

Chapter 2

Physical Limitations of Photovoltaic Conversion

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ABSTRACT

This chapter presents the factors that are included in the expression of the conversion efficiency of a solar cell. These factors are upper limited, and that is why the conversion efficiency could not exceed certain critical values. The chapter analyzes thermodynamic limitations, correction introduced by the atmosphere, Shockley-Queisser limitations (based on the detailed energy balance), as well as additional limitations. Then it discusses ways to improve the conversion efficiency and future research directions.

THERMODYNAMIC LIMITATIONS

One factor limiting the conversion efficiency is the thermodynamic efficiency. A solar cell converts the sun's thermal radiation into electricity. Therefore, thermodynamic laws may restrict the efficiency to lower values of Carnot efficiency:

$$\eta_T^{(c)} = 1 - \frac{T_c}{T_s} \quad (1)$$

where T_s is the sun's temperature and T_c is the cell's temperature. The sun is usually considered as a blackbody with temperature of 6000 K and the solar cell is considered to be in thermal equilibrium with the environmental temperature, so

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that $\eta_T^{(C)} = 95\%$. In reality, the sun is composed of plasma, so its behavior is closer to the thermal one of a metal, resulting in $T_s \approx 5800$ K. On the other hand, the solar cell is warmer than the environment (due to processes that are occurring in it), so that we can take $T_c \approx 320$ K and the yield falls to 94.5%. However, such a value is very high.

A closer analysis of the thermodynamic efficiency must take into account the thermal radiation laws. If we use the blackbody model, both for the Sun, and for the cell, and consider the cell in thermal equilibrium with the environment, we obtain the Landsberg yield (Markvart & Castañer, 2003; Landsberg & Badescu, 1998):

$$\eta_T^{(L)} = 1 - \frac{4}{3} \frac{T_c}{T_s} + \frac{1}{3} \left(\frac{T_c}{T_s} \right)^4 \quad (2)$$

A more precise calculation requires the cell's temperature evaluation when the Sun and the environment are in a thermodynamic equilibrium. Considering the heat exchange between the Sun and solar cell using the blackbody's laws, and the one between the environment and the cell corresponding to thermal contact, Müser obtained the heat balance equation, $4T_c^5 - 3T_a T_c^4 - T_a T_s^4 = 0$:

$$\eta_T^{(M)} = \left[1 - \left(\frac{T_c}{T_s} \right)^4 \right] \left[1 - \frac{T_a}{T_c} \right] \quad (3)$$

and the yield value of 85.6% (Markvart & Castañer, 2003; Badescu & Landsberg, 1998). The heat radiation corrections of metals reduce this value down to about 85.2%.

A particular problem which will be discussed again in the next paragraph refers to the Earth's atmosphere selective absorption. This moves the solar spectrum, giving the appearance of lower temperatures (the blackbody model, this apparent temperature is 5767 K), leading to $\eta_T^{(C)} = 94,8\%$,

$\eta_T^{(L)} = 93,1\%$, $\eta_T^{(M)} = 85,4\%$ (the metal heat radiation corrections reduce these values by about 0.4%).

When it comes to space applications, the situation changes. Here the environmental temperature is almost 0 K, and the cell losses appear only by thermal radiation. Even if we consider the cell isothermal and the circuit open, the cell temperature is:

$$T_c = \left(\frac{\Omega}{2\pi} \right)^{1/4} T_s = \sqrt{\frac{R_s}{\sqrt{2} D_{SP}}} T_s = 331 \text{ K} \quad (4)$$

($\Omega = 6,8 \cdot 10^{-5}$ Sr is the solid angle under the Sun is seen from Earth, $R_s = 696 \cdot 10^3$ km is the Sun's radius and $D_{SP} = 149,6 \cdot 10^6$ km is the Sun – Earth distance), so that the previously calculated yield decreases by about 0.1%. A more accurate calculation leads to a decrease of 0.2%. It can be seen that these corrections are insignificant.

CORRECTIONS INTRODUCED BY THE ATMOSPHERE

The Sun's spectrum is not exactly that of a blackbody (or metal). The solar photosphere and chromosphere introduce absorption lines (Fraunhofer lines), modifying the energy distribution. The Earth's atmosphere introduces more corrections, because of its much lower temperature, the existence of molecules (absorption bands instead of lines), the refractive index induced by the air currents oscillations, the water vapours and the thermal fluctuations, and the diffusion produced by dust and other matter (Fahrenbrunch, Bube, 1983; Smestad, 2002).

It is estimated that in ideal conditions (clean air, normal incidence), the solar spectrum in space (denoted AM 0 - 0 atmospheric mass), with full radiance of 1365 W/m^2 , is reduced to 70% of its full radiance (taking into account absorption

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