Exercise Series 1

Exercise 1: Irradiation & solar spectrum

a) What is the difference between AM1.5G and AM1.5D?

b) What does m indicate in the expression AMm? What is AM0?

c) How does AM0 differ from the idealized black body spectrum at 5800 K (Sun's surface temperature)? How does AM1.5G differ from AM0?

d) Calculate the area (A) of the sun's surface that is required to obtain 1 GW (i.e. the power delivered by a large nuclear power plant) of emitted radiation? Use the Stefan-Boltzmann law, $P_{\mathrm{em}} = A\,\sigma\,T_{\mathrm{sun}}^4$. Assume a surface temperature of $T_{\mathrm{sun}} = 5800\,\mathrm{K}$ and $\sigma = 5.67 \cdot 10^{-8}$ $\mathrm{W\,m^{-2}\,K^{-4}}$.

e) Suppose that the integrated radiation power density impinging on the earth's surface is $P = 1000\,\mathrm{W\,m^{-2}}$, and that 100 % of this power is absorbed. Calculate the total power absorbed by Earth. Earth's radius $R = 6370\,\mathrm{km}$.

f) In order to establish thermal equilibrium with the sun, the power absorbed by the earth must be equal to the power emitted by the earth in all spatial directions. Using the total power from the result of part e), calculate the earth's surface temperature using Stefan-Boltzmann's law suitable also for the radiation leaving the earth. Why does this calculation yield a temperature well below the mean earth surface temperature of 288 K?

Exercise 2: Temperature effect, STC & NOCT

Consider a PV array operating under standard test condition (STC, i.e. AM1.5G normalized to $1000\,\mathrm{W\,m^{-2}}$, ambient temperature (T_a) 25 °C). In these conditions, a cell without any encapsulation would receive an input power of $1000\,\mathrm{W\,m^{-2}}$ and operate at a temperature of 25 °C. However, when considering a PV array operating in the field, the cells are encapsulated in glass and polymers to protect them from external atmosphere (we call this entire system a "module"). Due to this encapsulation, cells generally operate at higher temperatures than the standard 25 °C, depending on the illumination they receive. To calculate the cells output power in these conditions, it is important to establish a new standard for cell temperature estimation in the module, called NOCT (Nominal Operating Cell Temperature), defined as the temperature reached by open circuited (OC) cells in a module under the conditions: irradiance on cell surface = $800\,\mathrm{W\,m^{-2}}$, air temperature = 20°C, wind velocity = 1 m/s, mounting = open back side. A module's nominal operating cell temperature (NOCT) is around 47 °C.
We consider here an incident power density P_in of $0.9\,\mathrm{kW\,m^{-2}}$.

a) Knowing that there is a 3 % array loss due to mismatched modules, dirt loss of 4 %, module power conversion efficiency (PCE) of 18 %, and the efficiency of the inverter is 95 %, calculate the output power (i.e. after the inverter) for $1\,\mathrm{m^2}$ of modules at 25 °C. This power is the module output power with "AC" losses only, without taking into account the higher cell temperature, that we will call P_AC.

b) Using the graphs plotted Fig. 1 which follow the Ross law: $T_\mathrm{cell} - T_\mathrm{air} = \mathrm{m} \cdot P_\mathrm{in}$ (with $T_\mathrm{air} = T_\mathrm{a}$ here), estimate the cell temperature in the module, with $T_\mathrm{a} = 22$ °C.

c) Knowing that the output power at the maximum power point (MPP) drops by 0.5 %/°C for cells temperatures above the STC temperature, estimate the real outpout power P_out of the module for $T_\mathrm{a} = 22$ °C. What happens if T_a 40 °C?

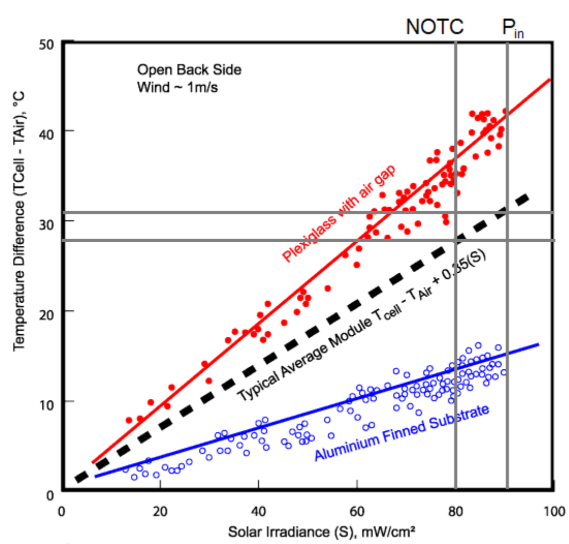

Figure 1: Temperature increases, above ambient levels, with increasing solar irradiance for different module types. [2]

Exercise 3: Key figure in Switzerland & the world

Assumptions: In Switzerland a solar panel of 1 W_p produces every year 1 kW h (i.e. 2 W_p produce 2 kW h). In North Africa a panel of 1 W_p produces 2.4 kW h every year (4.8 kW h for a 2 W_p panel).

- The world's annual energy consumption is 1.4×10^5 TW h
- Switzerland's annual energy consumption is 250 TW h
- The world's annual electricity consumption is 1.6×10^4 TW h
- Switzerland's annual electricity consumption is 58.8 TW h

a) The Sahara's surface is approximately 9 000 000 km^2. How much of this surface would have to be covered by solar arrays, that measure 1 m^2 and produce *(1)* 100 W_p (10 % efficiency) or *(2)* 200 W_p (20 % efficiency), to cover the world need in electricity, in energy?

b) Calculate the total energy impinging on the earth's surface from the sun each day. Assume a power density of 1000 W m^{-2} and 24 h of illumination. Compare this figure with the world's annual energy and electricity needs.

c) How many m^2 of solar arrays with modules of 1 m^2 and *(1)* 100 W_p (10 % efficiency) or *(2)* 200 W_p 20 % efficiency) each do we need in Switzerland to replace the Gösgen nuclear power plant that has an annual power output of 8000 GW h?

d) Hydro power plants cover 55 % of the annual electricity needs and 11 % of the annual energy needs in Switzerland. If you subtract this amount from the total annual consumption (electricity and energy, given above), how many % of Switzerland's surface area would you have to be covered with solar panels, measuring 1 m^2 each and an output power of *(1)* 100 W_p (10 % efficiency) or 200 W_p 20 % efficiency), in order to cover the remaining amount of electricity and energy (Switzerland's surface area: 41 285 km^2)? Do you think there are enough spots in Switzerland where these panels could be installed?

e) Assuming you mount a 1 m^2 module of 200 W_p (a temperature coefficient of 0 %/°C) on a tracker, and install it at the equator in a sunny plain (no shadows). How many kW h annual electricity per m^2 can you expect? *(1)* If the tracker perfectly follows the sun? *(2)* This corresponds to how many litres of oil (diesel generator has an efficiency of 25 % and 1 L = 10 kW h thermal)? *(3)* If the module remains still?