**Project Appendix**

This document will contain sample calculations and sources to the PV study carried out on the university:

I. **Sample Calculation**
   
   A. **Solar roof analysis**: The calculations for size, cost, AC output and 25yr output (with degradation) of solar system.

   **Roof space location**: Memorial Art Gallery

   **Total roof space** = 35286 ft\(^2\)

   Convert to m\(^2\) = 35286 ft\(^2\) * \(\frac{0.0929 \text{ m}^2}{\text{ft}^2}\) = 3278 m\(^2\)

   **Solar DC system size** = Solar roof area (m\(^2\)) * \(\frac{1 \text{ KW}}{\text{m}^2}\) * Module efficiency (15%)

   = 3278 m\(^2\) * \(\frac{1 \text{ KW}}{\text{m}^2}\) * 0.15

   = 492 KW

   **Cost of the system**: Solar system sizes and their respective prices were collected from the Solar Liberty (the largest solar energy installer in NY state) project proposal as shown in table 1. It was plotted as shown in figure 1 and the prices of the solar units in this study were extrapolated from the data mentioned.

   **Table 1: Set of proposed solar system sizes with their respective sizes**

<table>
<thead>
<tr>
<th>System Size/KW</th>
<th>Cost (Post-incentive)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.84</td>
<td>$44,510</td>
</tr>
<tr>
<td>56</td>
<td>$135,360</td>
</tr>
<tr>
<td>104.4</td>
<td>$224,460</td>
</tr>
</tbody>
</table>
Use equation of the line of fig.1 to get cost of system

\[ y = 2025.5x + 15785 \]

\[ = 2025.5 \times 492 \text{ KW} + 15785 \]

\[ = 1,011,777 \]

**AC System Output**

Regarding the AC System Output, it was derived from the [PVWatts Calculator](https://pvwatts.nrel.gov) with all the parameters being default except for array type which is fixed (roof mount).

\[ \text{AC system output} = 592,821 \frac{\text{KWh}}{\text{yr}} \]
RESULTS

584,433 kWh/Year*

System output may range from 687,076 to 602,901 kWh per year near this location.

<table>
<thead>
<tr>
<th>Month</th>
<th>Solar Radiation (kWh/m²/day)</th>
<th>AC Energy (kWh)</th>
<th>Value ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>1.97</td>
<td>25,453</td>
<td>1,442</td>
</tr>
<tr>
<td>February</td>
<td>2.19</td>
<td>36,317</td>
<td>3,339</td>
</tr>
<tr>
<td>March</td>
<td>4.44</td>
<td>52,191</td>
<td>3,361</td>
</tr>
<tr>
<td>April</td>
<td>5.14</td>
<td>57,311</td>
<td>3,591</td>
</tr>
<tr>
<td>May</td>
<td>6.24</td>
<td>69,311</td>
<td>4,464</td>
</tr>
<tr>
<td>June</td>
<td>6.23</td>
<td>65,851</td>
<td>4,241</td>
</tr>
<tr>
<td>July</td>
<td>6.32</td>
<td>68,264</td>
<td>4,396</td>
</tr>
<tr>
<td>August</td>
<td>6.03</td>
<td>64,147</td>
<td>4,131</td>
</tr>
<tr>
<td>September</td>
<td>5.22</td>
<td>54,636</td>
<td>3,515</td>
</tr>
<tr>
<td>October</td>
<td>3.33</td>
<td>39,464</td>
<td>2,473</td>
</tr>
<tr>
<td>November</td>
<td>2.43</td>
<td>28,506</td>
<td>1,832</td>
</tr>
<tr>
<td>December</td>
<td>1.08</td>
<td>24,003</td>
<td>1,546</td>
</tr>
<tr>
<td>Annual</td>
<td>4.37</td>
<td>584,434</td>
<td>37,639</td>
</tr>
</tbody>
</table>

Location and Station Identification

- Requested Location: University of Rochester
- Weather Data Source: Lat., Lon: 43.13, -77.62
- Latitude: 43.13° N
- Longitude: 77.62° W

PV System Specifications (Commercial)

- DC System Size: 452 kW
- Module Type: Standard
- Array Type: Fixed (roof mount)
- Array Tilt: 20°
- Array Azimuth: 180°
- System Losses: 14.09%
- Inverter Efficiency: 96%
- DC to AC Size Ratio: 1.2

Economics

- Average Retail Electricity Rate: 0.064 $/kWh

Performance Metrics

- Capacity Factor: 13.6%
25yr System Output
This study then assumes the solar systems have a lifespan of 25yrs at degrades at the rate of 2\% Year 1 and 0.2\% Years 2-25.

*Table 2: Derivation of 25yr average production factor for solar systems*

<table>
<thead>
<tr>
<th>Year</th>
<th>Degradation (%)</th>
<th>Cumulative Degradation (%)</th>
<th>Degraded Production (%)</th>
<th>Undegraded Production (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td></td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>0.2</td>
<td>2</td>
<td>98</td>
<td>100</td>
</tr>
<tr>
<td>3</td>
<td>0.2</td>
<td>2.2</td>
<td>97.8</td>
<td>100</td>
</tr>
<tr>
<td>4</td>
<td>0.2</td>
<td>2.4</td>
<td>97.6</td>
<td>100</td>
</tr>
<tr>
<td>5</td>
<td>0.2</td>
<td>2.6</td>
<td>97.4</td>
<td>100</td>
</tr>
<tr>
<td>6</td>
<td>0.2</td>
<td>2.8</td>
<td>97.2</td>
<td>100</td>
</tr>
<tr>
<td>7</td>
<td>0.2</td>
<td>3</td>
<td>97</td>
<td>100</td>
</tr>
<tr>
<td>8</td>
<td>0.2</td>
<td>3.2</td>
<td>96.8</td>
<td>100</td>
</tr>
<tr>
<td>9</td>
<td>0.2</td>
<td>3.4</td>
<td>96.6</td>
<td>100</td>
</tr>
<tr>
<td>10</td>
<td>0.2</td>
<td>3.6</td>
<td>96.4</td>
<td>100</td>
</tr>
<tr>
<td>11</td>
<td>0.2</td>
<td>3.8</td>
<td>96.2</td>
<td>100</td>
</tr>
<tr>
<td>12</td>
<td>0.2</td>
<td>4</td>
<td>96</td>
<td>100</td>
</tr>
<tr>
<td>13</td>
<td>0.2</td>
<td>4.2</td>
<td>95.8</td>
<td>100</td>
</tr>
<tr>
<td>14</td>
<td>0.2</td>
<td>4.4</td>
<td>95.6</td>
<td>100</td>
</tr>
<tr>
<td>15</td>
<td>0.2</td>
<td>4.6</td>
<td>95.4</td>
<td>100</td>
</tr>
<tr>
<td>16</td>
<td>0.2</td>
<td>4.8</td>
<td>95.2</td>
<td>100</td>
</tr>
<tr>
<td>17</td>
<td>0.2</td>
<td>5</td>
<td>95</td>
<td>100</td>
</tr>
<tr>
<td>18</td>
<td>0.2</td>
<td>5.2</td>
<td>94.8</td>
<td>100</td>
</tr>
<tr>
<td>19</td>
<td>0.2</td>
<td>5.4</td>
<td>94.6</td>
<td>100</td>
</tr>
<tr>
<td>20</td>
<td>0.2</td>
<td>5.6</td>
<td>94.4</td>
<td>100</td>
</tr>
<tr>
<td>21</td>
<td>0.2</td>
<td>5.8</td>
<td>94.2</td>
<td>100</td>
</tr>
<tr>
<td>22</td>
<td>0.2</td>
<td>6</td>
<td>94</td>
<td>100</td>
</tr>
<tr>
<td>23</td>
<td>0.2</td>
<td>6.2</td>
<td>93.8</td>
<td>100</td>
</tr>
<tr>
<td>24</td>
<td>0.2</td>
<td>6.4</td>
<td>93.6</td>
<td>100</td>
</tr>
<tr>
<td>25</td>
<td>0.2</td>
<td>6.6</td>
<td>93.4</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td><strong>Total</strong></td>
<td><strong>2,396.8</strong></td>
<td><strong>2,500</strong></td>
<td></td>
</tr>
</tbody>
</table>

25 Year Average Production Factor = \( \frac{2396.8}{2500} \times 100 = 95.9\% \)
25yr system output for Memorial Art Gallery = \(14,212,883 \frac{\text{KWh}}{\text{yr}}\)

\[
\text{Cost of electricity per KWh} = \text{Cost of system output} \times \frac{1}{\text{25yr output}} = \frac{\$1,011,777}{14,212,883 \text{ KWh}} = \$0.07 \text{ KWh}
\]

**Table 3: Solar roof analysis of University’s buildings**

<table>
<thead>
<tr>
<th></th>
<th>Total roof space (10^3*ft^2)</th>
<th>Available Solar Roof space (10^3*m^2)</th>
<th>Solar DC System Size (KW)</th>
<th>Cost of System ($)</th>
<th>AC System Output (KWh/Year)</th>
<th>25 yr Output including PV degradation (KWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Memorial Art Gallery</td>
<td>35</td>
<td>3</td>
<td>492</td>
<td>1,011,777</td>
<td>592,821</td>
<td>14,212,883</td>
</tr>
<tr>
<td>South Campus</td>
<td>180</td>
<td>17</td>
<td>2,515</td>
<td>5,109,071</td>
<td>2,987,497</td>
<td>71,625,241</td>
</tr>
<tr>
<td>Middle Campus</td>
<td>11</td>
<td>1</td>
<td>149</td>
<td>317,383</td>
<td>176,993</td>
<td>4,243,407</td>
</tr>
<tr>
<td>Eastman</td>
<td>62</td>
<td>6</td>
<td>864</td>
<td>1,766,772</td>
<td>1,026,321</td>
<td>24,606,046</td>
</tr>
<tr>
<td>River Campus</td>
<td>442</td>
<td>41</td>
<td>6,162</td>
<td>12,497,632</td>
<td>7,319,665</td>
<td>175,488,968</td>
</tr>
<tr>
<td>Medical Center</td>
<td>496</td>
<td>46</td>
<td>6,911</td>
<td>14,013,834</td>
<td>8,209,381</td>
<td>196,819,909</td>
</tr>
<tr>
<td>Total</td>
<td>1,226,580</td>
<td>113,953</td>
<td>17,093</td>
<td>34,716,469</td>
<td>20,312,678</td>
<td>486,996,455</td>
</tr>
</tbody>
</table>

**B. GHG Emissions Reduction: PURCHASED ELECTRICITY**

In this analysis, the energy data for FY18 was used to determine how solar PV could offset GHG emissions by \(1,2,5,10,15\) and \(20\)% respectively. The following calculations are performed: GHG emitted, saved, the cost and size of the solar system to offset the GHG emitted. Thereafter an offset comparison is done between solar and tree planting. A sample calculation would be shown for \(10\)% GHG emission (GHGE) reduction.

\[
\text{Reduction in purchased electricity} = (1.0 - 0.1) \times \text{yearly purchased electricity by the university} = 0.9 \times 147,989,128 \frac{\text{KWh}}{\text{yr}} = \frac{133,190,215}{\text{KWh}} \frac{\text{KWh}}{\text{yr}}
\]

\[
\text{CO}_2 \text{ emitted in tons} \frac{\text{yr}}{} = \text{CO}_2 \text{ emission factor} \left( \frac{\text{lb}}{\text{MWh}} \right) \times \text{purchased electricity reduction} = \frac{253.1}{\text{MWh}} \times 133,190.215 \frac{\text{MWh}}{\text{yr}} \times 0.0005 \frac{\text{tons}}{\text{lb}} \frac{\text{lb}}{\text{yr}} = 16,855 \text{ tons}
\]

\(^1\) NYUP power profile from the EPA provided the CO\(_2\) emission factor. [https://www.epa.gov/egrid/power-profiler#/]
\[
\text{CO}_2 \text{ Savings}_{R=10} \text{ in tons yr} = \text{GHGE}_{R=0} \text{ } - \text{GHGE}_{R=10}
\]

GHGE\(_{R=0}\) is the CO\(_2\) emitted throughout the FY18

\[
\text{CO}_2 \text{ Savings}_{R=10} \text{ in tons yr} = \text{GHGE}_{R=0} \text{ } - \text{GHGE}_{R=10}
\]

\[= 18728 - 16855 = 1873\]

**Following the same method to size and cost of solar system in section I.A.**

Therefore, Size of solar system required for offset = 11,372 KW

Price of system = $23,050,518

What if trees were used to offset the emissions

\[
\text{Tree quantity} = \frac{\text{CO}_2 \text{ Savings}_{R=10} \text{ tons to lb conversion rate}}{\text{Mature tree CO}_2 \text{ uptake rate per tree yr}}
\]

\[
= \frac{1873 \text{ tons yr}}{\frac{0.0005 \text{ tons}}{\frac{50 \text{ lb}}{\text{tree yr}}}} = 74,912 \text{ trees}
\]

Assuming it costs $1500 to plant a mature tree.

\[
\text{Cost of planting trees} = 74912 \text{ trees} \times \frac{$1500}{\text{tree}} = $112,368,145
\]

In the study the cost per tons of CO\(_2\) avoided was calculated.

\[
\text{Cost per tons of CO}_2 \text{ avoided} = \frac{\text{Cost of system} - \text{Cost of Electricity Not Spent}}{\text{CO}_2 \text{ savings over lifetime}}
\]

\[
= \frac{[$133,190,215 - \left(\frac{147,989,128 - 133,190,215}{\text{KWh}} \times $0.06 \times 25 \text{yr}\right)]}{1873 \text{ tons yr} \times 25 \text{yr}} = \$21 \text{ tons}
\]

**Note:**

- The rate of $0.06/KWh is the electricity rate which is a combination of the variable and fixed charge to the university.
- $21 per tons of CO\(_2\) avoided means it costs $21 to avoid a ton of CO\(_2\)
Table 4: GHG Emission analysis for the university at different rates

<table>
<thead>
<tr>
<th>% GHG Reduction</th>
<th>Purchased Electricity (KWh/yr)</th>
<th>GHG emission (tons/yr)</th>
<th>GHG Savings (tons/yr)</th>
<th>Solar PV - GHG Offset</th>
<th>Trees for GHG Offset</th>
<th>Trees Qty</th>
<th>Cost of planting trees</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CO₂ - Purchased Electricity</td>
<td>Solar DC Size (KW)</td>
<td>Cost of System ($)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>147,989,128</td>
<td>18,728</td>
<td>0</td>
<td>15,000</td>
<td>1,500</td>
<td>1,137</td>
<td>0.06</td>
</tr>
<tr>
<td>1</td>
<td>146,509,237</td>
<td>18,541</td>
<td>0</td>
<td>22,200</td>
<td>2,000</td>
<td>7,491</td>
<td>11,236,814</td>
</tr>
<tr>
<td>2</td>
<td>145,029,345</td>
<td>18,353</td>
<td>375</td>
<td>49,400</td>
<td>4,500</td>
<td>14,982</td>
<td>22,473,629</td>
</tr>
<tr>
<td>5</td>
<td>140,589,672</td>
<td>17,792</td>
<td>936</td>
<td>113,900</td>
<td>11,000</td>
<td>37,456</td>
<td>56,184,072</td>
</tr>
<tr>
<td>10</td>
<td>133,190,215</td>
<td>16,855</td>
<td>1,873</td>
<td>338,300</td>
<td>17,500</td>
<td>74,912</td>
<td>112,368,145</td>
</tr>
<tr>
<td>15</td>
<td>125,790,759</td>
<td>15,919</td>
<td>2,809</td>
<td>584,700</td>
<td>23,000</td>
<td>112,368</td>
<td>168,552,217</td>
</tr>
<tr>
<td>20</td>
<td>118,391,302</td>
<td>14,982</td>
<td>3,746</td>
<td>851,100</td>
<td>28,500</td>
<td>149,824</td>
<td>224,736,290</td>
</tr>
</tbody>
</table>

C. Maximum Solar Rooftop Solar PV investment

From Table 3 above,

Fully Utilized PV Rooftop System Size is 17 MW at a cost of $35M.

25-year cumulative output = 4.87*10^8 kWh over 25 years

\[ Value \text{ of } 25 - \text{year cumulative output} = 4.87 \times 10^8 \text{ kWh} \times \frac{0.06}{\text{KWh}} = \$29.2M \]

\[ 25 - \text{year return on investment} = \frac{\text{value}}{\text{cost}} = \frac{29.2}{35} = 0.834 \]

Figure 2. 25 Year Cumulative Annual Cashflow
D. Energy Comparison of ‘River Campus’ Peers

Boston University
Utilities Management: [http://www.bu.edu/cpo/what-we-do/energy/energy-sources/](http://www.bu.edu/cpo/what-we-do/energy/energy-sources/)
- It purchases its electricity from third parties and local distribution company, Eversource Energy.
- It purchases its natural gas and is transported by the local gas company, National Grid.
- Low temperature and hot water are handled by [Boston Water and Sewer Commission](http://www.bu.edu/cpo/what-we-do/energy/energy-sources/)
Purchase RECs: [http://www.bu.edu/sustainability/what-were-doing/bu-wind/](http://www.bu.edu/sustainability/what-were-doing/bu-wind/)

Bucknell University
On-site solar and wind: [https://www.bucknell.edu/life-bucknell/sustainability/energy-water-transportation](https://www.bucknell.edu/life-bucknell/sustainability/energy-water-transportation)
- Bucknell University is exploring the installation of a 2.1 peak megawatt (MWp) solar project in partnership with Encore Renewable Energy of Burlington, Vt.

Carnegie Mellon University
Purchase of RECs: [https://www.cmu.edu/environment/energy-water/energy-mix/index.html#:~:text=Renewable%20Energy%20Progress,of%20the%20university's%20electricity%20requirements.](https://www.cmu.edu/environment/energy-water/energy-mix/index.html#:~:text=Renewable%20Energy%20Progress,of%20the%20university's%20electricity%20requirements.)
- Carnegie Mellon University purchases Renewable Electricity Credits (RECs) of wind power from the Prairie Breeze wind energy farm in Nebraska.

On-site solar: [https://www.sunnyportal.com/Templates/PublicPageOverview.aspx?page=c2d8c09a-37f3-4891-83ae-b790b938274f&plant=a3842dd0-2d36-4b89-bff6-4a19f0c3d37b&slang=en-US](https://www.sunnyportal.com/Templates/PublicPageOverview.aspx?page=c2d8c09a-37f3-4891-83ae-b790b938274f&plant=a3842dd0-2d36-4b89-bff6-4a19f0c3d37b&slang=en-US)

Case Western Reserve University (CWRU)
Cogeneration, On-site, On-site Wind: [https://case.edu/sustainability/campus/energy](https://case.edu/sustainability/campus/energy)
It buys its electricity from The Medical Center Company (MCCo), a district energy system not-for-profit corporation.

Duquesne University
Duquesne operates a natural gas-fired power plant that produces approximately 75 percent of the power used for electricity and nearly 100 percent of the heating and cooling of the University's facilities.
It purchases the remainder of its energy needs from renewable sources—a combination of energy generation and renewable energy purchasing led to the University's 100-percent reliance on clean energy. It is procuring renewable energy certificates from Direct Energy.

Massachusetts Institute of Technology  
Cogeneration: https://sustainability.mit.edu/mit-central-utilities-plant  
On-site solar and wind: https://sustainability.mit.edu/site-renewable-energy  
It has five rooftops solar photovoltaic (PV) systems designed to produce an estimated 80,000-kilowatt hours (kWh) of clean energy annually.  
Off-site solar: https://sustainability.mit.edu/site-solar-farm,

Northwestern University  
Purchase RECs: https://isen.northwestern.edu/northwestern-honored-for-renewable-energy-use  
Off-site solar and Solar expansion:  

Northeastern University  
Energy generation: At Northeastern, 527,258 MMBTUs of energy for heating and cooling are generated from on-site combustion. Of this total, the two main sources are Natural Gas (96.8%), and Oil-distillate fuels (3.2%). Northeastern purchases non-electric energy from renewable sources.  

Syracuse University  
On-site Solar: https://sustainability.syr.edu/campus/energy/  
Purchase RECs:  
https://sustainability.syr.edu/campus/energy/#:~:text=Starting%20in%202005%2C%20SU%20has,to%20reduce%20SU's%20carbon%20footprint  
- SU has voluntarily purchased electricity each year from renewable sources. Currently 35%, or 41,000,000 kWh, of Green-E Certified American Wind is purchased.  
- It buys the rest of its electricity of retail electric suppliers.  

The University of Chicago- https://sustainability.uchicago.edu/sp/  
Energy Profile:  
https://d3qi0qp55mx5f5.cloudfront.net/sustainability/uploads/images/UChicago_OS_GHG_Emissions_Inventory_Overview_FY12-FY17.pdf  
- Natural gas and electricity usage in campus buildings contributes to approximately 70 percent of the University’s greenhouse gas emissions.
Campus-scale heating system: [https://www.gienergyus.com/project-university-of-chicago](https://www.gienergyus.com/project-university-of-chicago)  

University of Notre Dame
Co-generation and Campus-scale heating system:
[https://m.nd.edu/notredame/sustainability/_/power_plant](https://m.nd.edu/notredame/sustainability/_/power_plant)

- Notre Dame currently maintains three solar arrays separate from I&M: a 10-kilowatt array atop Fitzpatrick Hall, a 50-kilowatt array atop Stinson-Remick Hall and a 140-kilowatt array on Kenmore Street in South Bend.
- Indiana Michigan Power (I&M) solar project will provide clean energy credits equal to 10 percent of the University of Notre Dame’s total demand for electricity.

On-site Wind: [https://m.nd.edu/notredame/sustainability/_/wind_turbines](https://m.nd.edu/notredame/sustainability/_/wind_turbines)

Existing Hydro capacity:
[https://facilities.nd.edu/projects/current-major-projects/hydroelectric-plant/](https://facilities.nd.edu/projects/current-major-projects/hydroelectric-plant/)  

Extra Sources for University of Notre Dame’s utilities
- [https://www.nd.edu/stories/notre-dame-ceases-to-burn-coal/](https://www.nd.edu/stories/notre-dame-ceases-to-burn-coal/)
- [https://green.nd.edu/mission/strategy/](https://green.nd.edu/mission/strategy/)
- [https://green.nd.edu/get-involved/energy-emissions/energy-conservation-at-notre-dame/](https://green.nd.edu/get-involved/energy-emissions/energy-conservation-at-notre-dame/)

Monroe Community College
Cogeneration:
- MCC is in an agreement with Monroe Newpower, to purchase all of the electricity and heat produced by the new plant.

Cornell University
Cogeneration: [https://fcs.cornell.edu/departments/energy-sustainability/utilities/district-energy-combined-heat-power](https://fcs.cornell.edu/departments/energy-sustainability/utilities/district-energy-combined-heat-power)

On-site and off-site solar and existing hydroelectric:  

RIT:
On-site/Off-site solar and on-site wind: https://www.rit.edu/sustainablecampus/energy

Green energy rating
STARS Ratings: https://reports.aashe.org/institutions/participants-and-reports/
% RE in grid:
https://www.collegeconsensus.com/rankings/best-green-universities/
https://www.epa.gov/greenpower/green-power-partnership-top-30-college-university
(Carnegie Mellon University, RIT, Northwestern University, Boston University)


Duquesne U: https://duq.edu/news/releases/epa-again-designates-duquesne-as-green-power-champion


Syracuse University: https://www.epa.gov/greenpower/green-power-partner-list

U Notre Dame:
“Indiana Michigan Power (I&M) broke ground recently on a $37 million solar project that will provide clean energy credits equal to 10 percent of the University of Notre Dame’s total demand for electricity...”
The facility, which will be primarily underground, is expected to generate about 7 percent of the University’s electrical needs

Cornell University: https://sustainablecampus.cornell.edu/news/renewable-energy-covers-100-cornells-power-use-first-time-over-100-years