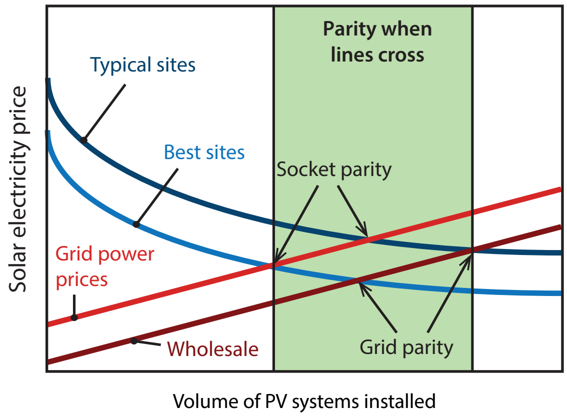

Figure 21.3: Grid and socket parity for PV systems (Adapted with kind permission from P. R. Wolfe [178]).

able technologies such as wind and hydro electricity. Wind and hydro electricity installations usually only can be financed by companies but are no option for a single consumer. In contrast, PV can be scaled down to the level of a single module, such that a house owner can become an electricity producer with his small scalable PV installation on his roof. The residential electricity price often also includes grid maintenance fees as well as taxes. The point, at which the LCoE of a PV system is equal to the price the consumer pays for electricity from the grid is called *socket parity* [179].

Distinguishing between grid parity and socket parity is useful in order to avoid confusion with the cost of energy production. Since residential costs are always higher than production costs, an area will reach socket parity before reaching grid parity, as illustrated in Fig. 21.3. The graph is showing the volume of installed PV systems versus the price of PV electricity. The installed volume can be directly correlated with time, as the past decade has seen the implemented PV volume rise tremendously. As capital costs decline with increasing volumes, the price of PV generated electricity is expected to decrease in the future. On the other hand, the price of fossil fuels is expected to rise because of increasing scarcity and cost linked to the right to emit CO_2 emissions into the atmosphere. These trends will lead to increasing prices for electricity generated with combusting fossil fuels.

To conclude, grid parity and socket parity are very useful concept to indicate the feasibility of a renewable energy technology. The closer a technology is to grid parity, the easier it can be integrated in the electricity mix. With the advancements in technology and the maturity of manufacturing processes, grid parity for solar is expected to be reached at many locations around the World in the next years.

21.2 PV system ecology

Besides discussing the economics of PV systems, it also is very important to consider their ecological and environmental aspects. The main reason for that is that the aim of photovoltaics is to generate electricity without any considerable effect on the environment. It is therefore very important to check the ecological aspects of the different PV technologies. In this section we will discuss different concepts to quantify the environmental impact of PV systems.

21.2.1 Carbon footprint

The concept of the *carbon footprint* estimates the CO_2 emissions caused by manufacturing PV modules and compares them with the reduction of CO_2 emissions due to the electricity generated with PV instead of combusting fossile fuels. A more analytical approach is to look at the total energy required to produce either the PV modules or all the components of a PV system. As the production processes vary considerably for the different PV technologies, the energy consumption for producing 1 kW_p varies considerably between the different technologies. If a complete *life cycle assessment* (LCA) is performed, it is tried to trace the energy and carbon footprints of the PV panels throughout their lifetime. Therefore LCA also is known as *cradle-to-grave analysis*.

21.2.2 Energy yield ratio

We now are going to introduce several indicators that are used to judge the different ecological aspects. The *Energy Yield Ratio* is defined as the ratio of the total energy yield of a PV module or system throughout its lifetime with all the energy that has to be invested in the PV system in that time. This invested energy not only contains the energy for producing the components, transporting them to the location and installing them but also the energy that is required to recycle the different components at the end of their lifecycle.

As the energy required for producing a PV system depends strongly on the PV technology and also on the quality of the panels, the energy yield ratio for the different technologies varies a lot. While the energy yield ratio for PV modules can be as large as 10 to 15, PV systems usually have a lower ratio because of the energy invested in the components other than the modules.

21.2.3 Energy payback time

A very important concept is the *Energy Payback Time*, which is defined as the total required energy investment over the lifetime divided by the average annual energy yield of the system,

$$\text{Energy Payback Time} = \frac{\text{totally invested energy}}{\text{average annual energy yield}}. \tag{21.4}$$

Note that the energy payback time is different from the economic payback time introduced in Section 21.1.

The energy payback time of typical PV systems is between 1 and 7 years and it also depends on location issues such as the orientation of the PV array as well as the solar irradiance throughout the year.

Figure 21.4 shows the specific primary energy required for producing PV modules with different technologies, where the term *specific* refers to the energy required per kW_p of produced modules. As we can see, the differences between the technologies are large. The

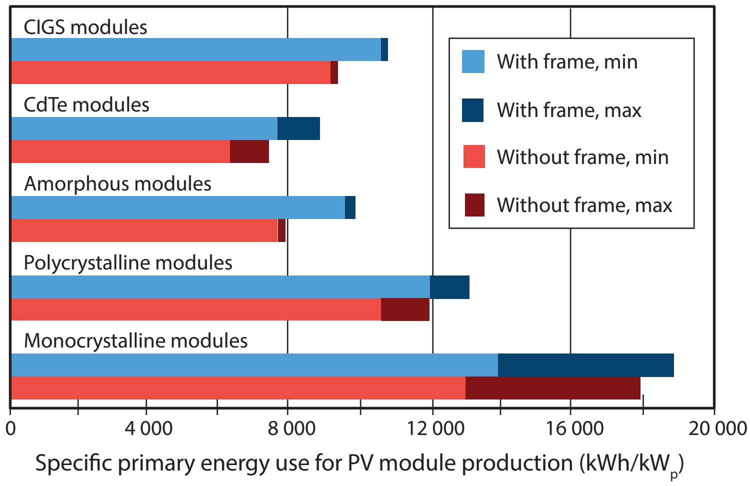

Figure 21.4: Specific primary energy used to produce PV modules of different technologies (Data from [180]).

specific energy required for producing thin-film modules from materials such as amorphous silicon, cadmium telluride and CIGS is significantly below that of modules made from polycrystalline and monocrystalline silicon, where the specific energy can reach values up to 12000-18000 kWh/kW$_p$. Because of further improvements in the module efficiency and the manufacturing process we however may expect that that the specific energy follows a decreasing trend.

For a PV system it is more difficult to allocate the energy that was used for its production, as all the components constituting the balance of system have to be taken into account. For example, for components like batteries and inverters the technologies and manufacturing processes may vary a lot between the different products available on the market. Nonetheless, studies were carried out that estimated the energy required by whole PV systems. Generally, as we can see in Fig. 21.5 the energy required for the BOS is significantly below that used for manufacturing the modules. In the figure, amorphous and crystalline silicon modules are compared. As expected, we see that the energy payback time in regions with high solar irradiance have significantly shorter energy payback times than regions with low irradiance. While a-Si:H based modules have a shorter energy payback time than c-Si based modules, the energy payback time for the module frame and the BOS of a-Si:H based systems can be significantly higher than that of c-Si based systems. This can be explained with the lower efficiency of a-Si:H that increases the required framing material per W$_p$.

The irradiance strongly influences the energy payback time and varies between two years (high irradiance) and six years (low irradiance). Roof-mounted systems always have a shorter energy payback time than systems mounted on the ground, mainly because of the BOS that is more energy extensive for ground-mounted systems.

No matter which PV technology is chosen, the energy payback time always is far below the expected system lifetime, which usually is between 25 and 30 years. For the PV systems discussed in Fig. 21.5, the energy yield ratio is between 4 and 10. Hence, the energy

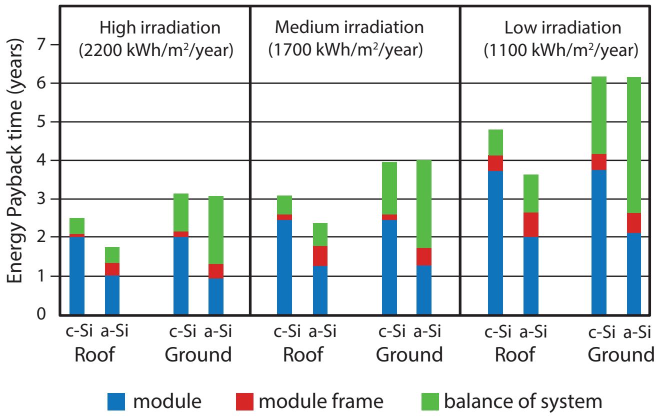

Figure 21.5: The energy payback time for the different components constituting PV systems (adapted with kind permission from E. Alsema) [181].

invested in the PV system is paid back several times throughout the life cycle of the PV system. The urban legend that PV modules require more energy to be produced than they will ever produced thus is not backed by any data. In contrast, the net energy produced is much larger than the energy required for PV production.

However, a lot of work still needs to be done and can be done. Some studies indicate that the energy required for producing PV modules can be reduced by up to 80%. Further, as the amount of installed PV systems becomes larger and larger, recycling of the components at the end of the lifecycle becomes very important. For example, the European Union introduced already several directives that induced recycling schemes for c-Si based PV modules.

21.2.4 Pollution

The last environmental issue that we want to mention is pollution caused by the production of PV modules. As many sometimes toxic chemicals are required for producing PV modules, this can be a serious threat to the environment. Therefore it is very important to have strong legislation in order to prevent pollution of the surroundings of PV factories. Especially in countries with weak environmental legislation pollution can be a severe problem that affects the environment and people living in the surroundings negatively.

21.3 Exercises

21.1 Table 21.1 shows the total area, sun hours per day and energy consumption of five different countries.

(a) If a PV system of 270 W_p is installed in each of these locations, in which country would be best to place the panels to obtain the maximum output?