energy generation process and of significant properties of PV cells. The second part will focus on the thermal modeling of a PV module and on the influence of external parameters on the operating temperature.

Solar PV physics

Solar PV systems are power-generating devices that convert electromagnetic energy into electricity. This physical phenomenon is due to the cell's material properties. The main component of a PV cell is silicon, which is a semiconductor: it is an insulator at low temperature and a conductor when heat energy is available, in other words, when there is light.

A semiconductor such as silicon consists in three main areas: the valence band where electron e^- are bounded to the atoms, the band gap which is a forbidden space, and the conduction band where electrons are moving as negative carriers and participate in electricity generation. For a valence electron to get to the conduction band there should be sufficient energy provided so that the electron can jump over the band gap,

leaving a hole h^+ in the valence band. Hence, if the absorbed photon's energy is equal or superior to the band gap energy E_g , which is 1.1 eV or $1.7622 \cdot 10^{-19}$ J for silicon, the electron will get to the conduction band with a release of heat in the last case, as shown on Figure 1. The energy carried by a photon is expressed as $E = h\nu$ or $E = \frac{hc}{\lambda}$. Thus, long wavelengths might not provide enough energy while the absorption of short wavelengths may generate heat.

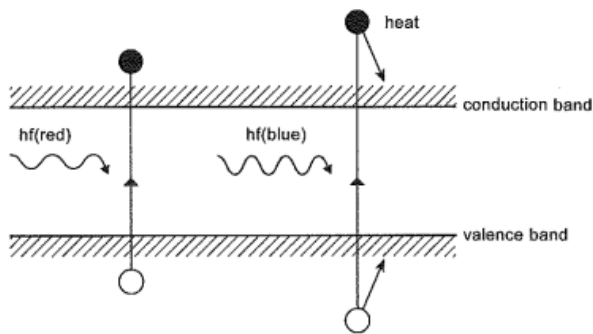


Figure 1. Schematic of a semiconductor

The performance of a PV cell is defined by the IV-curve, which shows the how the current inside the cell varies as a function of the voltage for a given solar irradiance. The current is proportional to the incident solar irradiance. In addition, a cell has two limiting parameters: the short circuit current obtained when $V = 0$, and the open circuit voltage obtained when $I = 0$. The output power of a cell can be calculated as $P_{out} = VI$. The maximum power delivered by the cell is $P_{mp} = V_{mp} \cdot I_{mp}$. The efficiency is defined as: $\eta = \frac{P_{out}}{P_{in}} = \frac{I_{mp} \cdot V_{mp}}{G \cdot A}$. When the temperature rises, I_{sc} increases slightly while V_{oc} drops as it is shown on Figure 2.

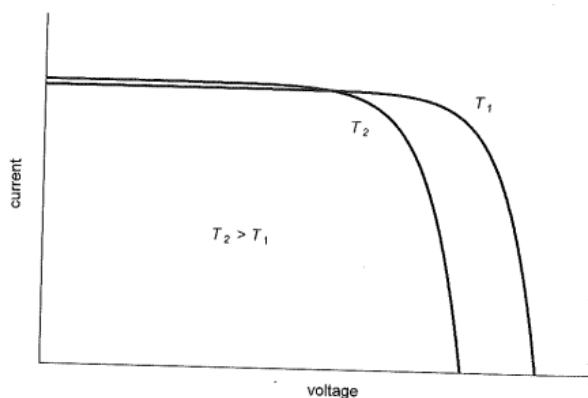


Figure 2. IV-curves for two different temperatures

For silicon materials, one has: $\frac{dV_{oc}}{dT} \cong -2 \text{ mV}/^\circ\text{C}$.

One can conclude that the temperature is an important issue for a solar module operation as it reduces significantly the electrical efficiency, increases thermal stress and degradation rates.

The operating temperature

A PV module might be used in a variety of climates, and so is expected to withstand harsh environmental conditions such as dust, salt, sand, wind and snow. A module is physically protected by the encapsulation structure, which needs to be carefully studied to provide a long life-time (usually between 15 and 20 years). Indeed, the encapsulants should have a high heat conduction coefficient so that conduction can cool the cells. It is also important that the top cover has a good resistance and a high transmission in the waveband 350-1200 nm. At typical encapsulation scheme is shown on Figure 3, where EVA stands for ethylene vinyl acetate.

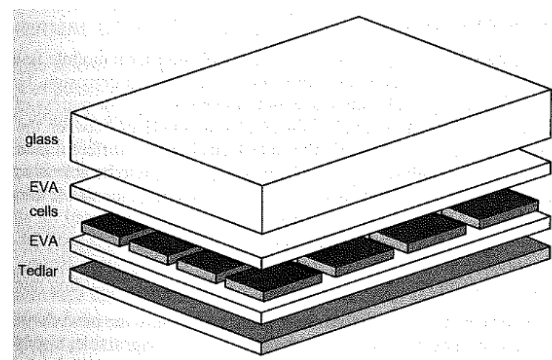


Figure 3. A typical laminated module structure

PV modules that are currently available on the market have an efficiency ranging between 10% and 15%. It means that between 10% and 15% of the incident irradiance is converted into electricity, and the remainder is converted into thermal energy that heats the cells. These heat losses cannot be estimated as they depend on the material's band gap and on the weather, i.e. the solar irradiance. However, a fraction of the sunlight is reflected on the front cover of the cell: it doesn't contribute to either the electrical power generation or the heating of the cells. Consequently, when trying to estimate the heat losses, one can consider that the incoming

irradiance which is not converted into electricity is $(1-\eta)G$, knowing that G is the solar irradiance. Hence, one assumes the following expression to calculate the heat losses: $G_h = (1-\eta)G - (\rho+\alpha)G$, where ρ and α are respectively the reflectance and the absorbance of the front cover of the cell. For common glass, $\rho = 0.04$ and $\alpha = 0.05$.

When studying the cell temperature, one needs to look at the thermal modeling of an encapsulated PV module. In Figure 4, a 5-layer module is considered with the same encapsulants as in Figure 3. The heat transfer processes involved are conduction and convection. In order to simplify the problem, heat transfers by radiation are neglected. Hence, the equations modeling heat transfer in the PV cell are:

$$G_h - q_{cell-glass} - q_{cell-Tedlar} = 0 \quad (1)$$

$$G_{abs} + q_{cell-glass} - q_{glass-air} = 0 \quad (2)$$

$$q_{cell-Tedlar} - q_{Tedlar-air} = 0 \quad (3)$$

Equation (1) states that heat generated into the cell is conducted through the encapsulants. The developed form of (1) is:

$$\begin{aligned} & (1 - \eta - (\rho + \alpha))G \\ &= -\frac{T_{cell} - T_{glass}}{\left(\frac{\rho_{glass}}{\rho_{glass}} + \frac{\rho_{EVA}}{\rho_{EVA}}\right)} - \frac{T_{Tedlar} - T_{cell}}{\left(\frac{\rho_{EVA}}{\rho_{EVA}} + \frac{\rho_{Tedlar}}{\rho_{Tedlar}}\right)} \\ &= -\frac{T_{cell} - T_{glass}}{R_{front}} - \frac{T_{Tedlar} - T_{cell}}{R_{back}} \end{aligned}$$

Hence,

$$T_{cell} = \frac{\left[\frac{T_{glass}}{R_{front}} - \frac{T_{Tedlar}}{R_{back}} - (1 - \eta - (\rho + \alpha))G\right]}{\frac{1}{R_{front}} - \frac{1}{R_{back}}}$$

T_{cell} is the variable to be evaluated but T_{glass} and T_{Tedlar} are not known.

Equation (2) states that the heat absorbed from the incident sunlight and heat conducted from the cell is released by natural convection with air. When developed, it becomes:

$$\begin{aligned} \alpha G - \frac{T_{cell} - T_{glass}}{\left(\frac{\rho_{glass}}{\rho_{glass}} + \frac{\rho_{EVA}}{\rho_{EVA}}\right)} &= h_{v_{wind}}(T_{glass} - T_{air}) \\ &= h_{v_{wind}}\Delta T_{glass} \end{aligned}$$

The convective coefficient is complicated to evaluate directly. It is generally determined experimentally for specific conditions. Besides, it depends on the temperature difference and so it would require to make an assumption on the difference value in order to get an expression of T_{glass} as a function of T_{cell} .

Similarly, one gets for equation (3):

$$\begin{aligned} -\frac{T_{Tedlar} - T_{cell}}{\left(\frac{\rho_{EVA}}{\rho_{EVA}} + \frac{\rho_{Tedlar}}{\rho_{Tedlar}}\right)} &= h_{v_{wind}}(T_{Tedlar} - T_{air}) \\ &= h_{v_{wind}}\Delta T_{Tedlar} \end{aligned}$$

It is noticeable that one cannot get an explicit expression of the cell temperature by looking at the heat balances. It would have been interesting to know how much the heat convection participate in the cell cooling and which operating temperature a module can reach under extremes conditions.

However, it is known that the cell temperature increases as the solar irradiance gets higher. But the incoming sunlight is not the only parameter that influences the cell temperature. The ambient air and the wind speed are to be taken into account as well as the solar irradiance. In order to determine a pV module operating temperature, there is an approximate expression given in [1]:

$$T_{cell}(^{\circ}C) = T_{air} + \frac{NOCT - 20}{800} * G$$

where T_{air} is in $^{\circ}C$, G in W/m^2 and NOCT stands for *nominal operating cell temperature*. It is defined as the temperature of a cell at *standard reference environment* (SRE), i.e. for an ambient temperature of $20^{\circ}C$, an irradiance of $800 W/m^2$, a wind speed of $1 m/s$ and an open rear surface mounting (the module is tilted at 45°). The best PV module operates at $NOCT = 33^{\circ}C$, the worst at $58^{\circ}C$ and a typical module at $48^{\circ}C$. Thus, the temperature of a typical module would be calculated as following:

$$T_{cell}(^{\circ}C) = T_{air} + 0.035 * G$$

If one wants to evaluate the cell temperature as a function of the wind speed, then one can use the following expression which applies for typical modules:

$$T_{cell}(^{\circ}C) = T_{air} + \frac{0.32}{8.91 + 2 * v_{wind}} * G$$

Then two different climatic conditions can be compared. In Sweden, let's consider a solar irradiance of 1000 W/m² during spring time in Sweden, with a wind speed of 9 m/s and an air temperature at 25°C. At 1m/s, $T_{cell} = 60^{\circ}C$, and at 9m/s, $T_{cell} = 25^{\circ}C$. If one makes a comparison with South Africa, by assuming an irradiance of 2550 W/m² and an air temperature of 30°C, one gets 119.29°C at 1m/s, and 60.32°C so almost twice less. Those values reveal that the wind speed is highly involved in the cooling of the module, and this natural process can be helpful under "extreme" weather conditions, in comparison to those in Sweden.

Conclusion

As a conclusion, three heat transfer processes occur in a PV module: conduction of the heat losses through the encapsulants, heat convection at the module front and back surfaces and radiation to the surroundings. PV modules have a good conversion coefficient as long as they operate at not too high temperatures. The rise of the module temperature is due to the heat released when photons carrying too much energy are absorbed. Thus, when estimating a PV module temperature, one should consider solar irradiance and wind speed. However an explicit expression of the module temperature has not been found, one can assume that it increases as the solar irradiance increases and decreases when the wind speed gets higher. Besides, the electricity output can be significantly enhanced in warmer countries with an appropriate cooling system, with air or even water. Another way to handle the heat issue is to consider hybrid photovoltaic/thermal (PVT) systems that combine the properties of both technologies in order to heat water in a house for instance.

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