Project for Yilei over Summer 2020

**Improved test spectrum for silicon solar cells**

Background

1. Review solar cell efficiency measurements and testing with solar simulators
2. Familiarize yourself with common spectra used (AM0, AM 1.5 G, AM 1.5 D) and what they mean
3. Try to find out why AM1.5G was chosen for most standardized testing
4. Figure out how AM1.5G spectrum is actually determined

Goal is to find best spectrum to use for testing silicon solar cells under the following assumptions

* Spectrum changes as a function of latitude due to atmospheric absorption
  + Depends on path length X absorption
  + Expect absorption to depend on wavelength
* Cell output depends on spectrum and intensity
  + Use ideal silicon cell properties (Auger-limited IV curve, current absorbed (λ))
  + Assume cell response and AR coating is independent of angle
* Assume flat solar panels with fixed tilt
  + Optimize tilt to maximize energy
* Ignore temperature dependence of cells for now
* Ignore cloud cover and humidity for now – too complicated
* Assume for now that all light is direct (instead of 90% direct and 10% diffuse)
  + This is expected to also depend on could cover and humidity

**Intensity only (do not need spectrum)**

1. Build a model for solar irradiance (P0 before transmission or P1 after transmission) vs. zenith angle as a function of time of day, day in year, latitude, and panel tilt, assuming intensity unchanged with zenith angle by Air Mass
   1. Calculate total energy captured and find best tilt vs. latitude (1-dimensional optimization)
   2. Calculate to 0.1-degree precision
   3. Plot best tilt vs. latitude
   4. Plot the energy captured per year vs. latitude
2. Add path length (AM) and absorption, assuming *wavelength-independent* absorption that changes with zenith angle
   1. Calculate total energy captured and find best tilt vs. latitude
   2. Add the best tilt vs. latitude on same plot in 1c
   3. Add the energy captured per year vs. latitude on the plot in 1d
3. Compare the average powers to the maximum daily power (~noon) at equinox
   1. Convert the energy captured per year in 2c to an average power (total energy divided by half the total hours) vs. latitude
   2. Calculate the maximum daily power at equinox directly from the AM1.0 power, using the absorption for increasing AM vs zenith angle, because at this condition we expect latitude = zenith angle
   3. Check directly that this is the same as the maximum daily power at equinox (or close)
   4. Plot the power vs. latitude (= zenith angle)
   5. Plot 3a and 3d all on the same plot
   6. Plot them again, normalizing to the value at zero latitude
   7. How do these two shapes compare?
4. Revise energy capture to include ideal power conversion efficiency (PCE) of silicon cells, Version 1
   1. PCE depends on input power density on cell (P1) and cell thickness (H) via the following equations
      1. J(V) = JL \* (P1/P00) - J0 \* exp(+2.92eV/2kBT)
      2. Where
         1. P00 = 1000 W/m2
         2. ni = 8.76 X 109
         3. T = 298 K
         4. H = 100 μm (only for this version)
         5. J0 = 5.175 E-21 A/cm2 (only for this version)
         6. JL = 0.04337 A/cm2 (only for this version)
      3. The function J(V)\*V, will have a maximum with respect to V
      4. Maximize J(V)\*V vs. V numerically
      5. Power Conversion Efficiency, η(P1) = JmVm/P1, where Jm and Vm are the values from the maximization
   2. Plot η(P1) for P1 from 1 to 1,000 W/m2
   3. Calculate total energy captured again, by multiplying P1 by η(P1) for each point in annual grid
   4. Find best tilt vs. latitude (1-dimensional optimization)
   5. Add the best tilt vs. latitude on same plot in 1c
   6. Add the energy captured per year vs. latitude on the plot in 1d – note that the numbers will be lower than before since the efficiency is less than 100%
   7. Calculate and plot an average Air Mass vs. latitude in the following way:
      1. AM\_ave = (Energy \* AM)/Total Energy, where the Energy and AM values are from each point in the annual grid
      2. Also plot AM vs. zenith angle on same plot
5. Revise energy capture to include ideal power conversion efficiency (PCE) of silicon cells, Version 2
   1. The cell efficiency actually depends on cell thickness, H, through the variable JL(H). And it turns out that there is an optimal thickness for silicon cells. The optimal cell thickness for AM1.5 is H ~ 100 μm. Under these conditions we can approximate that
      1. JL(H) = [33.11582 + 8.62434 \* LT -2.17858 \* LT2 +0.21387 \* LT3]/1000, in A/cm2
      2. Where LT = log10(H), with H in μm
      3. For H = 100 μm, this should give JL = 0.04337 A/cm2 as above
   2. To check this, plot η(P00, JL(H)), for H from 10 μm to 1 mm, using the following guidelines:
      1. J(V) = JL(H) - J0 \* exp(+2.92eV/2kBT)
      2. Where
         1. P00 = 1000 W/m2
         2. ni = 8.76 X 109
         3. T = 298 K
         4. J0 = e \* H \* 3.0E-29 \* (ni)2.92
      3. The function J(V)\*V, will have a maximum with respect to V
      4. Maximize J(V)\*V vs. V numerically
      5. Power Conversion Efficiency, η(P00) = JmVm/P00, where Jm and Vm are the values from the maximization

Note: for now, we are using AM1.5 to calculate JL(H) since it is standard and easier, but this is not really correct since we know the spectrum varies – this will be revised in the next section

* 1. Calculate total energy captured by multiplying P1 by η(P1, JL(H)) for each point in the annual grid. Note that P1 should be the power hitting the cell, i.e. *after transmission*. Please check this.
     1. J(V) = JL(H) \* (P1/P00) - J0 \* exp(+2.92eV/2kBT)
     2. Where
        1. P00 = 1000 W/m2
        2. ni = 8.76 X 109
        3. T = 298 K
        4. H = 100 μm (only for this version)
        5. J0 = e \* H \* 3.0E-29 \* (ni)2.92
     3. The function J(V)\*V, will have a maximum with respect to V
     4. Maximize J(V)\*V vs. V numerically
     5. Power Conversion Efficiency, η(P1, JL(H)) = JmVm/P1, where Jm and Vm are the values from the maximization
  2. Now there are 3 variables in the overall function for the energy capture: latitude, tilt and thickness. Optimize total energy vs. both tilt and thickness (2-dimensional optimization), for each latitude. The thickness, H, should come out to be ~ 100 μm and change slightly with latitude, since the power levels are changing. The tilt should be similar to previous values.
  3. Add the optimized tilt vs. latitude on same plot in 1c
  4. Add the energy captured per year vs. latitude on the plot in 1d
  5. Plot the optimized cell thickness, H\* vs. latitude
  6. These are expected to show that the best tilt vs. latitude changes slightly when we consider the cell design and that the cell design (H) depends slightly on latitude
  7. Why does the thickness change the way that it does? For each power, P1, from 10 to 10,000 W/m2, calculate/plot the thickness, H\* that maximizes the efficiency vs power.
  8. Plot H\* vs. energy captured per year, from the results above, which changes via latitude. I have done this and added it to the share drive.
  9. Calculate and plot an average Air Mass vs. latitude in the following way:
     1. AM\_ave = (Energy \* AM)/Total Energy, where the Energy and AM values are from each point in the annual grid. Add this to the similar plot from the section above.
     2. Also plot AM vs. zenith angle on same plot

**Intensity *and* spectrum**

We know that the spectrum does change with air mass, so we need to consider the wavelength-dependent absorption. The measurements and calculations related to this are actually quite complicated, so for now, we will estimate the spectral dependence which provides good enough values to help understand the overall picture.

We have a spectrum for AM0 and AM 1.5. This is in Tab 2 of the attached Excel sheet, called AM spectra. That is enough to estimate the spectrum for any Air Mass. We use the follow method:

Assume that I1.5 = I0 \* exp (-1.5\*α(λ)\*D), where α(λ) is the wavelength dependent absorption and D is the distance of one Air Mass. But we don’t actually need to find α(λ) and D, separately. So we define z(λ) = α(λ)\*D and write I1.5 = I0 \* exp (-1.5\*z(λ)). Then we can also write IAMX = I0 \* exp (-X\*z(λ)). We can rewrite these as:

-1.5\*z(λ)= ln(I1.5/I0)

-X\*z(λ)= ln(IX/I0)

Dividing one by the other gives:

X/1.5 = ln(IX/I0) / ln(I1.5/I0)

ln(IX/I0) = ln(I1.5/I0) \* X / 1.5

**IX = I0 \* exp [ln(I1.5/I0) \* X / 1.5]**

1. I have implemented this in the same Tab in Excel to get the spectrum SX(λ) for each AMX. The overall spectrum power should match the values you would expect from the transmission equation we used before. The agreement wasn’t quite right, so I adjusted the AM0 spectrum a bit to make them match better. After that the agreement is quite good.

You can see from the plots that the spectrum cuts off more and more in the UV end. This makes the AM38 more red, which is why the sun looks more red near the horizon.

So now we have a spectrum that varies with AM, which is a function of zenith angle. So we no longer use the formula that calculates the transmission vs. AM, since the spectra already include that.

1. We will also need the transmission, TX for each AMX. We had a simple one from before, but to be consistent, we will use the AMX spectra to calculate them. To do this, we integrate the entire spectrum (280 – 4000 nm), to get the power after transmitting through the air mass.

I have provided a sample calculation for TX for several AM values in the tab called AM TX. The value of Tx is given in Column AH of that tab. This shows how to calculate TX for any value of X.

1. JL now becomes an integral over the spectrum. This is given by

JL (X, H) = ∫ SX(λ) \* I(λ,H) dλ

Where X refers to the Air Mass. Normally this equation would be integrated over the full range of Lambda (280-4000 nm) that we have for the spectra but this full range is actually not needed since silicon does not absorb at higher wavelengths, so we can reduce the range to 280-1450 nm. Matlab has a built-in integration routine and you should use this, if possible, to save calculation time. I(λ,H) is an absorbance function given by:

where H is the sample thickness, as before, is the absorption coefficient of silicon and is the index of refraction of silicon. The reason we need to use the spectrum instead of the power is because the cell is sensitive to the spectrum, due to the absorbance function, I(λ).

I have provided a sample calculation for JL(X, H) for AM1.5 and AM5 in the next 2 tabs.

1. Calculate and plot the *cell efficiency* vs. AMX spectrum in the following way:
   1. J(V) = JL(X, H) - J0 \* exp(+2.92eV/2kBT)
   2. Where
      1. P00 = 1000 W/m2
      2. ni = 8.76 X 109
      3. T = 298 K
      4. H = 100 μm (only for this version)
      5. J0 = e \* H \* 3.0E-29 \* (ni)2.92
   3. The function J(V)\*V, will have a maximum with respect to V
   4. Maximize J(V)\*V vs. V numerically
   5. Power Conversion Efficiency, η(X) = (Jm \* Vm)/(P00 \* TX), where Jm and Vm are the values from the maximization

Why does the efficiency change the way that it does?

1. Recalculate the annual energy capture, including spectrum and ideal silicon cell properties
   1. Calculate total energy captured by multiplying P1 \* η(P1, JL(X, H)) for each point in the annual grid. Note that P0 is the power *before transmission*, and P1 is the power after transmission
      1. J(V) = JL(X, H) \* (P0/P00) - J0 \* exp(+2.92eV/2kBT)
      2. Where
         1. P1 = P0 \* TX
         2. P00 = 1000 W/m2
         3. ni = 8.76 X 109
         4. T = 298 K
         5. J0 = e \* H \* 3.0E-29 \* (ni)2.92
      3. The function J(V)\*V, will have a maximum with respect to V
      4. Maximize J(V)\*V vs. V numerically
      5. Power Conversion Efficiency, η(P1, JL(X, H)) = JmVm/P1, where Jm and Vm are the values from the maximization
   2. As before, there are still 3 variables in the overall function for the energy capture: latitude, tilt and thickness. The method to get there just became more complicated. Optimize total energy vs. both tilt and thickness (2-dimensional optimization), for each latitude. The thickness, H, should still come out to be ~ 100 μm and the tilt should be similar to previous values.
   3. Add the optimized tilt vs. latitude on same plot in 1c
   4. Add the energy captured per year vs. latitude on the plot in 1d
   5. Plot the optimized cell thickness, H\* vs. latitude on the previous one
   6. These are expected to show that the best tilt vs. latitude changes slightly when we consider the cell design and that the cell design (H) depends slightly on latitude
2. Calculate an *energy-weighted spectrum* vs. latitude, just for latitude = 45 degrees for now
   1. I will explain further when we get to this
   2. [Sum of (energy \*spectrum(λ))]/ [Sum of energy]
   3. Compare these to AM spectra

**Further improvements**

1. Consider the effects listed below, and recalculate an energy-weighted spectrum vs. latitude (*do* need spectrum)
   1. average temperature vs time of day, day in year, latitude
      1. affects cell parameters and cell temperature
      2. Consider different levels of temperature, with respect to median for latitude – low, medium and high?
   2. cloud cover affects spectrum, intensity and angular distribution
      1. Consider different levels of cloud cover – low, medium and high?
   3. include an angular dependence for cell response

Later steps

* Put global population into bins for latitude, temperature, and cloud cover
* Calculate population weighted test spectrum
* Repeat calculations and cell parameter sensitivity for tandem (2J) cells