the optimum. This also means there is no need to carry out expensive civil works to level the site of PV arrays, despite it being an extended custom in large PV plants.

The case of stand-alone systems designed to feed equipment having a constant consumption throughout the year is an especially interesting one, and deserves particular mention. The design criterion here is to maximise the energy captured during the period of least radiation, rather than throughout the year. As might be expected, such receivers are positioned perpendicular to the winter sunlight, which leads to recommend a tilt angle $\beta \approx \phi + 10^\circ$.

20.9.2 Sun-tracking Surfaces

At the moment, tracking mechanisms are little used in photovoltaics, but in the future they are likely to become much more common, mainly associated with relatively big grid-connected PV plants, where these mechanisms have already demonstrated very high reliability. As a particular example, the 100 kWp tracking system at the Toledo-PV plant [39] is in routine operation with 100% of availability from 1994 (about 66 000 h when writing this chapter).

Tracking about two axes maintains the receiver surface always perpendicular to the sun ($\beta = \theta_{ZS}$; $\alpha = \psi_S$). Hence, it allows collecting the maximum amount of energy possible. Mainly depending on the clearness index, the comparison with an optimally tilted fixed surface leads to the ratio $G_{dy}(2\text{ axes})/G_{dy}(\beta_{opt})$ varying from 1.25 to 1.55 (column 4 divided by column 8 of Table 20.5). However, it is expensive to implement, because it uses relatively complicated mechanisms and takes up a great deal of space, due to the shadows cast. For these reasons, several types of one-axis trackers are usually preferred.

Azimuthal one-axis trackers rotate around their vertical axis, in such a way that the azimuth of the receiver PV surface is always the same as that of the sun's azimuth. Meanwhile, the tilt angle keeps constant ($\beta = \beta_{cons}$ and $\alpha = \psi_S$). The incidence angle is given by the difference between the surface's tilt angle and the solar zenith angle ($\theta_S = \theta_{ZS} - \beta_{cons}$). Obviously, the amount of collected radiation depends on the inclination of the surface, being the maximum for a value close to the latitude. Again, the sensitivity of the annual capture of energy to this inclination angle is relatively low. A typical value of approximately 0.4% loss from each degree of deviation from the optimum inclination can be assumed. Note that an azimuthal tracker tilted to the latitude collects up to 95% of the yearly irradiation corresponding to the case of two-axes tracking (column 5 divided by column 4 of Table 20.5).

One-axis trackers turning around a single axis–oriented N–S and tilted at an angle β_{NS} to the horizontal are also of great interest. It can be seen that, in order to minimise the solar incident angle, the rotation angle of the axis, $\psi_{NS} - 0$ at noon – must be

$$\tan \psi_{NS} = \frac{\sin \omega}{\cos \omega \cos \beta_\Delta - [\mathrm{sign}(\phi)] \tan \delta \sin \beta_\Delta} \tag{20.54}$$

where $\beta_\Delta = \beta_{NS} - abs(\phi)$. The corresponding solar incident angle is given by

$$\cos \theta_S = \cos \psi_{NS}(\cos \delta \cos \omega \cos \beta_\Delta - [\mathrm{sign}(\phi)] \sin \delta \sin \beta_\Delta) + \sin \psi_{NS} \cos \delta \sin \omega \tag{20.55}$$