

The proof of the theorem is rather simple and is brought in here because it uses relationships of instrumental value. It is straightforward to see that

$$\dot{n}_x = \dot{n}_{\text{rad}}; \quad \dot{e}_x = \varepsilon \dot{n}_x = \dot{e}_{\text{rad}}; \quad \dot{\omega}_x/T_a = \dot{\omega}_{\text{rad}}/T_{\text{rad}}; \quad \dot{e}_{\text{rad}} - T \dot{s}_{\text{rad}} = \mu_x \dot{n}_x + \dot{\omega}_x \quad (4.46)$$

where, again, the suffix *rad* labels the thermodynamic variables of the original radiation.

The equality of the energy and the number of photons of the original and equivalent radiation proves that the power production is unchanged. Furthermore, the last relationship can be introduced in equation (4.44) to prove that the calculation of the entropy production rate also remains unchanged.

Taking all this into account, the application of equation (4.44) to the SQ solar cell is rather simple. Using the SQ cell model for the power and using the room-temperature equivalent radiation (of chemical potential  $\mu_s$ ) of the solar radiation, we obtain

$$\begin{aligned} T_a \dot{S}_{\text{irr}} &= - \int_{\varepsilon_g}^{\infty} qV [\dot{n}(T_a, \mu_s) - \dot{n}(T_a, qV)] d\varepsilon + \int_{\varepsilon_g}^{\infty} [\mu_s \dot{n}(T_a, \mu_s) + \dot{\omega}(T_a, \mu_s)] d\varepsilon \\ &\quad - \int_{\varepsilon_g}^{\infty} [qV \dot{n}(T_a, qV) + \dot{\omega}(T_a, qV)] d\varepsilon \\ &= \int_{\varepsilon_g}^{\infty} [\dot{\omega}(T_a, \mu_s) - \dot{\omega}(T_a, qV)] d\varepsilon + \int_{\varepsilon_g}^{\infty} [(\mu_s - qV) \dot{n}(T_a, \mu_s)] d\varepsilon \end{aligned} \quad (4.47)$$

The integrand is zero for  $qV = \mu_s$ , but as  $\mu_s$  varies with  $\varepsilon$  it is not zero simultaneously for all  $\varepsilon$ . To prove that it is positive, we differentiate with respect to  $qV$ . Using  $d\dot{\omega}/d\mu = -\dot{n}$ ,

$$\frac{d(T_a \dot{S}_{\text{irr}})}{dqV} = - \int_{\varepsilon_g}^{\infty} [\dot{n}(T_a, \mu_s) - \dot{n}(T_a, qV)] d\varepsilon = I/q \quad (4.48)$$

Thus, for each energy, the minimum of the integrand also appears for  $qV = \mu_s(\varepsilon)$ . Since this minimum is zero, the integrand is non-negative for any  $\varepsilon$  and so is the integral, proving also the thermodynamic consistence of this cell from the integral perspective. Furthermore, the minimum of the entropy, which for the non-monochromatic cell is not zero, occurs for open-circuit conditions. However, the ideal monochromatic cell reaches zero entropy production, and therefore reversible operation, under open-circuit conditions, and this is why this cell may reach the Carnot efficiency, as discussed in a preceding section.

## 4.4 THE TECHNICAL EFFICIENCY LIMIT FOR SOLAR CONVERTERS

We have seen that with the technical definition of efficiency – in whose denominator the radiation returned to the sun is not considered – the Carnot efficiency cannot be reached with a PV converter. What then is the technical efficiency upper limit for solar converters?

We can consider that this limit would be achieved if we could build a converter producing zero entropy [33]. In this case, the power that this converter can produce,