What is the highest photovoltaic conversion efficiency ?

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Much research is currently under way with the aim of increasing the conversion efficiency beyond the Shockley-Queisser single junction limit but the maximum attainable efficiency that can be achieved remains the subject of research. Most frequently discussed are the efficiencies obtained by converting each spectral component with optimum efficiency (the so-called infinite tandem, see [1]) and the maximum efficiency determined by Landsberg [2] (see also [3,4]). We shall show that these two efficiency limits are intimately related and, if viewed on a rigorous footing, both provide a glimpse of a different aspect of the conversion process. When combined, a new efficiency is limit is obtained which is some 8.4% lower than the Landsberg efficiency, and about 1.6% lower than the infinite tandem efficiency obtained by deVos [1]. The new efficiency limit, in effect, represents a description of the conversion process taking place under constant pressure rather than constant volume which has been assumed in the theoretical treatments up till now.

The Landsberg efficiency [2 - 4] has been obtained by various arguments differing in the degree of rigour exercised in the derivation and, perhaps most importantly, in the interpretation. We shall consider Landsberg efficiency in terms of the maximum quantity of work W that can be extracted by cooling a volume V of black-body radiation with internal energy $U(T_S)$, entropy $S(T_S)$and pressure $p(T_S)$, from temperature T_S of solar radiation which will be here taken as 6000K, to the ambient temperature $T_o \cong 300$K. It is shown in standard texts (see, for example, [5]) that the maximum work W is equal to the availability (or exergy) of the radiation, and given by

$$W = U(T_S) - T_o S(T_S) + Vp(T_o) \tag{1}$$

Expression (1) can be summarised in a nutshell as the work that can be carried out in a reversible iso-entropic processes which cools the photon gas from T_S to T_o , bearing in mind that the ambient radiation exerts counter pressure $p(T_o)$ and work done against it does not contribute to the useful work. Equation (1) can be evaluated by standard methods [5], giving the usual result

$$\eta_L = W / U(T_s) = 1 - \tfrac{4}{3}\left(T_0/T_s\right) + \tfrac{1}{3}\left(T_0/T_s\right)^4 = \left(1 - T_0/T_s\right) - \tfrac{1}{3}\left(1 - \left(T_0/T_s\right)^3\right) \tag{2}$$

Note that, unlike the Carnot efficiency, the Landsberg efficiency is defined in terms of the internal energy rather than the heat absorbed by the engine.

One can take a different route and write Eq. (1) using the spectral components u_ν, s_ν and $p_\nu(T)$ of the internal energy, entropy and pressure to show that the maximum work (2) is equal to

$$W = \int N_\nu(T_s)\, w_\nu \, d\nu \tag{3}$$

where the spectral availability w_ν is given by

$$w_\nu = u_\nu - T_o s_\nu + p_\nu(T_o) v_\nu \tag{4}$$

where $N_\nu(T_s)$ is the number of photons and v_ν is the volume per photon at frequency. Equation (4) gives an expression for the exergy (maximum work) that can be carried out, using a classical heat engine, by a photon of monochromatic radiation at frequency ν.

One can readily translate these results to a photovoltaic device. Clearly, the spectral availability w_ν (4) divided by the elementary charge gives the maximum open circuit voltage that can be produced by a solar cell with bandgap $h\nu$ that absorbs only in a narrow near-monochromatic spectral range. The current of such a cell is easily determined in terms of the photon flux ϕ_ν and furnishing the appropriate fill factor we easily find the maximum power and thus the efficiency.

These results can be compared with the infinite tandem efficiency given by deVos [1]. The deVos result determines the open circuit voltage using Carnot efficiency, in effect including only the first term in the second expression for the Landsberg efficiency (2). It include the reduction in work due to the ambient counter pressure that makes up the full availability. This correction is not large but reduces the maximum attainable photovoltaic efficiency of the infinite tandem from 86.5% to 84.9%. This should be compared to the full Landsberg efficiency of 93.3% but which does not take into account the entropy generation due to kinetic nature of the conversion process.

References

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