Solutions to Chapter 11:

Hint: In the next exercises only estimations are done. There are different ways to the solution therefore the presented solutions are to be considered only as example solutions. However, the alternative solutions should yield similar results.

Exercise 11.1: Potential Estimation for Pitched Roofs

a) From Figure 2.7: The Saarland is situated around Saarbrücken in South-West Germany:

$$H' \approx \underline{1075 \frac{\text{kWh}}{\text{m}^2 \cdot \text{a}}}$$

Theoretical potential: $W_{\text{Theo}} = A \cdot H' = 2750\ \text{km}^2 \cdot 1075 \frac{\text{kWh}}{\text{m}^2 \cdot \text{a}} = 2.956 \cdot 10^{12} \frac{\text{kWh}}{\text{a}} \approx \underline{3 \cdot 10^{12} \text{kWh/a}}$

b) Roof surfaces: $A_{\text{Pitch}} \approx 0.3\,\% \cdot 2750\ \text{km}^2 = \underline{7.71\ \text{km}^2}$

Optical energy on pitched surface (incl. inclination losses of 15 %, see Table 11.1):

$$W_{\text{Optical\_Pitch}} \approx 1200 \frac{\text{kWh}}{\text{m}^2 \cdot \text{a}} \cdot 0.85 \cdot \frac{H'}{H} \cdot A_{\text{Pitch}} \approx 1200 \frac{\text{kWh}}{\text{m}^2 \cdot \text{a}} \cdot 0.85 \cdot \frac{1075}{1000} \cdot 7.71\ \text{km}^2 \approx \underline{8.45\ \text{TWh/a}}$$

c) Power: $P_{\text{STC}} = A_{\text{Pitch}} \cdot E_{\text{STC}} \cdot \eta_{\text{Module}} = 7.71\ \text{km}^2 \cdot 1000 \frac{\text{W}}{\text{m}^2} \cdot 0.2 = \underline{1.54\ \text{GWp}}$

Electrical energy: $W_{\text{Elec\_Pitch}} = W_{\text{Optical\_Pitch}} \cdot \eta_{\text{System}} = 8.45 \cdot 10^9 \frac{\text{kWh}}{\text{a}} \cdot 0.18 = \underline{1.52\ \text{TWh/a}}$

Exercise 11.2: Potential Estimation for Free Areas

a) From Figure 2.7: The Saarland (around Saarbrücken) has a latitude of about 49 °,

Smallest noonday solar altitude in winter with Equation (2.6):

$$\gamma_{S\_Min} = 66.6\,° - \varphi = 66.6\,° - 49\,° = \underline{17.6\,°}$$

Area utilization factor with Equations (10.4) and (10.5):

$$f_{Util} = \frac{b}{d_{Min}} = \frac{\sin(\gamma_S)}{\sin(\gamma_S + \beta)} = \frac{\sin(17.6\,°)}{\sin(17.6\,° + 20\,°)} = 49.6\ \% \approx \underline{50\ \%}$$

b) Module area: $A_{Module} = f_{Util} \cdot A_{Free\_Area} = 0.5 \cdot 10\,000\ \text{m}^2 = \underline{5000\ \text{m}^2}$

PV-Power: $P_{STC} = A_{Module} \cdot E_{STC} \cdot \eta_{Module} = 5000\ \text{m}^2 \cdot 1000\ \frac{\text{W}}{\text{m}^2} \cdot 0.2 = \underline{1\ \text{MWp}}$

Electrical energy with Equation (11.3): $W_{Electrical\_PV} = A_{Module} \cdot f_{Util} \cdot \eta_{Module} \cdot E_{STC} \cdot \frac{H'}{H} \cdot Y_F$

$$\Rightarrow W_{Electrical\_PV} = 10\,000\ \text{m}^2 \cdot 0.5 \cdot 0.2 \cdot 1000\ \frac{\text{W}}{\text{m}^2} \cdot \frac{1075}{1000} \cdot 900\ \frac{\text{kWh}}{\text{kWp} \cdot \text{a}} = \underline{967\,500\ \text{kWh/a}}$$

Alternative way of solution:

Electrical Energy: $W_{Electrical} = W_{Optical} \cdot \eta_{System}$

$$\Rightarrow W_{Electrical} = 1200\ \frac{\text{kWh}}{\text{m}^2 \cdot \text{a}} \cdot \frac{H'}{H} \cdot A_{Module} \cdot \eta_{System} \approx 1200\ \frac{\text{kWh}}{\text{m}^2 \cdot \text{a}} \cdot \frac{1075}{1000} \cdot 5000\ \text{m}^2 \cdot 0.18 \approx \underline{1.2\ \text{Mio. kWh/a}}$$

c) According to Section 10.1.4 energy corn yields an electrical energy of about 17 000 kWh/a.
Thus, photovoltaics on the same area yields about the 57- to 70-fold of electrical energy!

Exercise 11.3: Market and Price Development

a) The learning rate is the percentage by which the costs of a product are reduced, when the cumulated production of the product has doubled.

b) The grid parity denotes the point in time at which the electric energy from a PV plant is cheaper than the normal price of the electricity for the end user.

Exercise 11.4: Nowadays Electricity Supply System

a) “Control energy” denotes the energy that has to be provided to balance unforeseen short time differences between electricity offer and electricity demand.

b) Once the grid frequency deviates more than ±0,01 Hz from the standard frequency 50 Hz, the control power has to be provided. This has to be fully established within 30 seconds and then has to be maintained for at least 15 minutes.

c) The respective power plants withhold some percentage of their generation power free as reserve.

d) PV and wind power have a good compensation potential. At sunshine, mostly only a weak wind will blow and vice versa. Also seasonally, they compensate each other well: In winter term, wind energy dominates, in summer term solar energy.

Exercise 11.5: Future Energy Supply

a) It is assumed that in future more applications like electric vehicles or heat provision (Power-to-Heat) will lead to a higher electricity demand.

b) The German Federal Ministry of the Environment (FME) assumes that the electric vehicle batteries existing in 2050 will provide about 180 GWh as external electricity storage capacity. For an assumed mean load of the electricity grid of 70 GW a maximum time of 180 GWh / 70 GW = 2.6 h can be calculated.

c) The Power-to-Gas-Technology facilitates a seasonal storage for electricity, as the produced “renewable methane” can be stored in natural gas storages. The efficiency from electricity over methane to electricity again lies between 30 and 38 %. Ideally, the heat produced by the conversion processes should also be used.