Homework 1 Submission – CBE 9413 Intro to Sustainable Energy Systems

Submitted by: Kaushal Kaloo (N15105320)

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Disclaimer: I have collaborated with Anu Deshmukh and Harsh Gandhi on Q1& 2 of this homework. Gemini was used to modify the existing Github code to solve questions 1 – 3.

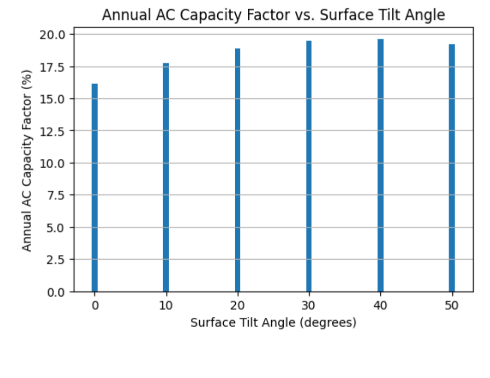
Problem 1

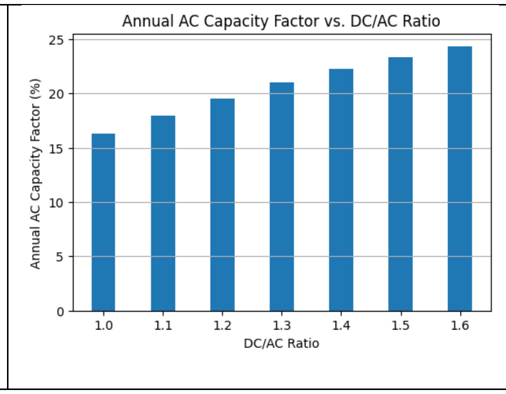
1. We need to model PV performance at the following two sites:
   a) MA (Boston, 42.3°N, 71.1°W, Time Zone: America/ New York)
   b) AZ (Phoenix, 33.4°N, 112.1°W, Time Zone: America/ Phoenix)
2. We will modify the code provided in Course Github to define the following functions:

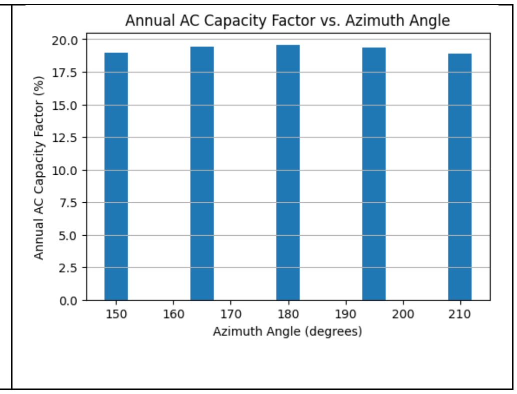
```
def download_nsrdb_data(lat, lon, tz)
def pvsizing(lat, lon, tz, PlantCapacityDC, surface_tilt, azimuth_angle, dc_ac_ratio)
```

These functions will give us flexibility of obtaining PV plant performance by varying location and module specific parameters while keeping other parameters constant.

3. The annual AC electricity generation from 100 MW DC solar PV plant at the above two sites using assumptions provided in Q1 are:
   3.1. Boston, MA – 142643 MWh/ year (AC CUF: 19.5%)
   3.2. Phoenix, AZ – 180979 MWh/ year (AC CUF: 24.8%)
4. The performance in solar PV is consistent with what we learnt in lecture: **locations near the equator (lower latitude) receive higher solar irradiance in general**.
5. Next, we will vary the module/ plant parameters to see their effect on annual AC CUF. The following figures capture the variation in AC CUF for Boston, MA.
   5.1. CUF improves with increasing surface tilt angle and **peaks near latitude angle** (we discussed this behavior in the lecture for fixed tilt systems)
   5.2. AC CUF **improves with higher inverter loading ratio** (however, from economics point of view optimal ILR should be 1.2-1.3 (this is beyond scope of the current exercise)).
   5.3. CUF improves with azimuth angle and **peaks when panel is facing south** (angle = 180°) for fixed tilt systems). This is true for systems located in the northern hemisphere as it will receive maximum solar irradiance in this direction (converse is true for systems in southern hemisphere).







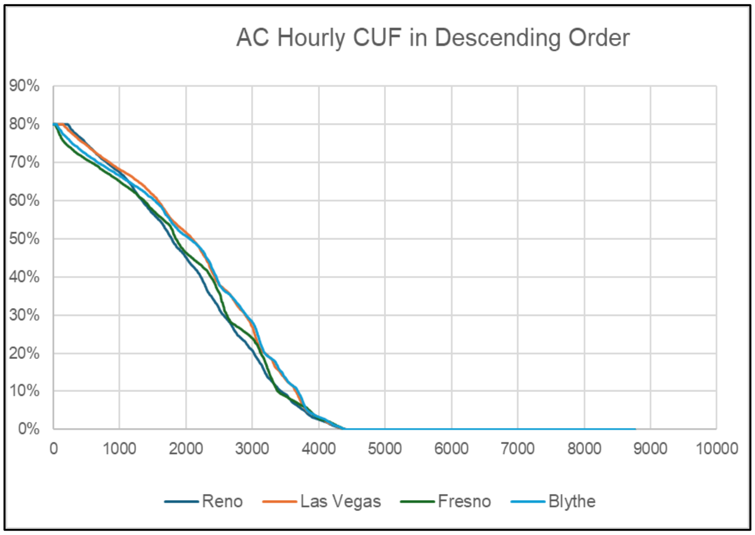
6. We can use `scipy.optimize` to find out optimal parameters for PV system performance in both locations by maximizing annual AC CUF as the objective function subject to given bounds.

Boston, MA	**Phoenix, AZ**
1) Optimal Surface Tilt: 34.6°	1) Optimal Surface Tilt: 30.80°
2) Optimal Azimuth Angle: 182°	2) Optimal Azimuth Angle: 185°
3) Optimal DC/AC Ratio: 1.50	3) Optimal DC/AC Ratio: 1.50
4) Maximum Annual AC CUF: 23.5%	4) Maximum Annual AC CUF: 29.7%

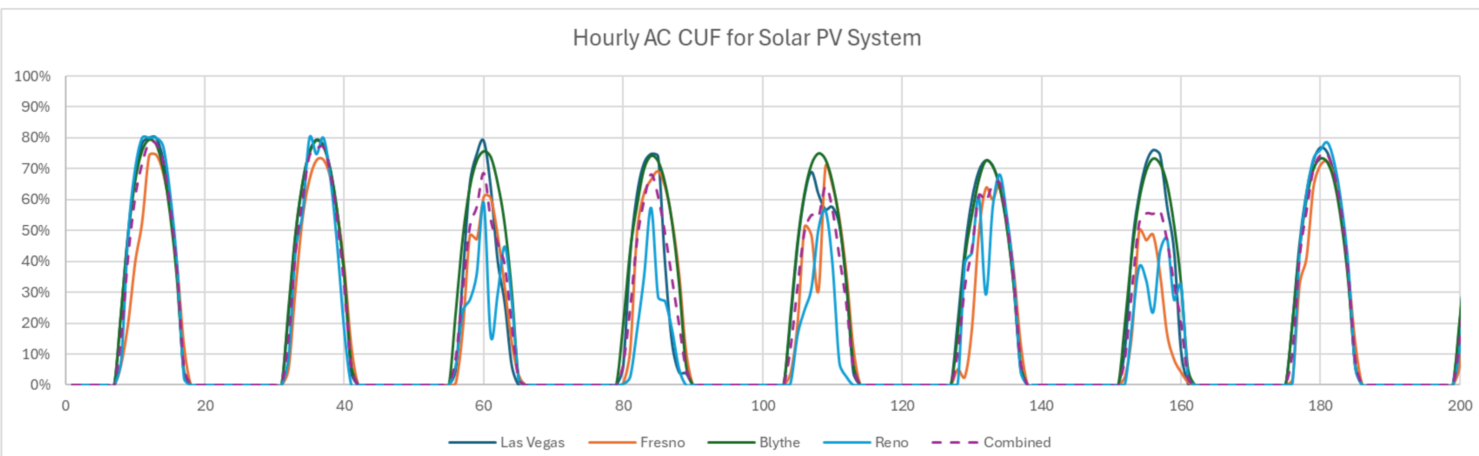
7. The results of optimization confirm our intuition from above graphs and demonstrate how PV system performance is optimized. However, higher ILR (upper bound) may not be economically optimal.

Problem 2

1. The annual avg. AC CUF for independent 100 MW DC PV plant at each location is as follows:
   1.1. Reno – 19.8%, Las Vegas – 21.5%, Fresno – 20.0%, Blythe – 21.2%
2. For a combined system of 25 MW DC PV plant at each location, we can estimate the annual avg. AC CUF as a weighted average. It turns out to be **20.6%.**
3. The plot of hourly AC CUF time series sorted in descending order looks as follows for all 4 locations:



4. To better understand the variability of hourly AC CUF, we can plot daily variation in CUF.



5. We can observe that there is greater intermittency in solar CUF at Reno and Fresno, however **for the combined solar PV plant the CUF is improved** (because of higher CUF at other two locations for same hours) but the output is strongly correlated because of geographical proximity.
6. The calculation of CoV for both systems further confirms this: the **CoV is marginally better for a combination of 4 solar PV locations**.
7. However, coupling standalone solar PV systems with wind/ other non-solar sources of RE can smoothen intermittency to a greater extent.

SN	Location	Standalone PV				Combined
		Reno	Las Vegas	Fresno	Blythe	
1	**Mean**	19.8%	21.5%	20.0%	21.2%	20.6%
2	**SD**	0.275	0.284	0.269	0.278	0.269
3	**CoV (SD/Mean)**	1.385	1.320	1.348	1.307	1.304

Problem 3

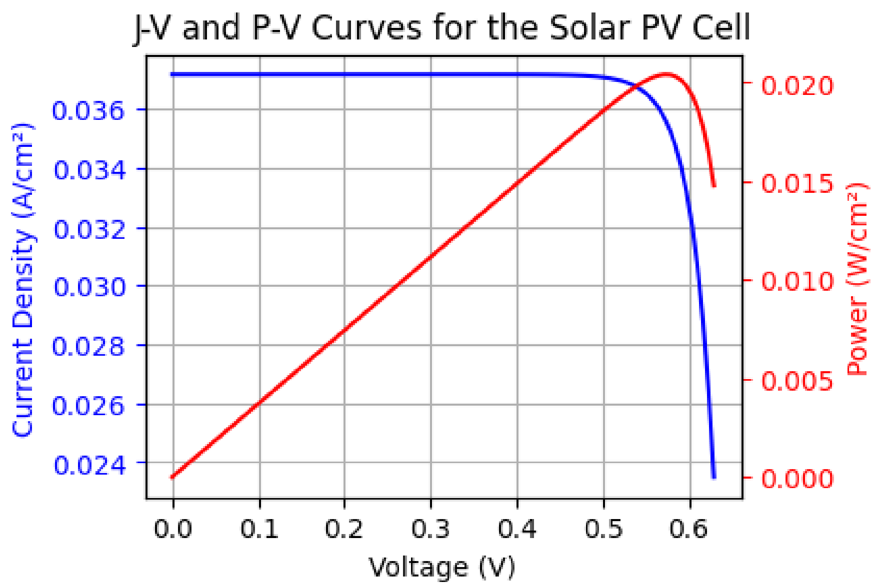
1. We will get solar irradiance data for both locations using our earlier defined function.
2. Assume CSP plants are generating power only during the hours when the solar radiation collected by the receiver > absorber re-radiation losses.
3. The modified expression for fraction of heat recovery can be used as a condition to estimate the min. DNI level required for CSP plant to generate electricity. Mathematically, we can **set $f_{heat} \geq 0$ to get DNI_{min} for each location (DNI_{min} = 102 W/m^2).**
4. We will obtain **useful DNI time series (DNI ≥ DNI_{min})** at both locations and estimate annual avg. useful DNI. This value can be used to calculate the heat fraction recovered and hence, electricity generated (using Carnot efficiency of 35%) for CSP system.
5. **For solar PV, we will use GHI component of irradiance** to estimate electricity generation (as solar PV can also use DHI component, which CSP cannot).
6. To obtain C ratio required to match solar PV performance, we will use Goal Seek to achieve 20% S2E in CSP by varying the C ratio.
7. The following table summarizes performance of CSP vs Solar PV at both locations.

SN	Particulars	CSP		Solar PV	
		Ivanpah, CA	Boston, MA	Ivanpah, CA	Boston, MA
1	Annual Avg. S2E efficiency	19.1%	11.8%	20% (Given)	
2	Annual Ele. Gen., MWh	410	178	429	300
3	C ratio required to match PV performance	560	1600	-	

8. We can draw following conclusions from the results:
   - 8.1. S2E efficiency for Ivanpah, CA is ~19% due to **good DNI profile as compared to Boston, MA** (annual avg. DNI is 336 W/m2 in Ivanpah compared to 203 W/m2 in Boston).
   - 8.2. This again has to do with lower latitudes as one of the reasons for better DNI.
   - 8.3. Thus, CSP systems in locations such as Ivanpah, CA can compete with solar PV in terms of S2E efficiency.
   - 8.4. In contrast, we will need to triple the C ratio (~1600) for CSP collectors in locations such as Boston, MA to achieve S2E efficiency which is comparable to solar PV.

<u>Problem 4</u>

1. Short circuit current density (Jsc) is **37.17 mA/cm^2** and short circuit current (Isc) is **0.223 A**.
2. Open circuit cell voltage (Voc) is **0.629 V.**
3. Voltage corresponding to maximum power (Vmpp) can be estimated from optimization of power function (P = V x I (V)).
4. Voltage at Maximum Power Point (Vmpp) is **0.574 V** and Maximum Power (Pmax) density is **0.0204 W/cm^2.**



5. Fill Factor (FF) for the solar PV cell is **0.873**.
6. Theoretical S2E Efficiency of the cell is **20.41%.** <u>Assumption: Standard Test Condition incident solar irradiance of 1000 W/m2.</u>