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Solar Analysis

The first step in the calculations is determining the solar insolation in the region that SPAAV will be located, which is Lake Ontario. The data for average daily insolation can be found on the National Renewable Energy Laboratory (NREL) website and is reported on an hourly basis. The insolation data is given in the form of three categories; global horizontal irradiance (GHI), direct normal irradiance (DNI), and diffuse horizontal irradiance (DHI).

The time that is recorded for the data is in clock time which has to be converted into solar time for calculating the insolation available to the solar array. To convert clock time into solar time, the following equations are used.

$$ST = CT + \frac{4\,min}{1^o}(\mathrm{LTM} - \mathrm{LL}) + \mathrm{E} + 1 \qquad (1)$$

$$E = 9.87\sin 2B - 7.53\,cosB - 1.5\,sinB \qquad (2)$$

$$B = \frac{360}{364}(n - 81) \qquad (3)$$

LTM is the local time meridian and LL is the local latitude. CT and ST are clock time and solar time, respectively. Next is to determine the amount of solar insolation available. To do this, the following angles of the collector location have to be determined:

$$\delta = 23.45\sin\left[\frac{360}{365}(n - 100)\right] \qquad (4)$$

$$H = \frac{15^o}{hr}(12 - ST) \qquad (5)$$

$$\sin\beta = cosL\cos\delta\cosh + sinL\sin\delta \qquad (6)$$

$$\cos\theta = \cos\beta\cos(\Phi_s - \Phi_c)\sin\Sigma + \sin\beta\cos\Sigma \qquad (7)$$

$$\sin\Phi_s = \frac{\cos\delta\sinh}{\cos\beta} \qquad (8)$$

The variables used in the above equations are:

- δ - Solar declination
- β - Solar altitude angle
- ϕ_s - Solar azimuth angle
- ϕ_c - Collector azimuth angle
- H - Hour angle
- Σ - Tilt angle of the module
- n - Day of the year

To make up for the boat rocking due to waves on the lake, a changing tilt angle is used and then averaged for the hour. The tilt angle was assumed to oscillate from -12.5 degrees to 12.5 degrees. Each of the above equations we calculated starting at a tilt of -12.5 degree and increasing by 0.5 degrees until +12.5 degrees is reached. These values are then averaged together for each hour of each day to get an ideal amount of insolation with oscillation of the boat.

Using this information we are able to calculate the beam radiation on the collector (I_{BC}), the diffuse radiation on the collector (I_{DC}) and the reflected radiation on the collector (I_{RC}) for a horizontal collector. The sum of these values is the total insolation on the collector (I_C). The formulas for these calculations are shown below, where is the incidence angle.

$$I_{DC} = I_{DHI}\left(\frac{1+\cos\Sigma}{2}\right) \qquad (9)$$

$$I_{RC} = I_{GHI}\left(\frac{1-\cos\Sigma}{2}\right) \qquad (10)$$

$$I_{BC} = I_{DNI}\cdot\cos\theta \qquad (11)$$

$$I_C = I_{DC} + I_{RC} + I_{BC} \qquad (12)$$

Once these values were determined for each hour of each day, they were averaged together to get the average daily insolation. The resulting figure below shows the insolation for each day of the months April through August.

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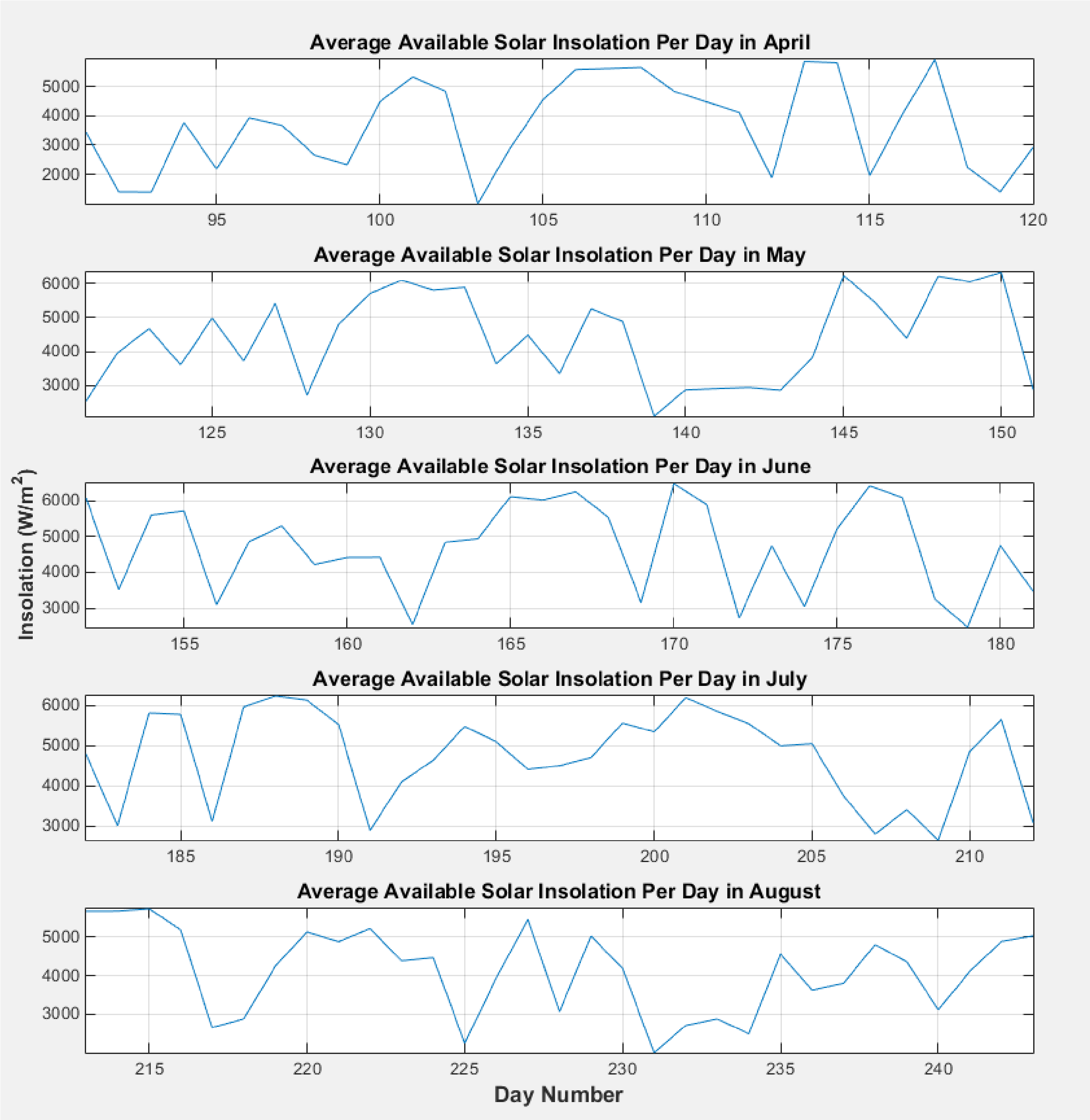

Figure 1: Average solar insolation per day for each month.

Once the available insolation is known for each day over each month, an average is taken to get the average daily insolation for each of the five months. To determine the amount of energy that the solar array must provide, the "peak hours" approach was used. The peak hours takes the average daily insolation available and assumes that this value is the number of hours that 1000 w/m^2 is available from the sun. The DC power required for the array to produce to meet the energy requirement is found using the following equation:

$$P_{DC} = \frac{Energy\ Required}{Derate \cdot (\frac{hr}{day}\ Peak\ Sun) \cdot \frac{day}{month}} \quad (13)$$

The derate factor in the above equation accounts for the losses that occur for various factors such as wiring, inverters and transformers, mismatch, diodes and connections, etc. For this analysis, a derate factor of 0.75 was used based on the derate table provided by NREL.

The amount of modules needed in the solar array to meet the energy requirement can be determined by dividing P_{DC} by the wattage rating of the solar module:

$$Number\ of\ Modules = \frac{P_{DC}}{Modules\ Peak\ Power} \quad (14)$$

Once the minimum number of modules are known for the system, constraints for the charge controller have to be looked at. These constraints are the maximum voltage and maximum current rating of the charge controller. The charge controller that is used for this analysis is the EPSolar eTracer ET4415BND which has a maximum voltage rating of 150 volts and a maximum current rating of 45 amps. The following equations are used to find the maximum number of modules allowed per string due to maximum voltage and maximum current of the charge controller:

$$Actual\ V_{OC} = Rated\ V_{OC}[1 - (Temp\ Coeff\ of\ V_{OC})(T_{Cell} - T_{STD})] \quad (15)$$

$$\text{Number of Modules Per String Due to Voltage} = \frac{\text{Rated Charge Controller Voltage}}{\text{Actual } V_{OC}} \quad (16)$$

$$\text{Number of Modules Per String Due to Current} = \frac{\text{Rated Charge Controller Current}}{\text{Module } I_{SC}} \quad (17)$$

Actual V_{OC} is calculated because at lower temperatures, solar modules will produce more voltage. The average lowest temperature for each month is used for T_{cell}. Temperature Coefficient of V_{OC} is found on the spec sheet for the solar module. TSTD is a standard testing temperature and is equal to 25°C.

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Solar Module Specs		
Peak Power	100	Watts
Vmpp	18	Volts
Impp	5.56	Amps
Voc	21.9	Volts
Isc	6.13	Amps
NOCT	45	C
Temp Coef Voc	0.0032	%/degC
Efficiency	14.63	%
Area	0.6834	m^2

Figure 2: Solar module specs

Month	Daily Average Insolation [kWh/day/m^2]	DC Power Needed (over 8 hours per day) [kWh]	Number of Modules	Max Panels Per String For Charge Controller	Max Modules Per String for Max Current of Charge Controller
April	3.68	2.304, 4.32, 6.336, 8.352	8.36, 15.67, 22.98, 30.30	7.78	7.34
May	4.40	2.304, 4.32, 6.336, 8.352	6.98, 13.08, 19.18, 25.29	7.9	7.34
June	4.70	2.304, 4.32, 6.336, 8.352	6.54, 12.26, 17.98, 23.70	8.02	7.34
July	4.74	2.304, 4.32, 6.336, 8.352	6.49, 12.16, 17.84, 23.52	8.09	7.34
August	4.14	2.304, 4.32, 6.336, 8.352	7.41, 13.90, 20.39, 26.87	7.97	7.34

Figure 3: Determining factors for the array design from month to month