EXERCISE 3:

Concentrating Solar Power (CSP), Tower Plant

Technical characteristics

The PS20 plant located near Seville, Spain, went into operation in April 2009. It has 20 MWe of power generating capacity. It consists of a solar field of 1255 mirrored heliostats of 120 m^2 area each. Each heliostat reflects solar radiation onto the receiver on the 162 m high tower. The receiver converts 92% of received sunlight into steam, generating electricity through a steam turbine. The receiver in the solar tower is designed to deliver 55 MW_{therm}. The plant is designed to generate 50 GWh_{el} / yr**.**

Questions:

- With a latitude of 37° and an atmosphere albedo of 30%, compute the annual direct irradiance at the plant site.

Using the formulas of the course, we can reproduce the case for Sevilla to estimate global annual irradation.

With

$$1 + 0.033\cos\left[2\pi\left(\frac{D}{365}\right)\right] = \left(\frac{\bar{r}}{r}\right)^2$$

we compute the distance $r_{\text{Earth-Sun}}$ for all days D = 1 to 365 of the year.

With

$$\delta = 23.45\left(\frac{\pi}{180}\right)\sin\left[2\pi\left(\frac{(284+D)}{365}\right)\right]$$

we compute the declination δ for all days D = 1 to 365 of the year.

From δ we can then also obtain sinδ and tanδ for all days D of the year.

From the latitude ϕ = 37° (0.646 radians) we obtain sinϕ and tanϕ.

With

$$H_{D/2} = \arccos(-\tan\delta\tan\phi)$$

and the constant tanϕ and variable tanδ over the year, we can obtain the solar hour angle (and therefore the duration of sunshine) for any day D = 1 to 365 of the year.

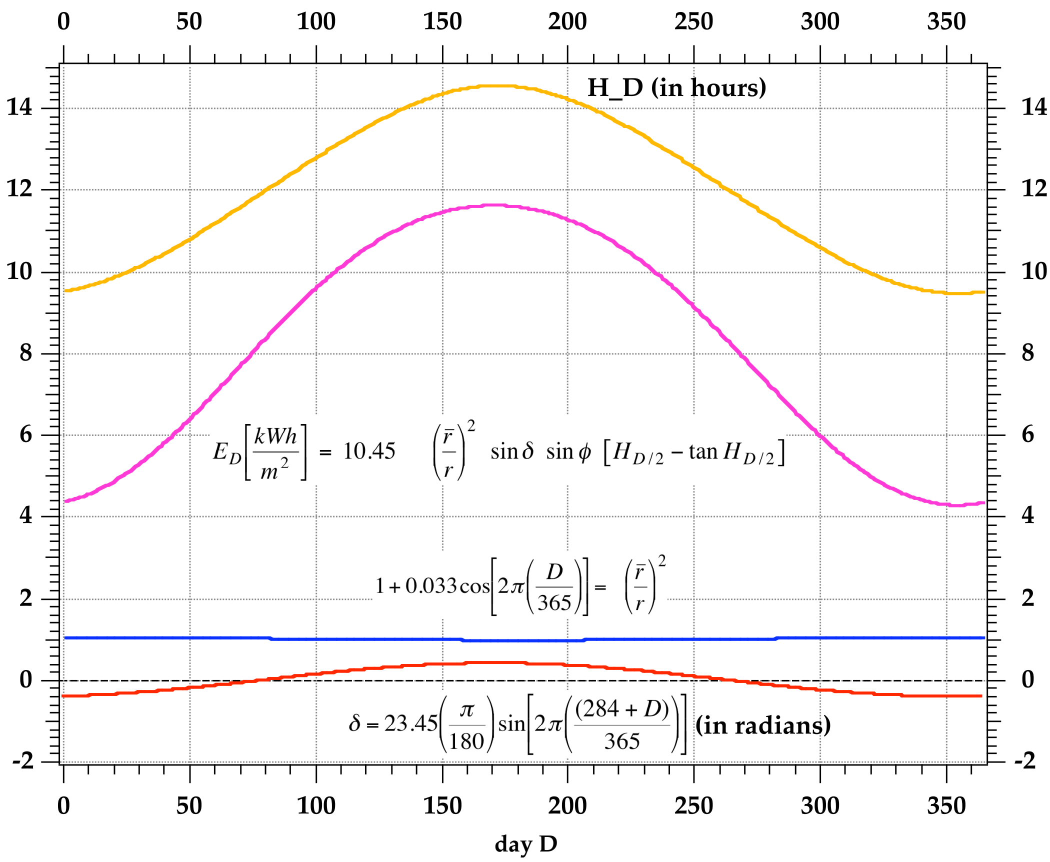
Finally, with

$$E_D\left[\frac{kWh}{m^2}\right] = 10.45 \quad \left(\frac{\bar{r}}{r}\right)^2 \quad \sin\delta \ \sin\phi \ \left[H_{D/2} - \tan H_{D/2}\right]$$

and the computed values for ϕ (constant for Sevilla), and r, δ and $H_{D/2}$ (varying over the year every day from D = 1 to 365), we can compute the solar irradiance input in kWh per square meter of horizontal plane for every day in the year.

We can implement this calculation simply in excel or a matlab script and sum over all D from 1 to 365. Plots of the different values over the year are given below.

We obtain for the annual irradiance, which is global and extraterrestrial, E_{tot} = 2971 kWh/m^2.



We now correct this value for the Earth albedo (reflection lost to outer space, -30%), which gives the GLOBAL irradiance potentially arriving to the ground in Sevilla.

We thus obtain 2971 kWh/m^2 x 0.7 = 2080 kWh/m^2 per year.

- Calculate the efficiencies: (a) of the thermal cycle; (b) of the heliostats field; (c) global (plant).

(a) of the thermal cycle, or pcu (power conversion unit):

This is easily obtained from the 20 MW electric power generated from 55 MW thermal power arriving at the receiver.

η_{pcu} = 20/55 = 36.4 %

(b) of the heliostats field:

This includes all losses of shading, blocking, cosine, attenuation and spillage, as seen in the course. In addition, the receiver thermal efficiency is given as 92%.

Total area of collectors : 120 m^2 x 1255 = 150'600 m^2
Total radiation input in the heliostat field : 150'600 m^2 x 2080 $kWh/m^2.yr$ = 313'208'656 kWh/yr = 313.2 GWh/yr.

Annual load : power generated (50 GWhe) dived by constant net power of the cycle (20 MW_{el}) = 2500h
(28.5 %).

The receiver is designed to deliver 55 MW_{therm}. Multiplied with the 2500 operating hours, this totals 55 MW x 2500h = 137'500 MWh = 137.5 GWh_{therm}.

The receiver thermal efficiency is 92%, hence it received from the heliostat field 137.5 GWh / 0.92 = 149.46 GWh_{therm}.

Finally, the heliostat field efficiency is then the ratio of 149.46 GWh delivered to the receiver and 313.2 GWh primary radiation input, or 149.46/313.2 = 47.7%

(c) plant efficiency :

heliostat field thermal efficiency x receiver thermal efficiency x pcu thermal-to-electrical efficiency = 0.477 x 0.92 x 0.3636 = 16%

- Compute the X-Y extension in the figure, assuming that the 1255 heliostats are roughly regularly distributed in a circle ($\Rightarrow$ X $\approx$ Y) tangent to the receiver tower. The land use for each heliostat is equal 5 times its mirror area.

Total heliostat area = 150'600 m^2

Total land use = 5 x 150'600 = 753'000 m^2

Approximating this with a circle, 753'000 m^2 = $\pi.R^2$, we easily obtain for R = 490 m, hence X = Y = 1 km.

We can deduce from this a solar electric power generation "density", i.e. 20 MW_{el} for 753'000 m^2, or 26.6 W_{el}/m^2, and more importantly, a yearly energy density, i.e. 50 GWh_{el} for 753'000 m^2 of occupied land, or 66.4 $kWh_{el}/m^2.yr$

In other words, even for an area fully occupied with a solar power plant, its 'primary' efficiency with respect to the extraterrestrial solar energy input (2971 $kWh/m^2.yr$) and 'effective' efficiency with respect to really available solar energy at the location of interest (2080 $kWh/m^2.yr$) is

66.4 / 2971 = 2.2%

66.4 / 2080 = 3.2%