Box 3.1 Efficiency of photosynthesis

What is the efficiency of photosynthetic energy conversion? The answer depends on exactly what type of efficiency is meant. If it is quantum efficiency at low to moderate light intensities, then the answer is nearly 100%, as nearly every photon absorbed drives photochemistry. If it is the fraction of solar energy striking the Earth that is converted into biomass, then the number is only 0.2% (Hall and Rao, 1999). Perhaps the most informative calculation concerns the percentage of the energy absorbed by a photosynthetic organism operating under ideal conditions that is stored as carbohydrate and oxygen.

To make this calculation, it is necessary to know both the energy stored as chemical energy and the energy input as photon energy. To calculate the first quantity, we use Eq. A20 and the free energies of formation tabulated in Table A1. The balanced chemical equation of photosynthesis must be used. Here we will write this equation in terms of the production of one O_2 molecule, as that is how measurements of quantum requirement are traditionally reported.

$$H_2O + CO_2 \rightarrow \frac{1}{6}(\text{glucose}) + O_2 \qquad \text{(B1)}$$

So the standard state free energy stored is:

$$\Delta G^0 = \frac{1}{6}\Delta G_f^0(\text{glucose}) + \Delta G_f^0(O_2) - \Delta G_f^0(H_2O) - \Delta G_f^0(CO_2) \qquad \text{(B2)}$$

$$\Delta G^0 = \frac{1}{6}(-914.54) + (0) - (-237.19) - (-394.38) \qquad \text{(B3)}$$

$$\Delta G^0 = +479.1 \text{ kJ mol}^{-1} \qquad \text{(B4)}$$

This must be compared with the energy input from light. Warburg measured quantum requirements for O_2 production as low as 3. The energy content of the light energy can be calculated from a slightly modified version of Eq. A3:

$$E = (QR)\frac{hc}{\lambda}N_A \qquad \text{(B5)}$$

where QR is the quantum requirement and N_A is Avogadro's number, 6.022×10^{23} mol^{-1}. We need to multiply by Avogadro's number because the thermodynamic calculation is made for a mole of molecules, whereas Eq. A3 applies to a single photon of light, taken for this calculation to be at 680 nm. Substituting the values of the parameters, we obtain an energy input of 528.5 kJ mol^{-1}. The efficiency is therefore $(479.1/528.5) \times 100$, or approximately 91%.

The consensus modern values for the quantum requirement of oxygenic photosynthesis are 9–10. We will use 10 for our calculation, which gives an energy input of 1761.4 kJ mol^{-1}, which results in an efficiency of energy storage of 27%.

While the value of 27% may seem low, we can obtain a perspective by comparing it with energy conversion efficiencies of semiconductor solar cells, which rarely exceed 10%. Indeed, the 27% represents a maximum efficiency of absorbed monochromatic light under ideal conditions. When the efficiency that might be expected under field conditions is calculated using the full incident solar spectrum, and various losses are included, the estimated efficiency drops to about 5% (Bolton and Hall, 1979).