CBE/CUSP 9413 Sustainable Energy Systems - Fall 2025
Homework 1

Solar energy – 100 points

HW due end of day September 22nd, 2025

Note: this homework will require use of codes posted on the class github repository related to solar energy data extraction and PV modeling - https://github.com/dharik13/CBE9413-Energy-Systems/tree/main

1. PV system operation (30 points)

As we discussed in class, the performance of photovoltaic (PV) systems depends strongly on location, design choices (e.g., tilt, azimuth, inverter loading ratio (ILR)) and dynamic weather conditions. Here, we will quantitatively understand these factors by comparing PV performance in two different locations: a) MA (Boston, 42.3°N, 71.1°W), b) AZ (Phoenix, 33.4°N, 112.1°W)

This problem will require to work with the PVlib python package. Please refer to PVlib installation guide and available material online to setup the package. You will also find the example code "*PV_hourly_output_modeling.py*" helpful in solving this problem.

Consider a 100 MW DC PV system installed at each of the two locations, assuming 2022 weather and the following design specifications:

- Fixed-tilt orientation at latitude tilt, facing south
- Inverter loading ratio (ILR) = 1.2.
- Unless specified otherwise, you can use all other PV system parameters to the default values provided in the example code *"PV_hourly_output_modeling.py"*.

Question:

i. Estimate the annual AC electricity generation (MWh/year) at the two locations for the above assumptions
ii. For the fixed tilt system, vary the following parameters to identify the parameters which yields the maximum annual AC generation at each location.
    - ILR variation from 1.0 to 1.5
    - Tilt angle from 0° (flat) to latitude +15°
    - Azimuth –30° east of south to +30° west of south

What did you learn from comparing the results from the two locations?

2. PV system operation - Effect of geographic smoothing (20 points)

One way of dealing with intermittency in PV generation is to take advantage of variation in solar availability across locations.

Suppose you plan to install a 100 MW DC PV system in the Pacific Time Zone and have identified four potential sites

- Blythe - 33.668 ºN, 114.756 ºW

- Las Vegas - 36.4489 °N , 114.7617 °W
- Reno - 40.7199 °N, 117.0628 °W
- Fresno - 36.5852 °N, 120.3792 °W

Calculate the annual average capacity factor from the 100 MW DC system

i. Installing the entire 100 MW DC system at each individual location.

ii. Installing 25 MW DC at each of the four locations.

For each system, sort the hourly capacity factor time series in descending order and plot the resulting sorted time series and calculate the coefficient of variation (CoV) for the hourly capacity factor for the two systems.

Based on the calculated CoV and the plot, what can you say about the variability in hourly power generation from the two systems?

For your calculations, assume PV system configuration specified in Problem 1, part i

3. CSP vs. PV plant performance (30 points)

In class, we calculated the fraction of heat recovered at the absorber from a concentrated solar thermal system with concentration factor C and absorber temperature (T_a) as follows:

$$f_{heat} = \left(1 - \frac{\sigma T_a^4}{C \frac{F_S^{es}\sigma}{\pi} T_{sun}^4}\right)$$

We can use a variant of this expression to model a realistic system by modifying the above expression as follows:

- model incident solar radiation with time-varying direct normal incidence (DNI_t)
- incorporate losses during radiation emissions (ϵ_{loss}) and absorption (α_{loss})
- account for losses associated with concentrators (η_{field})

The revised expression for the fraction of incident solar energy recovered as heat at the absorber is given:

$$f_{heat} = \left(\alpha_{loss}\eta_{field} - \frac{\epsilon_{loss}\sigma T_a^4}{CDNI_t}\right)$$

Compare the annual average solar-to-electricity efficiency and the annual electricity generation for the 2022 weather year for both a concentrated solar thermal power plant and a photovoltaic (PV) plant at two different locations.

i. Ivanpah, CA (35.552 °N, 115.459 °W)

ii. Boston, MA (42.3555 °N, 71.0565 °W)

Make the following assumptions for modeling solar thermal and PV plants:

Solar thermal plant:

- T_a = 600 °C , C= 500, η_{field} = 0.6, heat to power conversion efficiency (η_{th}) = 35%
- Assume plant is generating power only during the hours when the solar radiation collected by the receiver > absorber re-radiation losses

- 1 m^2 solar collection area (i.e. area of mirrors concentrating sunlight on to absorber)
- Emissivity (ϵ_{loss}) = 0.88
- Absorptivity (α_{loss}) = 0.95

Solar PV:

- Sun to electricity efficiency = 20%
- 1 m^2 area for solar cells

iii. What solar concentration ratio is needed for the solar thermal plant at each location to produce the same amount of annual electricity as the PV plant?

Note: this problem will require to work download solar insolation data from the National Solar Radiation Database (NSRDB). You will also find the example code "*insolation_calculation_onesite.py*" helpful in solving this problem.

3. Solar photovoltaic system efficiency (20 points)

A silicon solar cell (single-junction) has area A = 6.0 cm^2. Under AM1.5-like illumination the incident photon flux (integrated over two spectral bands) is:

- 400–600 nm: $\Phi_1 = 1.80\times10^{17}$ photons s^{-1} cm^{-2} and quantum efficiency (QE) = 0.90
- 600–800 nm: $\Phi_2 = 1.00\times10^{17}$ photons s^{-1} cm^{-2} and quantum efficiency (QE) = 0.70

Assume:

- Cell operating temperature T = 27 ^oC
- Diode saturation current density $J_0 = 1.0\times10^{-12}$ A cm^{-2}
- Ignore parasitic resistances in the cell

Tasks:

i. Compute the short-circuit current density J_{sc} (A/cm^2) and short-circuit current I_{sc} (A).
ii. Compute V_{oc} for the cell.
iii. Estimate the voltage corresponding to the maximum power density point for the cell and estimate the maximum power density
iv. Estimate the fill factor for the solar cell
v. Estimate the cell's solar to electricity efficiency based on the incident solar power η = P_max / P_in. (make and state any assumption you need for this step)