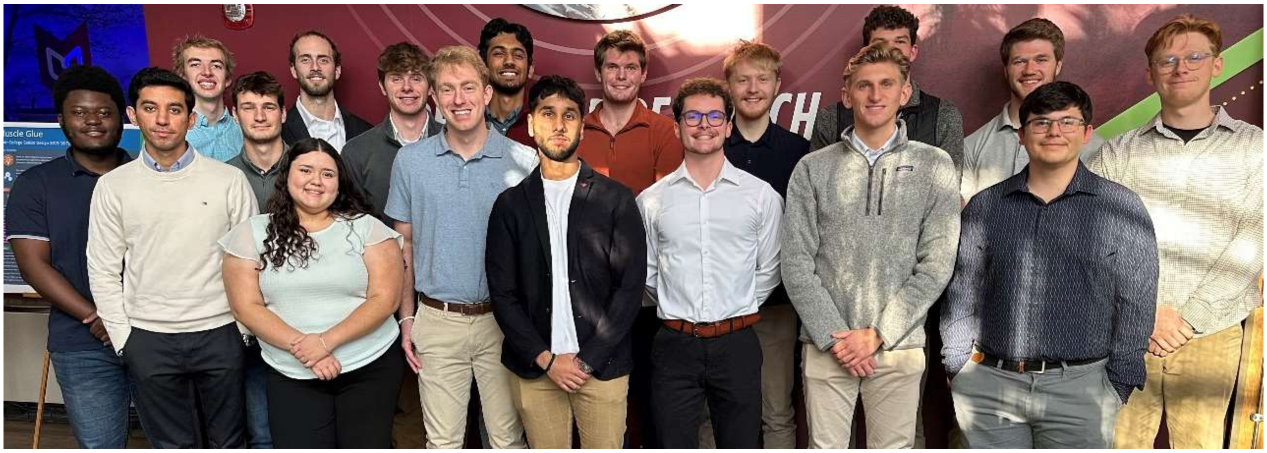
Feasibility of Solar Power at Calvin University

Engineering 333B

Professor Heun

December 12, 2024



From left to right and rear to front: Steven Koopmans, Brandon Eenigenburg, Daniel John, Colton Vanderhoning, Nickolas Heuker, Nicholas Henz, Ethan Koeman, Ryan Antwi-Donkor, Samuel Sands, John Gibes, Kyle Zwarg, Ibhar Kamran, Diana Bracamonte, Drew Barcelow, Vardhan Adhikari, Ethan Wayne, Ryan Westra, and Hunter Hicks.

Executive Summary

To push Calvin University forward in its pledge to be carbon neutral by 2057 and reduce peak power usage on campus, the ENGR 333 class was assigned to research, model, and determine the feasibility of a solar farm for Calvin University. The research done found that up to 14% of Calvin University's energy could be produced from solar energy. A cost analysis showed that the university could be generating approximately $209,000 starting in 2024 by installing 7 solar systems on campus before overproduction occurs, based on the current electricity data of Calvin. Thus, it is the class's recommendation to move forward with developing a solar farm, specifically with the package of up to 7 systems initially.

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Introduction

In the world today, one of the greatest challenges is eliminating carbon dioxide emissions from energy generation and consumption. Calvin University is committed to lowering carbon emissions to reduce costs, minimize environmental impact, and demonstrate care and stewardship for creation, as mentioned in Calvin's Statement on Sustainability.[1] Although progress towards carbon neutrality has been uneven in recent years, the university stays true to its commitment to achieving this goal.[2]

Calvin University is also facing the need to upgrade its energy infrastructure with many systems in need of replacement, which provides the opportunity to replace carbon dioxide-emitting technology with more environmentally friendly options. Specifically, in this proposal, Engineering 333 Section B examined the feasibility and design of a solar farm for Calvin University.

Results

Engineering 333B, which is the second section of the Thermal Systems Design course, was given the task of developing and exploring the feasibility of a solar farm. The class worked in conjunction with Section A, a structural engineering class, and a physics class. The class was split into five sub-sections based on the multiple types of solar farms - infrastructure & modeling, ground on-campus, ground off-campus, rooftop, and car park. Each team's specific results are further detailed in the Appendices. The overall class was able to determine viable locations for solar panels as well as the projected power output per location, both detailed more in Appendix A. Each team also determined solar panels, inverters, and specific parameters for each location.

Using the excel calculators mentioned more in depth in the Appendices, the financials over time based on the cost calculations for each site, with given standard parameters of MARR being 7%, a lifetime of 20 years per system, an inflation rate of 3.68%, and a real inflation rate of energy of 0.241%. The sensitivity analysis was done with respect to life span, the inflation rate, and the inflation adjusted energy rate. 7 packages were assembled based on the kWh/$ calculations and feasibility of implementation, with the best performing systems included in a linear progression shown in Table 2.

Table 1. Financial Base Summary (The Total Capital Investment does not include the 30% reimbursement available from the IRA).

Financial Base Case Summary									
Package Number	**MARR Adjusted Lifetime Net Return (2024$)**	**Unadjusted Lifetime Net Cash Flow (2044$)**	**Payback Period (Years)**	**MARR Adjusted Lifetime ROI (%)**	**Total Capital Investment* (2024$)**	**IRA Adjusted Capital Investment (2024$)**	**IRR (%)**	**Rated Power (MW)**	**Total Carbon Offset (%)**
1	$231,323	$730,223	7	50%	$393,974	$275,782	17%	0.29	0.7%
2	$362,783	$1,316,549	8	35%	$883,085	$618,159	14%	0.65	1.5%
3	$368,932	$2,028,515	9	16%	$1,965,463	$1,375,824	10%	1.36	3.3%
4	$320,580	$2,198,933	10	12%	$2,383,254	$1,668,278	9%	1.63	3.9%
5	$296,076	$2,344,787	11	10%	$2,687,107	$1,880,975	9%	1.82	4.4%
6	$90,330	$2,277,053	12	2%	$3,237,216	$2,266,051	8%	2.14	5.3%
7	$33,469	$2,376,418	12	1%	$3,572,191	$2,500,534	7%	2.32	5.8%

Conclusions

Based on the results, a solar farm is feasible and recommended for Calvin University. Specifically, the return rate is reduced with increased scale, with the highest IRR correlated to the smallest system. The returns are also highly sensitive to lifetime. Thus, the recommendation for the university is package 2 or 3, which consist of the roofs of the Aquatic Center, the Van Noord Arena, and the Hekman Library/Hiemenga Hall complex (for package 3) to maximize the return rate while also increasing carbon offsets.

Other factors that should be included in future analysis include examining the effect of a potential geothermal system at Calvin, as that would alter the electricity consumption of Calvin. Currently the newly built athletic facilities utilize geothermal systems, and Calvin hopes to expand geothermal usage to help with the energy consumption associated with the University's HVAC usage.

Figures & Tables

Table 2. Proposed package progression.

Package 1	Package 2	Package 3	Package 4	Package 5	Package 6	Package 7
Roof - Aquatic Center	Roof - Aquatic Center	Roof - Aquatic Center	Roof - Aquatic Center	Roof - Aquatic Center	Roof - Aquatic Center	Roof - Aquatic Center
	Roof - Van Noord Arena	Roof - Van Noord Arena	Roof - Van Noord Arena	Roof - Van Noord Arena	Roof - Van Noord Arena	Roof - Van Noord Arena
		Roof - HH + Hekman Lib	Roof - HH + Hekman Lib	Roof - HH + Hekman Lib	Roof - HH + Hekman Lib	Roof - HH + Hekman Lib
			Roof - Devos Comm	Roof - Devos Comm	Roof - Devos Comm	Roof - Devos Comm
				Roof - Prince Conf Center	Roof - Prince Conf Center	Roof - Prince Conf Center
					Seminary Field	Seminary Fields
						Lake Drive Lawn

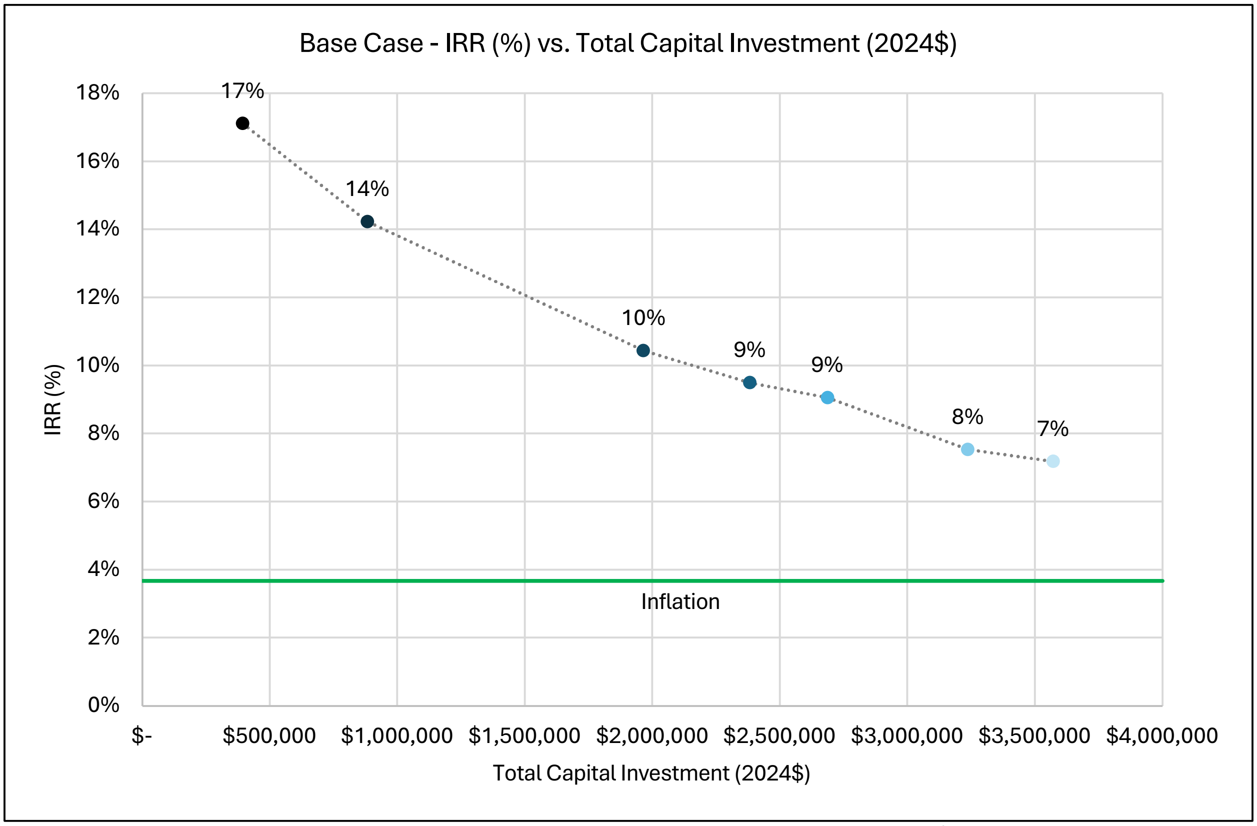


Figure 1. Base case - IRR (%) vs. total capital investment (2024$) by package

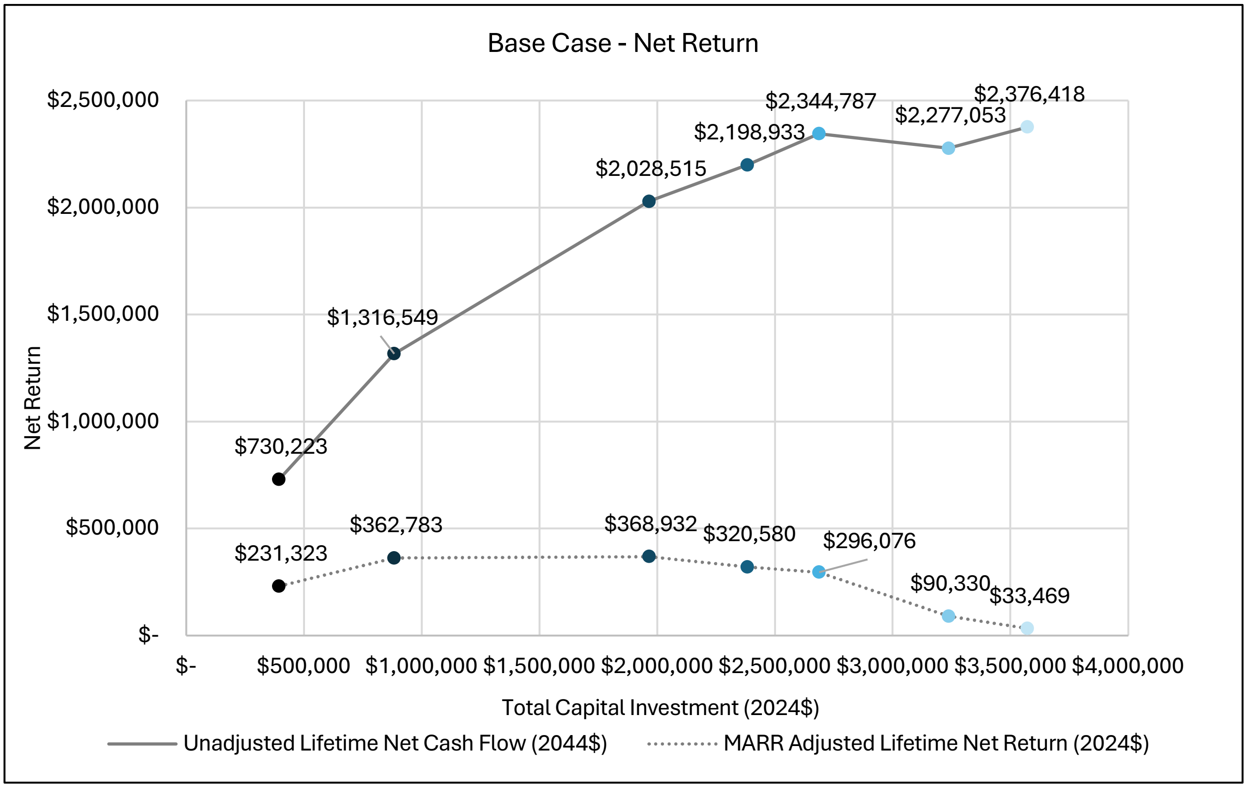


Figure 2. Base case - net return by package.

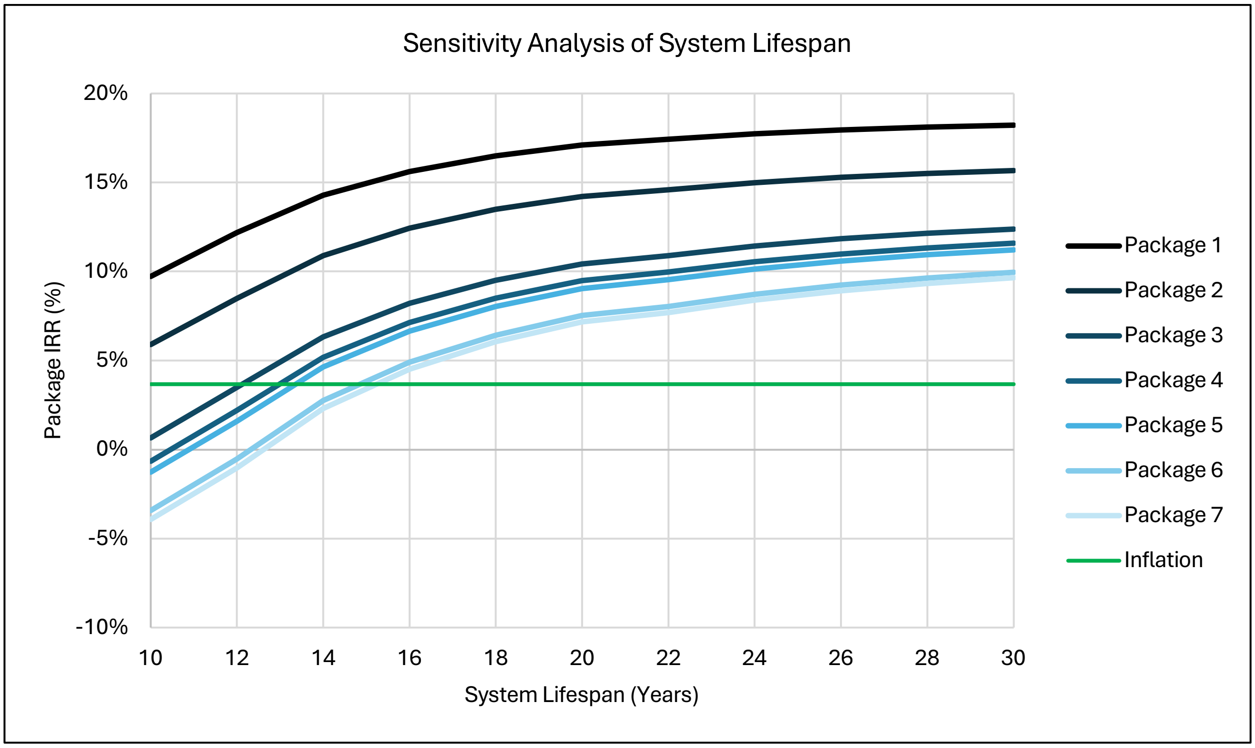


Figure 3. Sensitivity analysis of system lifespan.

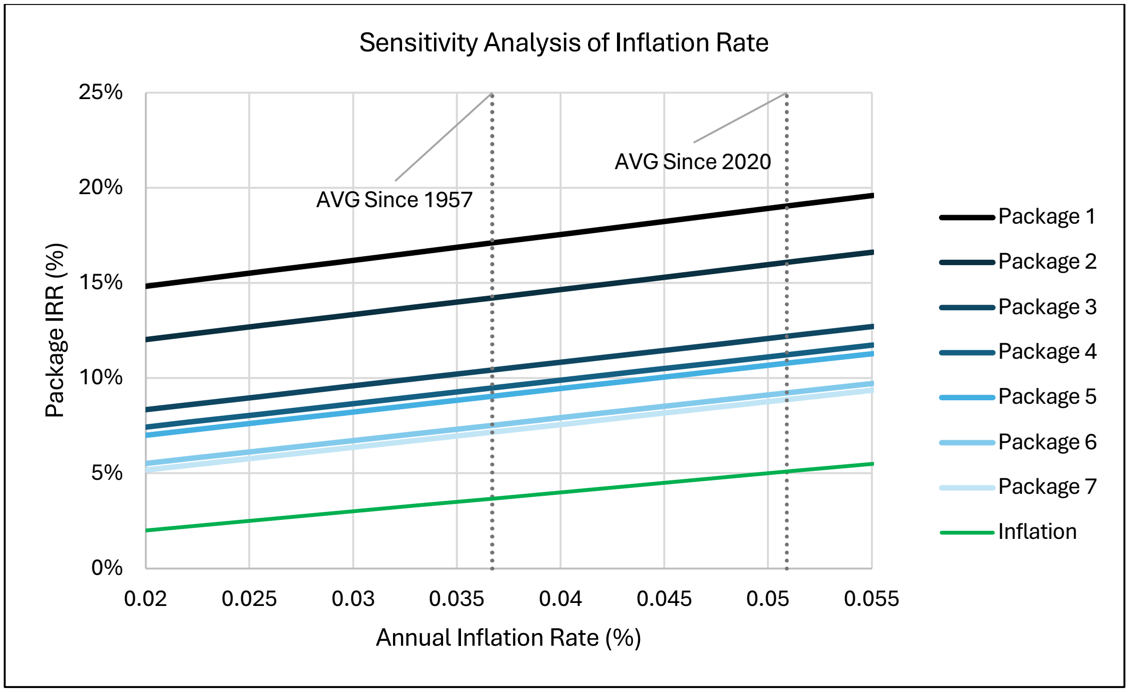


Figure 4. Sensitivity analysis of inflation rate by package.

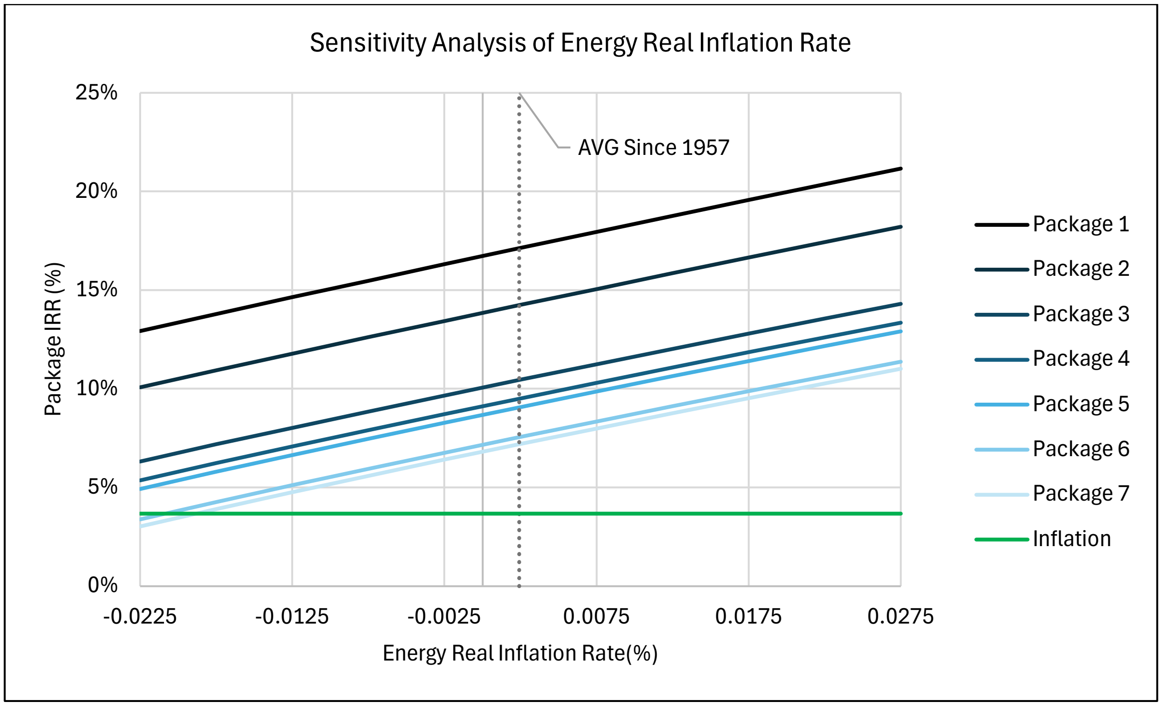


Figure 5. Sensitivity analysis of energy real inflation rate by package.

References

"Calvin College Advances Its Commitment to Environmental Sustainability." Calvin University, 17 July 2024, calvin.edu/news-stories/calvin-college-advances-its-commitment-environmental-sustainability.

"Sustainability Commitments about Calvin | Calvin University." Calvin University, 2020, calvin.edu/about/sustainability/sustainability-commitments.

Appendix A (Overview: Infrastructure & Modeling)

Introduction

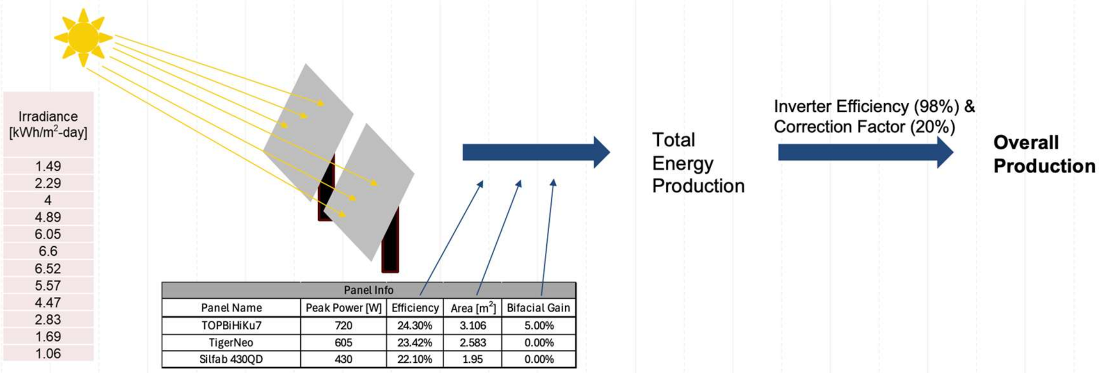
The infrastructure and modeling team was involved in a variety of activities that are referenced throughout the report. The main objective of the team was to facilitate the modeling of various systems as well as directly compare the cost, size, and electrical capacity of such various ideas and configurations to find the most optimal design based on predetermined metrics that are drawn from existing campus conditions. In Appendices B-E, the specific determinations of the calculator, the number of panels, the type of panel, and energy calculations are included, within Appendix B a more general overview of the modeling and calculations of all the other different subsections can be found.

Methods

The infrastructure and modeling group consisted of Daniel John, Ethan Koeman, Ibhar Kamran, and Steve Koopmans. The team utilized multiple online calculators including Sunny Design for initial calculations, Helioscope for mapping out locations to determine placement of arrays and an online irradiance calculator (Footprint Hero) for the typical irradiance in Grand Rapids, Michigan. Communication with the groups initially involved a specification form to then model and became individual conversations with each group. The team made final calculations on multiple excel calculators.

Results

Based on the complete results from the energy calculator, shown per system in Appendices B-F, the overall energy production was determined, with the process of calculations shown in Figure 6 below. The energy production is a function of the irradiance area, number of panels, efficiency, and bifacial gain. The correction factor of 20% was utilized to include unconceivable losses that were not included elsewhere in the calculator.



Irradiance [kWh/m^2-day]
1.49
2.29
4
4.89
6.05
6.6
6.52
5.57
4.47
2.83
1.69
1.06

Panel Info				
Panel Name	Peak Power [W]	Efficiency	Area [m^2]	Bifacial Gain
TOPBiHiKu7	720	24.30%	3.106	5.00%
TigerNeo	605	23.42%	2.583	0.00%
Silfab 430QD	430	22.10%	1.95	0.00%

Figure 6. Variables involved from external solar energy to overall energy production.

A graph summarizing the kW produced by each of the sites is shown below in Figure 7.

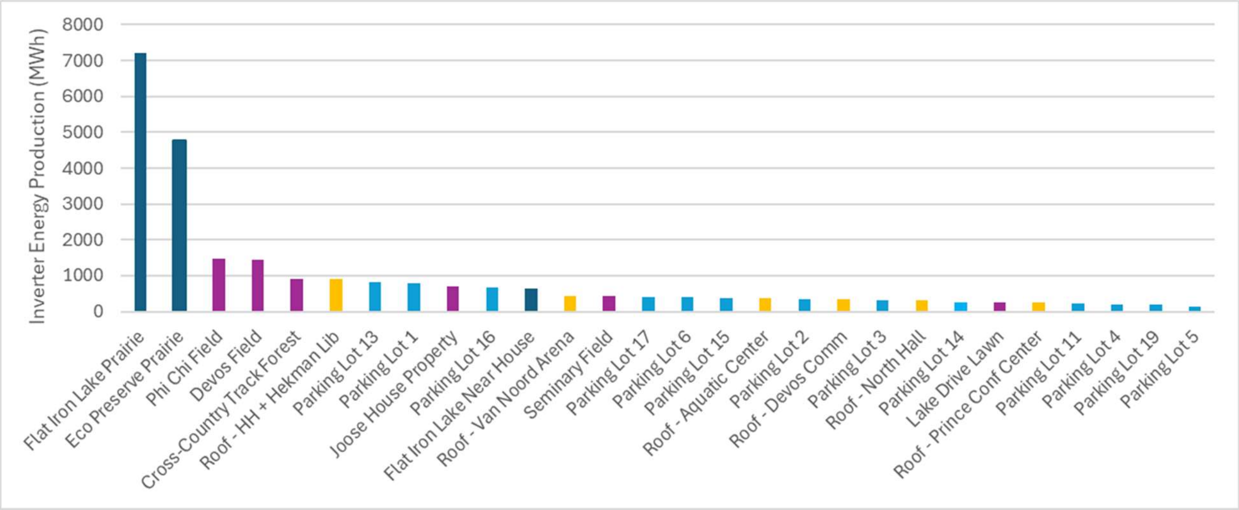


Figure 7. First-year overall energy production (MWh) by section.

With energy production calculations, the cost results were then determined using quotes from Agathon Solar and IronRidge software, with the $/W values of racking, installation, grid installation, and solar panel installation. Using the values and the energy production results, the first-year cost calculations were carried out, and the results are shown in detail in Appendix A1.

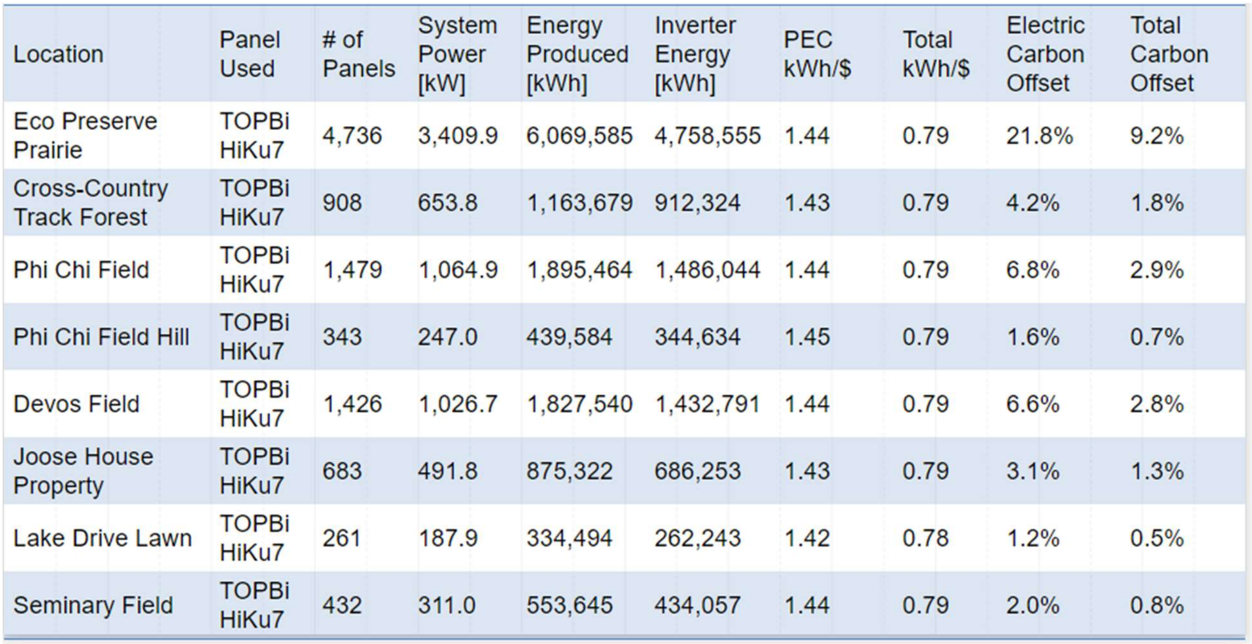
Based on the energy produced and the cost results, the kWh/$, which is an efficiency of sorts, was determined for each system as well. Additionally, the energy calculations and Calvin's energy use was used to determine Calvin electric and total carbon offsets.

Conclusions

The excel calculator that was designed by the infrastructure and modeling section enabled for the other groups to calculate the energy production and the costs associated with each system. The figures show the overall energy production by section and the overall cost productions for each system. More detailed energy and cost production results are discussed in the following Appendices. These results ultimately form the foundation for the financial analysis done in the main body of the report.

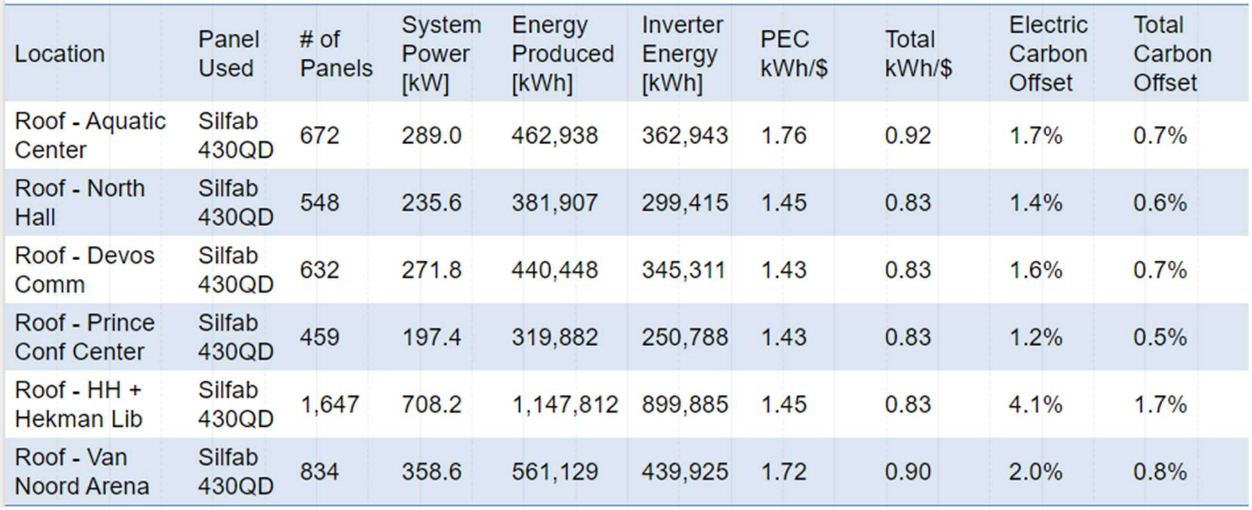
Figures & Tables

Table 3. Ground on-campus farm energy production, cost, and carbon offset results.



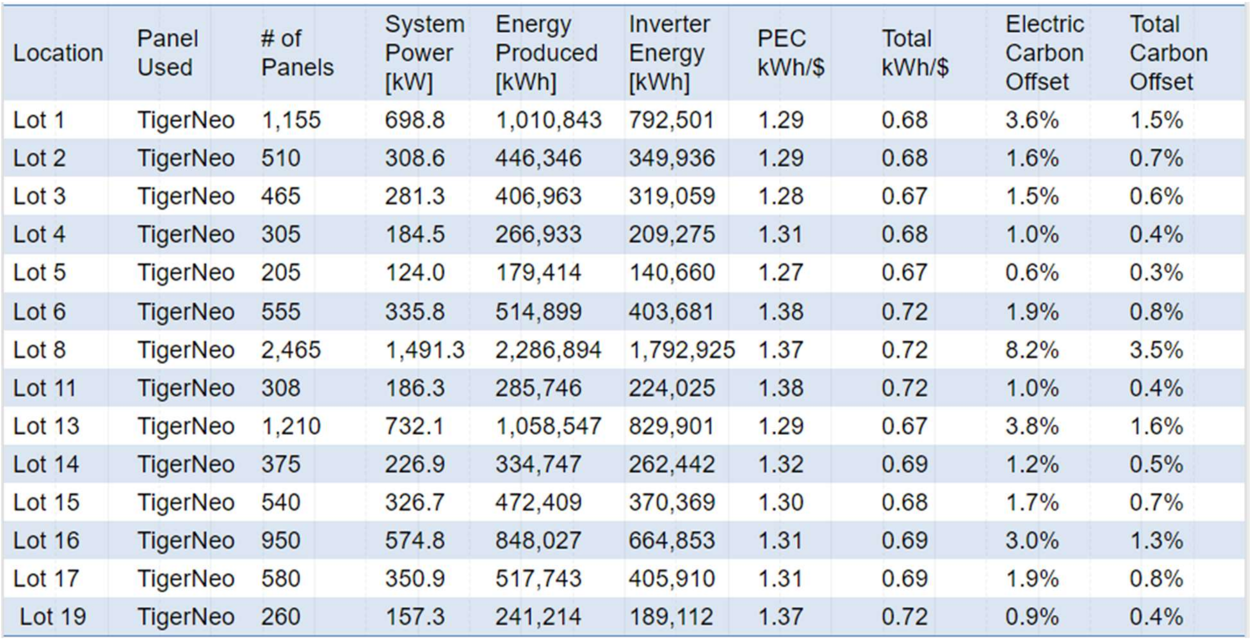
Location	Panel Used	# of Panels	System Power [kW]	Energy Produced [kWh]	Inverter Energy [kWh]	PEC kWh/$	Total kWh/$	Electric Carbon Offset	Total Carbon Offset
Eco Preserve Prairie	TOPBi HiKu7	4,736	3,409.9	6,069,585	4,758,555	1.44	0.79	21.8%	9.2%
Cross-Country Track Forest	TOPBi HiKu7	908	653.8	1,163,679	912,324	1.43	0.79	4.2%	1.8%
Phi Chi Field	TOPBi HiKu7	1,479	1,064.9	1,895,464	1,486,044	1.44	0.79	6.8%	2.9%
Phi Chi Field Hill	TOPBi HiKu7	343	247.0	439,584	344,634	1.45	0.79	1.6%	0.7%
Devos Field	TOPBi HiKu7	1,426	1,026.7	1,827,540	1,432,791	1.44	0.79	6.6%	2.8%
Joose House Property	TOPBi HiKu7	683	491.8	875,322	686,253	1.43	0.79	3.1%	1.3%
Lake Drive Lawn	TOPBi HiKu7	261	187.9	334,494	262,243	1.42	0.78	1.2%	0.5%
Seminary Field	TOPBi HiKu7	432	311.0	553,645	434,057	1.44	0.79	2.0%	0.8%

Table 4. Roof solar farm energy production, cost, and carbon offset results.



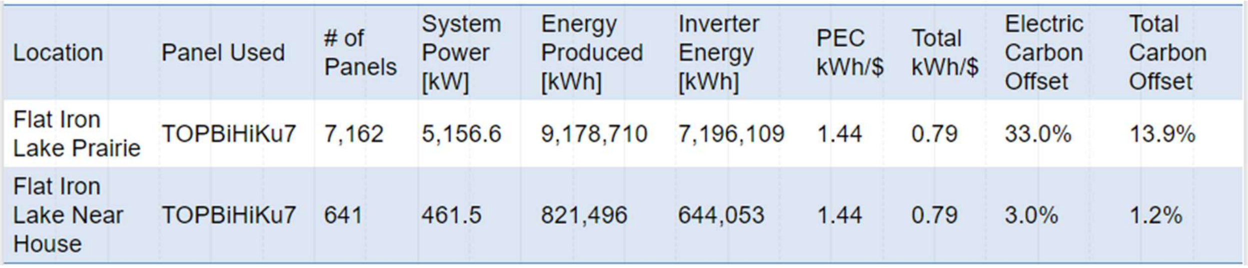
Location	Panel Used	# of Panels	System Power [kW]	Energy Produced [kWh]	Inverter Energy [kWh]	PEC kWh/$	Total kWh/$	Electric Carbon Offset	Total Carbon Offset
Roof - Aquatic Center	Silfab 430QD	672	289.0	462,938	362,943	1.76	0.92	1.7%	0.7%
Roof - North Hall	Silfab 430QD	548	235.6	381,907	299,415	1.45	0.83	1.4%	0.6%
Roof - Devos Comm	Silfab 430QD	632	271.8	440,448	345,311	1.43	0.83	1.6%	0.7%
Roof - Prince Conf Center	Silfab 430QD	459	197.4	319,882	250,788	1.43	0.83	1.2%	0.5%
Roof - HH + Hekman Lib	Silfab 430QD	1,647	708.2	1,147,812	899,885	1.45	0.83	4.1%	1.7%
Roof - Van Noord Arena	Silfab 430QD	834	358.6	561,129	439,925	1.72	0.90	2.0%	0.8%

Table 5. Carpark solar farm energy production, cost, and carbon offset results.



Location	Panel Used	# of Panels	System Power [kW]	Energy Produced [kWh]	Inverter Energy [kWh]	PEC kWh/$	Total kWh/$	Electric Carbon Offset	Total Carbon Offset
Lot 1	TigerNeo	1,155	698.8	1,010,843	792,501	1.29	0.68	3.6%	1.5%
Lot 2	TigerNeo	510	308.6	446,346	349,936	1.29	0.68	1.6%	0.7%
Lot 3	TigerNeo	465	281.3	406,963	319,059	1.28	0.67	1.5%	0.6%
Lot 4	TigerNeo	305	184.5	266,933	209,275	1.31	0.68	1.0%	0.4%
Lot 5	TigerNeo	205	124.0	179,414	140,660	1.27	0.67	0.6%	0.3%
Lot 6	TigerNeo	555	335.8	514,899	403,681	1.38	0.72	1.9%	0.8%
Lot 8	TigerNeo	2,465	1,491.3	2,286,894	1,792,925	1.37	0.72	8.2%	3.5%
Lot 11	TigerNeo	308	186.3	285,746	224,025	1.38	0.72	1.0%	0.4%
Lot 13	TigerNeo	1,210	732.1	1,058,547	829,901	1.29	0.67	3.8%	1.6%
Lot 14	TigerNeo	375	226.9	334,747	262,442	1.32	0.69	1.2%	0.5%
Lot 15	TigerNeo	540	326.7	472,409	370,369	1.30	0.68	1.7%	0.7%
Lot 16	TigerNeo	950	574.8	848,027	664,853	1.31	0.69	3.0%	1.3%
Lot 17	TigerNeo	580	350.9	517,743	405,910	1.31	0.69	1.9%	0.8%
Lot 19	TigerNeo	260	157.3	241,214	189,112	1.37	0.72	0.9%	0.4%

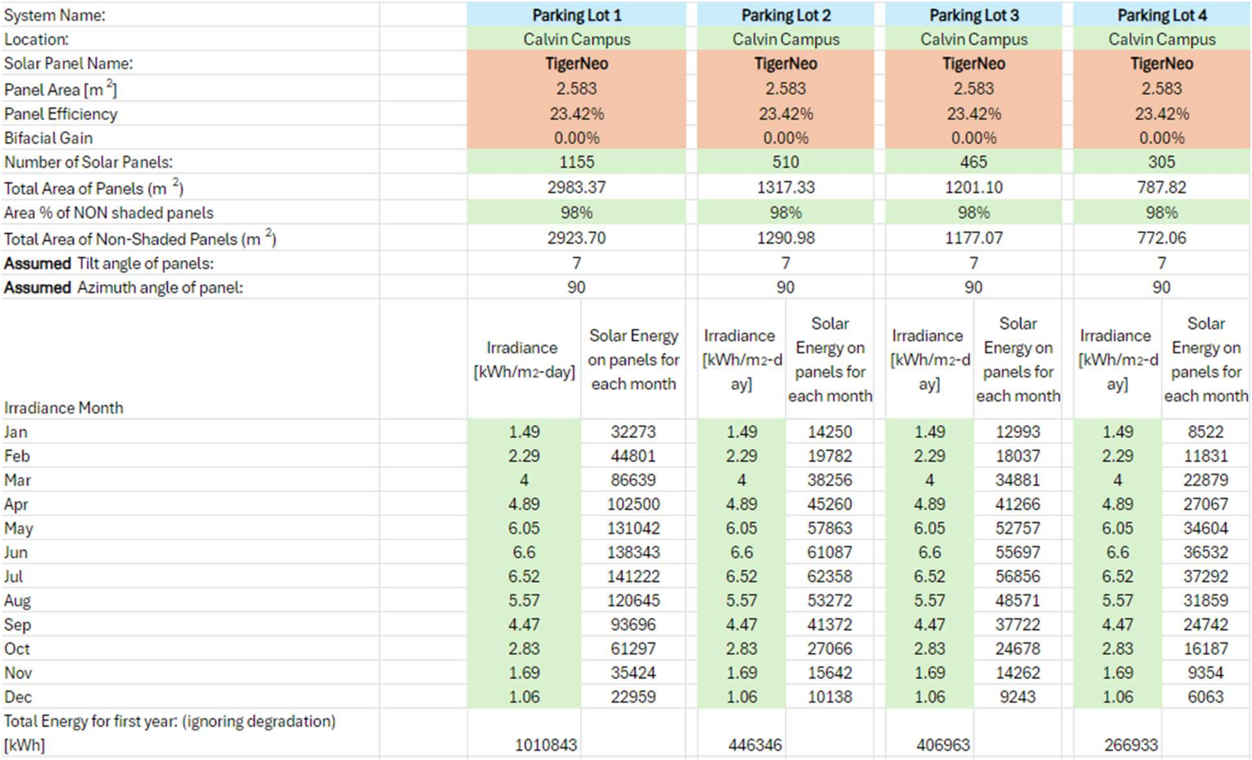
Table 6. Ground off-campus solar farm energy production, cost, and carbon offset results.



Location	Panel Used	# of Panels	System Power [kW]	Energy Produced [kWh]	Inverter Energy [kWh]	PEC kWh/$	Total kWh/$	Electric Carbon Offset	Total Carbon Offset
Flat Iron Lake Prairie	TOPBiHiKu7	7,162	5,156.6	9,178,710	7,196,109	1.44	0.79	33.0%	13.9%
Flat Iron Lake Near House	TOPBiHiKu7	641	461.5	821,496	644,053	1.44	0.79	3.0%	1.2%

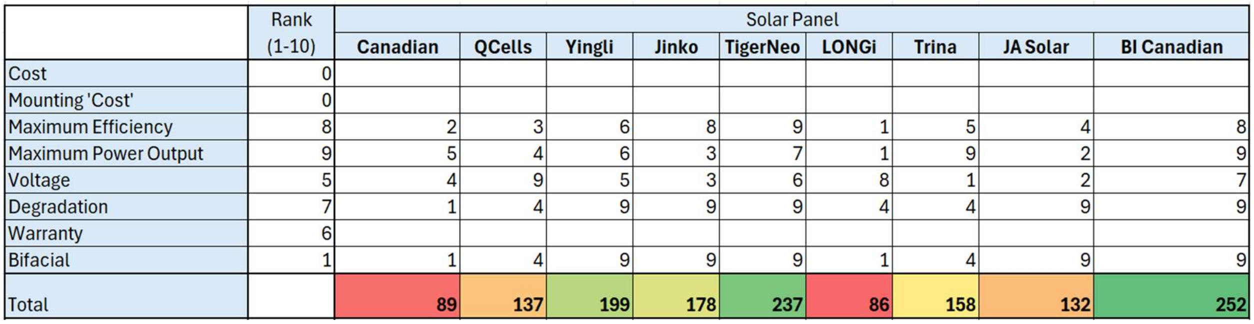
Appendix A1

Table 7. A Microsoft Excel calculator developed to find the energy outputs of various solar panel projects.



System Name:		Parking Lot 1		Parking Lot 2		Parking Lot 3		Parking Lot 4	
Location:		Calvin Campus		Calvin Campus		Calvin Campus		Calvin Campus	
Solar Panel Name:		TigerNeo		TigerNeo		TigerNeo		TigerNeo	
Panel Area [m^2]		2.583		2.583		2.583		2.583	
Panel Efficiency		23.42%		23.42%		23.42%		23.42%	
Bifacial Gain		0.00%		0.00%		0.00%		0.00%	
Number of Solar Panels:		1155		510		465		305	
Total Area of Panels (m^2)		2983.37		1317.33		1201.10		787.82	
Area % of NON shaded panels		98%		98%		98%		98%	
Total Area of Non-Shaded Panels (m^2)		2923.70		1290.98		1177.07		772.06	
Assumed Tilt angle of panels:		7		7		7		7	
Assumed Azimuth angle of panel:		90		90		90		90	
Irradiance Month		Irradiance [kWh/m_2-day]	Solar Energy on panels for each month	Irradiance [kWh/m_2-day]	Solar Energy on panels for each month	Irradiance [kWh/m_2-day]	Solar Energy on panels for each month	Irradiance [kWh/m_2-day]	Solar Energy on panels for each month
Jan		1.49	32273	1.49	14250	1.49	12993	1.49	8522
Feb		2.29	44801	2.29	19782	2.29	18037	2.29	11831
Mar		4	86639	4	38256	4	34881	4	22879
Apr		4.89	102500	4.89	45260	4.89	41266	4.89	27067
May		6.05	131042	6.05	57863	6.05	52757	6.05	34604
Jun		6.6	138343	6.6	61087	6.6	55697	6.6	36532
Jul		6.52	141222	6.52	62358	6.52	56856	6.52	37292
Aug		5.57	120645	5.57	53272	5.57	48571	5.57	31859
Sep		4.47	93696	4.47	41372	4.47	37722	4.47	24742
Oct		2.83	61297	2.83	27066	2.83	24678	2.83	16187
Nov		1.69	35424	1.69	15642	1.69	14262	1.69	9354
Dec		1.06	22959	1.06	10138	1.06	9243	1.06	6063
Total Energy for first year: (ignoring degradation) [kWh]		1010843		446346		406963		266933	

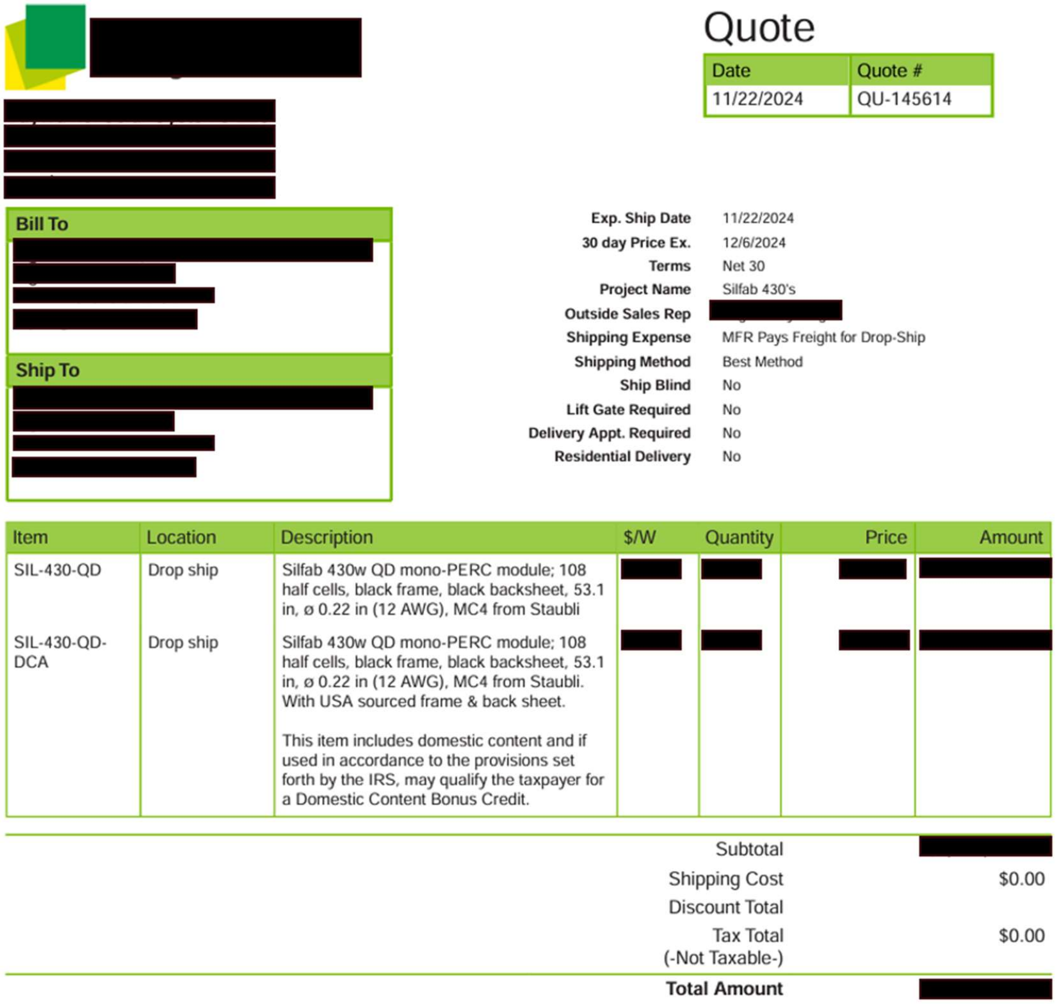
Table 8. A sample of the team's solar panel decision matrix calculator in Microsoft Excel for the ground mounted.



	Rank (1-10)	Solar Panel								
		Canadian	**QCells**	**Yingli**	**Jinko**	**TigerNeo**	**LONGi**	**Trina**	**JA Solar**	**BI Canadian**
Cost	0									
Mounting 'Cost'	0									
Maximum Efficiency	8	2	3	6	8	9	1	5	4	8
Maximum Power Output	9	5	4	6	3	7	1	9	2	9
Voltage	5	4	9	5	3	6	8	1	2	7
Degradation	7	1	4	9	9	9	4	4	9	9
Warranty	6									
Bifacial	1	1	4	9	9	9	1	4	9	9
Total		**89**	**137**	**199**	**178**	**237**	**86**	**158**	**132**	**252**

Table 9. Costs [$/W/ based by mounting type.

Mounting Type	Racking [$/W]	Installation [$/W]	Grid Installation [$/W]	Solar Panel [$/W]
Parking Lot	0.57	0.5	0.3	0.25
Rooftop Slanted	0.26	0.5	0.15	0.39
Rooftop Flat	0.43	0.5	0.15	0.39
Ground	0.5	0.5	0.3	0.41



[redacted]

[redacted]

Quote

Date	Quote #
11/22/2024	QU-145614

Bill To

[redacted]

Ship To

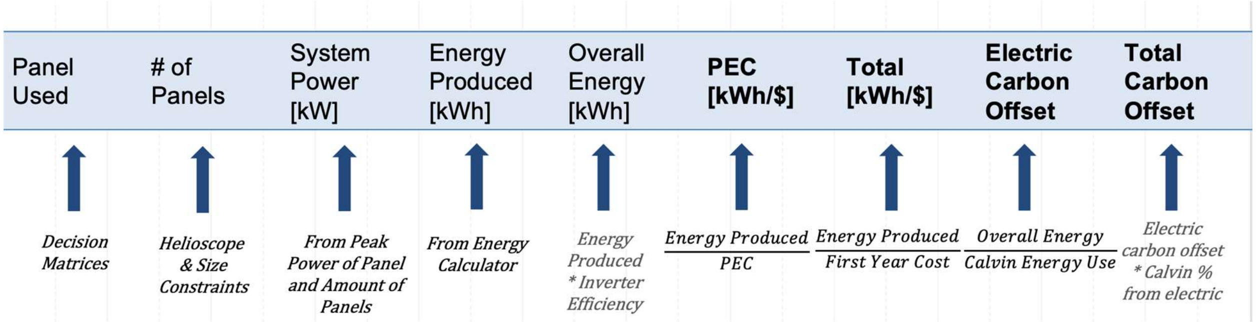
[redacted]

Exp. Ship Date	11/22/2024
30 day Price Ex.	12/6/2024
Terms	Net 30
Project Name	Silfab 430's
Outside Sales Rep	[redacted]
Shipping Expense	MFR Pays Freight for Drop-Ship
Shipping Method	Best Method
Ship Blind	No
Lift Gate Required	No
Delivery Appt. Required	No
Residential Delivery	No

Item	Location	Description	$/W	Quantity	Price	Amount
SIL-430-QD	Drop ship	Silfab 430w QD mono-PERC module; 108 half cells, black frame, black backsheet, 53.1 in, ø 0.22 in (12 AWG), MC4 from Staubli	[redacted]	[redacted]	[redacted]	[redacted]
SIL-430-QD-DCA	Drop ship	Silfab 430w QD mono-PERC module; 108 half cells, black frame, black backsheet, 53.1 in, ø 0.22 in (12 AWG), MC4 from Staubli. With USA sourced frame & back sheet. This item includes domestic content and if used in accordance to the provisions set forth by the IRS, may qualify the taxpayer for a Domestic Content Bonus Credit.	[redacted]	[redacted]	[redacted]	[redacted]

Subtotal	[redacted]
Shipping Cost	$0.00
Discount Total	
Tax Total (-Not Taxable-)	$0.00
Total Amount	[redacted]

Figure 8. Example quote from Agathon Solar that provided installation costs.



Panel Used	# of Panels	System Power [kW]	Energy Produced [kWh]	Overall Energy [kWh]	**PEC [kWh/$]**	**Total [kWh/$]**	**Electric Carbon Offset**	**Total Carbon Offset**
Decision Matrices	*Helioscope & Size Constraints*	*From Peak Power of Panel and Amount of Panels*	*From Energy Calculator*	*Energy Produced * Inverter Efficiency*	$\frac{\text{Energy Produced}}{\text{PEC}}$	$\frac{\text{Energy Produced}}{\text{First Year Cost}}$	$\frac{\text{Overall Energy}}{\text{Calvin Energy Use}}$	*Electric carbon offset * Calvin % from electric*

Figure 9. Descriptions and calculations involved for energy, cost, and carbon offset.

Figure 10. Campus map showing on-campus locations to be modeled and calculated for energy and cost.

Appendix B (Ground On-Campus)

Introduction

One appealing mode of solar power is ground-mounted arrays. Ground-mounted arrays require minimal structural and installation costs, and do not rely on previously existing infrastructure. The Ground-On Campus team identified seven sites for solar panels that produce an optimal amount of power for Campus. These sites were selected based on land geometry, size, solar irradiance, and the likelihood of the land being available for solar installations. Some of the challenges faced were the competing interests of various groups on campus land; for example, large areas of currently free land on the northwest side of campus are likely the site of Calvin's upcoming football field and were therefore disqualified as potential location.

Methods

Calvin's campus has many open, undeveloped spaces and wooded areas with no current use. The team, including Vardhan Adhikari, Diana Bracamonte, John Gibes, and Kai Zwarg, surveyed possible areas and evaluated their potential. Clearing costs were a key consideration, leading to the rejection of most wooded areas except a parcel south of Campus Drive, north of the cross-country course, due to high tree removal costs and poor optics of leveling green spaces. The eco preserve prairie, covered in light shrubbery, was suggested for its potential to host many panels. However, it is unlikely Calvin would install solar panels in the eco preserve due to its protected status (confirmed by Jamie Skillen, a geography professor and director of the preserve) and other economic factors.

The team met with Dirk Pruis to discuss Calvin's strategic plan and identify areas likely to face resistance for solar farm planning. Dirk noted that the northwest fields might be used for a future football stadium, and a strip south of the eco preserve was part of the country course and unavailable. Diana surveyed the KE residents to see what east campus field would be beneficial to use for solar panels, the results were Devos Field over Phi-Chi field.

The final sites that were selected is as follows, in the order of most panels to least: the Eco Preserve Prairie, Phi Chi field and the nearby hill, Devos Field, the cross-country track forest, the Hampshire Drive property, and the north entrance lawn on Lake Drive. A map with all locations labeled can be found in Figure 11. For the selection of panels, the team used various criteria such as efficiency, wattage per square foot, and weight. The team consulted the Infrastructure and Modeling Team, which utilized a panel decision matrix and recommended the Canadian Solar model TOPBiHiKu7. The panel had an STC rating of 720 W, an efficiency of 23.2%, and a weight of 37.8 kg (83.34 lbs). With the land size for the seven locations and solar panel identified, the data was handed to the modeling team. Collaboration with the Infrastructure and Modeling team streamlined solar optimization. A spreadsheet with Helioscope data gave quick estimates of ideal outputs for each location, enabling efficient layout testing. The infrastructure team incorporated Michigan's irradiance data for a more realistic analysis, ensuring the final designs aligned with actual performance expectations. Additionally, the Physics 133 class's simulation data provided a more in-depth study of year-round power generation when optimizing tilt and azimuth angles, as well as calculating the real cost savings provided by each system.

To estimate the total cost, the team consulted Greg Oliver from Agathon Solar, who recommended using IronRidge for design and cost estimation. The team decided on ground screws for rack securing, as they are more cost-effective and feasible for Michigan's ground conditions. IronRidge calculated cumulative panel costs, while data from campus utility drawings were used to map the campus grid and plan cable routing. This information was then handed to the infrastructure team for routing length estimates.

Results

The total max rated power generated across all locations is 7,393 kW, with a combined total of 10,268 solar panels installed. The cumulative purchase cost of these solar systems amounts to $13,092,892. This data highlights the scale and investment in renewable solar energy projects at these sites, showcasing the significant resources allocated to ensure sustainable energy production. Detailed data at each site can be found in Table 10.

The largest-producing and most expensive site from the data was the Eco Preserve Prairie, which was simulated to have a lifetime generation of 6,069,585 kWh and a total cost of $6,035,976. The least was found to be Lake Drive Lawn with production of 334,494 kWh and a cost of $334,975. Energy production and the costs of each project can be found in Table 10 as well.

Conclusions

Although the larger installations such as the Eco Preserve Prairie or Devos Field provide the most power of the ground-mounted on-campus options, when the class looked for projects to add to their final recommendation, only the smallest installations, namely Lake Drive Lawn and the Seminary Field, were included. This is because massive projects such as the Eco Preserve Prairie quickly push the total power production to overproduction. Additionally, on average, ground-mounted arrays cost slightly more than roof arrays, which makes roof arrays the priority. Despite this, some implementation of ground-mounted arrays on Calvin's campus would be a sustainable use of Calvin's land and a good addition to Calvin's solar farm.

Figures & Tables

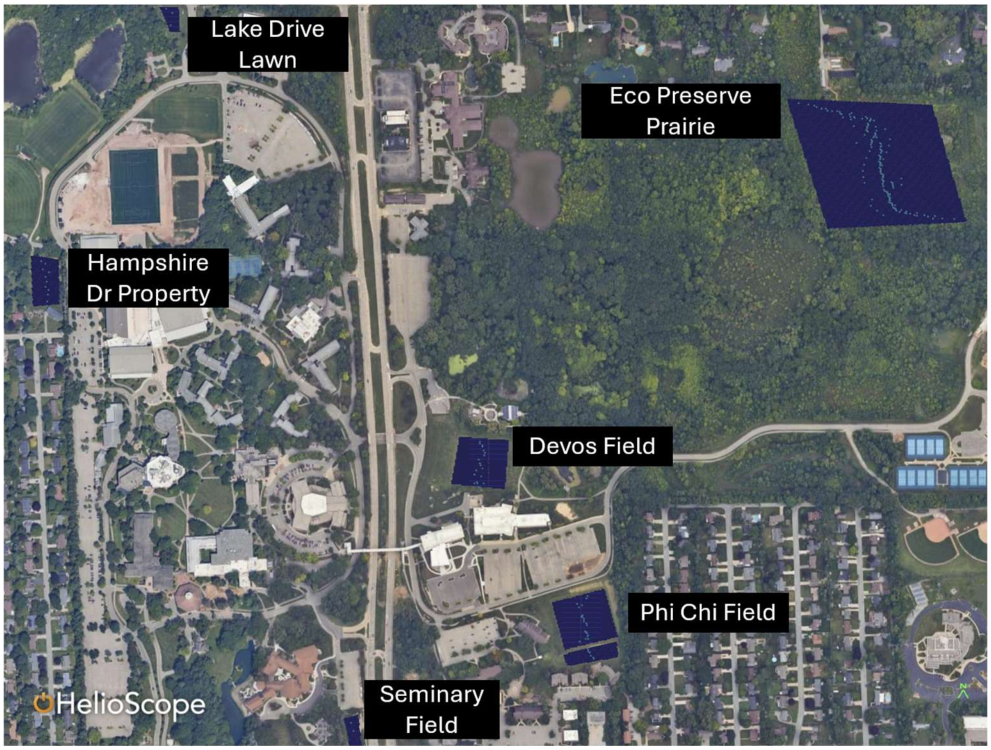


Figure 11. Campus Map Showing Ground-Mounted Locations.

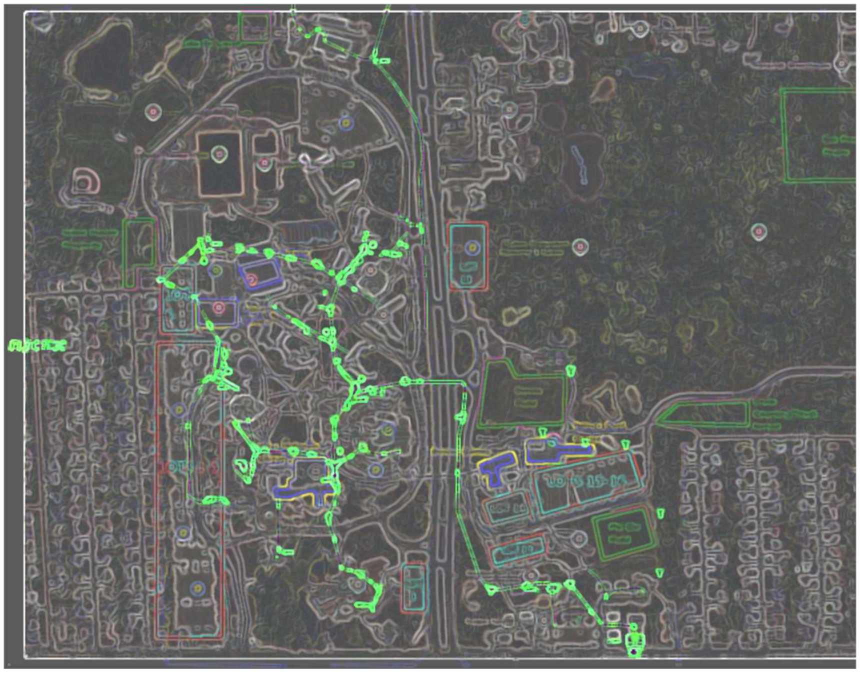
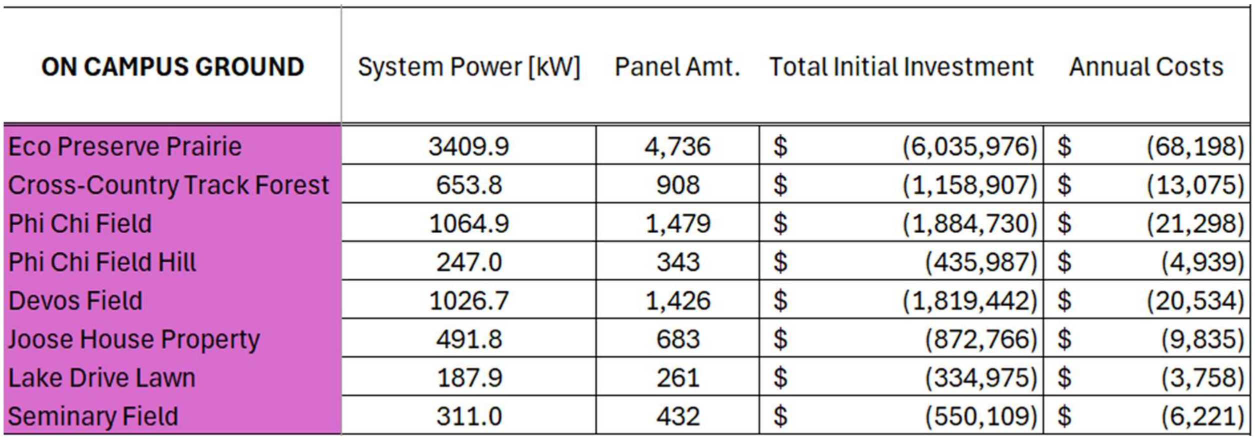


Figure 12. Map Showing Campus Power Distribution Lines.

Table 10. Power and Cost Breakdown by Project.



ON CAMPUS GROUND	System Power [kW]	Panel Amt.	Total Initial Investment	Annual Costs
Eco Preserve Prairie	3409.9	4,736	$ (6,035,976)	$ (68,198)
Cross-Country Track Forest	653.8	908	$ (1,158,907)	$ (13,075)
Phi Chi Field	1064.9	1,479	$ (1,884,730)	$ (21,298)
Phi Chi Field Hill	247.0	343	$ (435,987)	$ (4,939)
Devos Field	1026.7	1,426	$ (1,819,442)	$ (20,534)
Joose House Property	491.8	683	$ (872,766)	$ (9,835)
Lake Drive Lawn	187.9	261	$ (334,975)	$ (3,758)
Seminary Field	311.0	432	$ (550,109)	$ (6,221)

Appendix C (Ground Off-Campus)

Introduction

The Ground Off-Campus team identified two potential sites at Flat Iron Lake Preserve for solar energy production. These locations, selected for their solar irradiance, land availability, and zoning flexibility, align with Calvin University's sustainability goals. Solar installations at these sites would reduce the university's reliance on fossil fuels and carbon dioxide emissions. Additionally, they could stabilize Calvin's energy use during peak sunlight hours, reducing strain on the local grid and reducing costs. By utilizing these off-campus sites, the university could generate renewable energy year-round, demonstrating its commitment to environmental stewardship and carbon neutrality.

Methods

The team, consisting of Drew Barcelow, Ryan Antwi-Donkor, and Brandon Eenigenburg, selected two university-owned sites: a prairie west of the lake and an area near a Calvin-owned house to the east (Figures 13 and 14). These locations were chosen for their clear, flat terrain, ideal for solar panel installation. Using GIS mapping tools, the team calculated the available land area, eliminating the need for property acquisition costs.

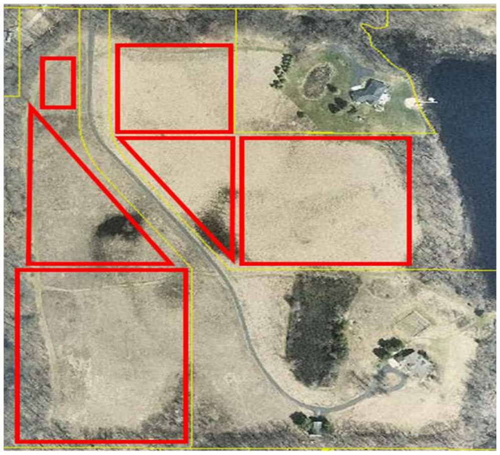


Figure 13. Flat Iron prairie.

Figure 14. Flat Iron near house site.

For the solar panels, the Canadian Solar 715-watt model was selected due to its 23.3% efficiency, outperforming comparable models. While heavier at 83.33 pounds, this poses no issue for ground-mounted installations. These panels were paired with inverter and racking systems suitable for larger-scale solar farms. Compatibility with Consumers Energy's solar buy-back program, supported by Michigan state policies, was a key consideration.

Performance modeling, based on solar irradiance data and site acreage, estimated energy production. Although the sites showed high energy potential, the ability of the local grid at Flat Iron to sustain the generated power required evaluation. Initial plans for battery storage were rules out due to logistical challenges.

Results

Energy production for the two sites was calculated based on average monthly irradiance, panel efficiency, and bifacial gains. The prairie site is projected to generate 8,815,223 kWh in its first year, while the near-house site will produce 788,965 kWh, as shown in Table 11. These sites contribute approximately 28% of the total energy output from all projects.

Connecting these systems to the grid requires careful consideration. The near-house site, with a system capacity of 462 kW, falls below Consumers Energy’s 550 kW limit for direct connection to the 25 kV distribution network. In contrast, the prairie site’s 5,157 kW capacity exceeds this limit, requiring upgrades such as three-phase service and enhanced power lines. These improvements incur additional costs, including a $6,500 interconnection application fee and a $250-$300 feasibility review. Using historical data from MISO’s website, the estimated energy buyback rate through Consumers Energy is $0.08/kWh (see Figure 15).

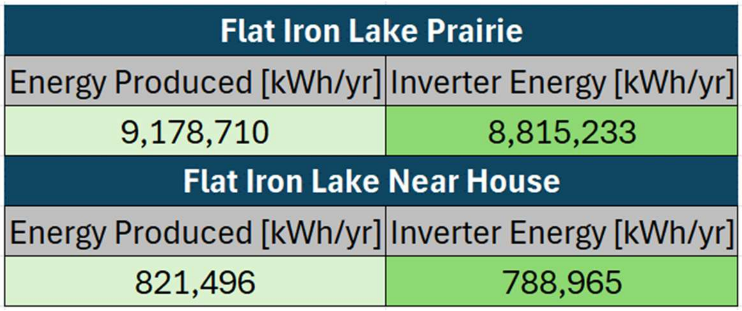
Cost analysis divided expenses into purchased equipment and installation plus interconnection costs (Appendix C1). The total cost for the prairie site is $9,132,143, while the near-house site totals $816,540 (Table 12). Hosting capacity data indicates the near-house site can connect directly to the grid without significant upgrades, while the prairie site requires substantial investment to accommodate its higher capacity. Key cost metrics are summarized in Table 14, which provide insight into the financial viability of the projects and their contributions to carbon neutrality.

Conclusions

The Flat Iron Lake Preserve sites offer significant potential for advancing Calvin University’s sustainable initiatives. The near-house site is a smaller-scale project that integrates easily into the existing grid, while the prairie site, with its higher energy output, requires infrastructure upgrades. Despite these challenges, the environmental and financial benefits of these installations make them promising steps toward carbon neutrality. By utilizing these solar farms, Calvin University can reduce energy costs, decrease its carbon footprint, and solidify its commitment to renewable energy. Although they were not included in the recommended package of on-campus locations, off-campus solar installations could be a worthwhile investment for Calvin University.

Figures & Tables

Table 11. Energy production at both sites.



Flat Iron Lake Prairie	
Energy Produced [kWh/yr]	Inverter Energy [kWh/yr]
9,178,710	8,815,233
Flat Iron Lake Near House	
Energy Produced [kWh/yr]	Inverter Energy [kWh/yr]
821,496	788,965

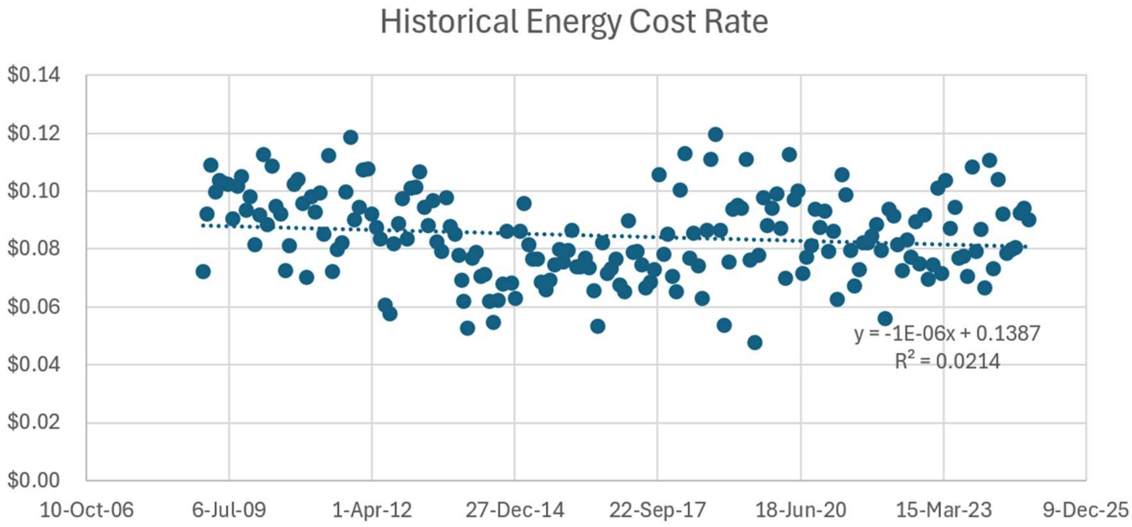
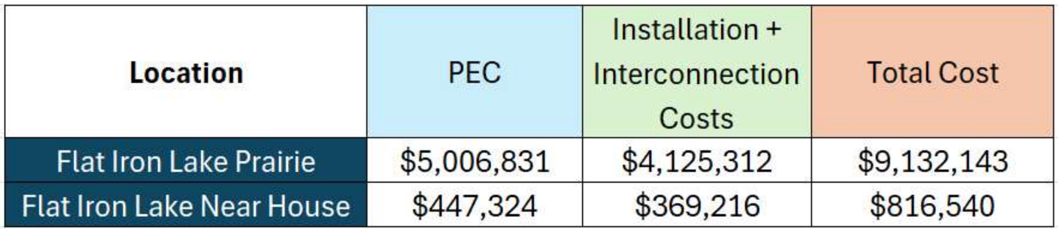


Figure 15. The historical MISO data analyzed.

Table 12. Shows cost breakdowns for both sites.



Location	PEC	Installation + Interconnection Costs	Total Cost
Flat Iron Lake Prairie	$5,006,831	$4,125,312	$9,132,143
Flat Iron Lake Near House	$447,324	$369,216	$816,540

Table 13. Shows system details for both sites.

OFF CAMPUS	System Power [kW]	Inverter Amount	Panel Amount	Total Initial Investment	Annual Costs
Flat Iron Lake Prairie	5157	69	7162	$9,132,143	$103,133
Flat Iron Lake Near House	462	6	641	$816,540	$9,230

Table 14. Shows cost metrics for both sites.

OFF CAMPUS	Total Initial Investment/Project Power Rating [$/W]	First Year Energy/Initial Investment [kWh/$]	Payback Period [Years]	30-Year Return on Investment [%]	Carbon Neutrality of Electricity [%]
Flat Iron Lake Prairie	1.77	0.79	9	36%	17%
Flat Iron Lake Near House	1.77	0.79	9	36%	2%

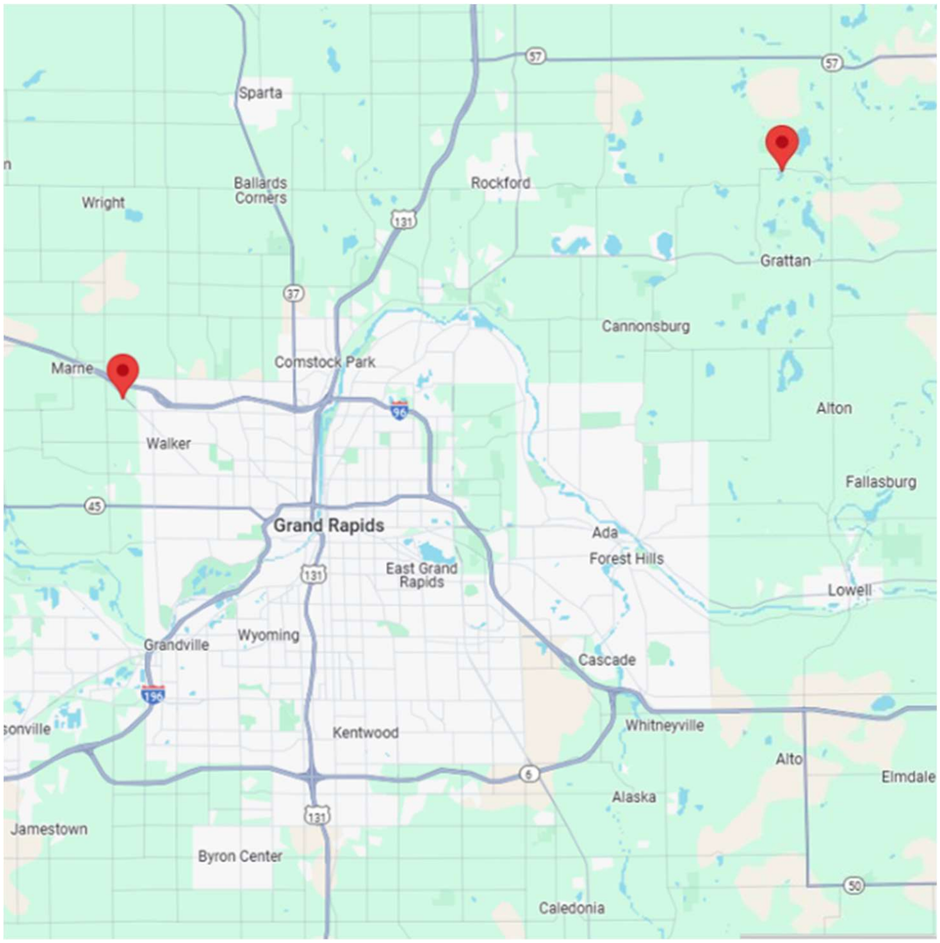
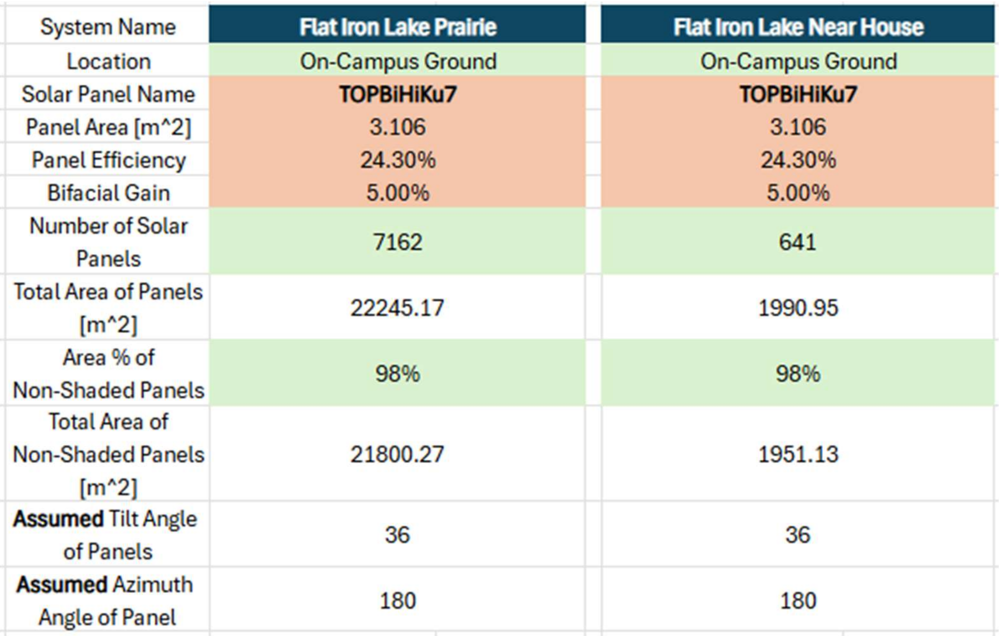


Figure 16. Shows the locations of the off-campus locations.

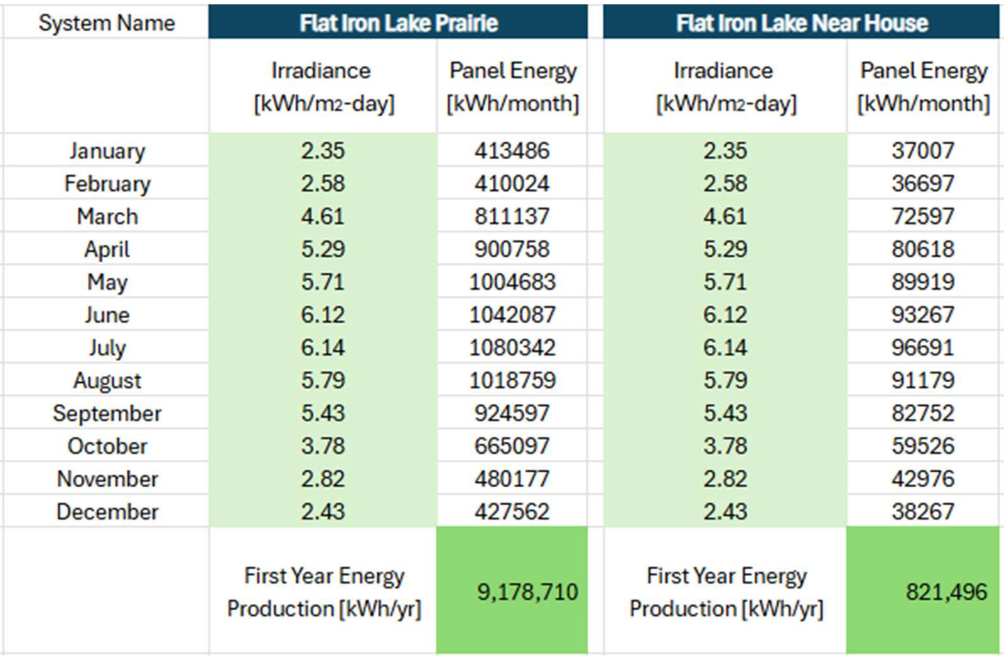
Appendix C1

Table 15. Shows the energy production.



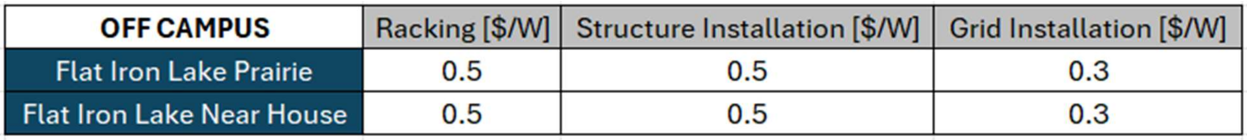
System Name	Flat Iron Lake Prairie	Flat Iron Lake Near House
Location	On-Campus Ground	On-Campus Ground
Solar Panel Name	**TOPBiHiKu7**	**TOPBiHiKu7**
Panel Area [m^2]	3.106	3.106
Panel Efficiency	24.30%	24.30%
Bifacial Gain	5.00%	5.00%
Number of Solar Panels	7162	641
Total Area of Panels [m^2]	22245.17	1990.95
Area % of Non-Shaded Panels	98%	98%
Total Area of Non-Shaded Panels [m^2]	21800.27	1951.13
Assumed Tilt Angle of Panels	36	36
Assumed Azimuth Angle of Panel	180	180

Table 16. Shows the energy production calculation process.



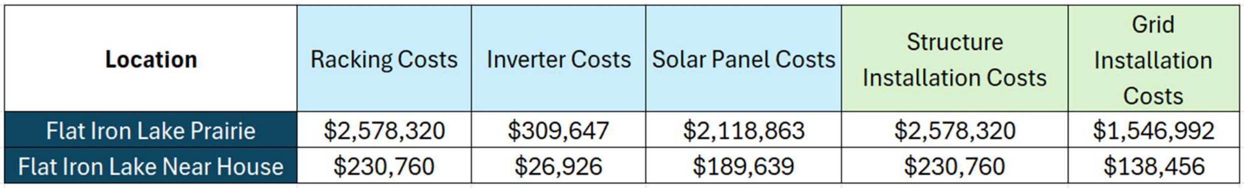
System Name	Flat Iron Lake Prairie		Flat Iron Lake Near House	
	Irradiance [kWh/m_2-day]	Panel Energy [kWh/month]	Irradiance [kWh/m_2-day]	Panel Energy [kWh/month]
January	2.35	413486	2.35	37007
February	2.58	410024	2.58	36697
March	4.61	811137	4.61	72597
April	5.29	900758	5.29	80618
May	5.71	1004683	5.71	89919
June	6.12	1042087	6.12	93267
July	6.14	1080342	6.14	96691
August	5.79	1018759	5.79	91179
September	5.43	924597	5.43	82752
October	3.78	665097	3.78	59526
November	2.82	480177	2.82	42976
December	2.43	427562	2.43	38267
	First Year Energy Production [kWh/yr]	9,178,710	First Year Energy Production [kWh/yr]	821,496

Table 17. Shows cost per power for racking and installation costs.



OFF CAMPUS	Racking [$/W]	Structure Installation [$/W]	Grid Installation [$/W]
Flat Iron Lake Prairie	0.5	0.5	0.3
Flat Iron Lake Near House	0.5	0.5	0.3

Table 18. Shows farther cost breakdown for both sites.



Location	Racking Costs	Inverter Costs	Solar Panel Costs	Structure Installation Costs	Grid Installation Costs
Flat Iron Lake Prairie	$2,578,320	$309,647	$2,118,863	$2,578,320	$1,546,992
Flat Iron Lake Near House	$230,760	$26,926	$189,639	$230,760	$138,456

Appendix D (Rooftop)

Introduction

The rooftop team identified six roofs which could sufficiently house solar panels and provide optimal solar production to reduce the overall peak of Calvin University's energy usage. This involved identifying which rooftops were viable to install panels on, which panel would be the most cost and weight efficient and finding the total cost and the return for different systems on different rooftops.

Methods

The team examining the rooftops consisted of Nickolas Heuker, Ethan Wayne, Ryan Westra, and Colton Vanderhoning. The six roofs chosen for the Calvin University Solar Array were the Venema Aquatic Center, North Hall, Devos Communication Center, Prince Conference Center, Hiemenga Hall, Hekman Library, and Van Noord Arena. These selections were based off several characteristics including size, orientation, structural capabilities, age, and condition.

The first factors considered were the age and condition of each roof on campus. This data was provided by Tremco, a construction products group, which conducted a detailed analysis of the roofs' ages and conditions, along with recommendations for whether they should be maintained, repaired, or fully replaced. Each roof was assigned a priority level for implementing these recommendations, with Priority I being the most urgent and Priority III the least. Based on this information, the selected roofs were either in fair condition or scheduled for replacement in the near future.

Another factor considered was the size of the roof. The selected roofs are among the largest on campus, allowing for the installation of a significant number of solar panels and enhancing overall power production. Another key consideration was roof orientation. In Michigan, south-facing roofs offer better solar energy potential, so these were prioritized over others. Initially, the analysis focused on the Venema Aquatic Center and Van Noord Arena roofs, as their southern orientation and optimal tilt angle made them more suitable for solar arrays compared to flat roofs. The roofs selected were also not affected by shading from other objects. In collaboration with the structural teams from ENGR 327, the roofs were analyzed for their ability to support solar panels. The analysis confirmed that the roofs are structurally sound for this purpose, accounting for factors such as the weight of each panel, the racking system for installation, and snow loads based on Michigan's snowfall. Models were developed using Helioscope, a commercial solar panel modeling software, which allowed the team to determine the number of panels and peak output based on the selected solar panel type, tilt angle, and azimuth angle. The rooftop team selected the Silfab SIL-430 QD DCA solar panel as the optimal choice. This decision was based on key factors such as price, weight, size, and recommendations from an industrial consultant at Agathon Solar. For flat roofs, the optimal tilt angle was determined to be 30.5°, a value established in collaboration with PHYS-131 teams to ensure suitability for West Michigan's climate. The azimuth angle varied for each roof to maximize the number of panels that could be installed. Additionally, every solar array design was reviewed to ensure compliance with standard building codes. The main components when analyzing cost include panel price, installation price, and operational and maintenance costs. The cost for the Silfab SIL-430 QD solar panel was evaluated on a per watt basis, where the cost per watt of the panel was 0.4348 [$/W].

The installation and maintenance costs were estimated from a report by the National Renewable Energy Laboratory (NREL) outlining cost benchmarks for Q1 in 2021. Installation costs were evaluated based on the size of the system, with each roof's production similar in size to those in the report, these values were then converted to 2024 dollars. The different components which make up the installation costs for the Calvin solar array are shown in Table D1 in the Appendix. The maintenance costs were evaluated based on a fixed number evaluated by NREL and brought to 2024 dollars. These results were verified with quotes provided by Agathon Solar, with models provided by the Infrastructure and Modeling team.

Results

Table D4 presents the lifetime costs of the solar system over a thirty-year period, which is the average lifespan of a solar panel before requiring replacement. The rooftops selected on campus offer the most cost-effective options for solar arrays, with payback periods ranging from twelve to fourteen years. Although North Hall was initially included as one of the rooftops for the solar array, ENGR 327 determined that insufficient data was available to confirm the roof's structural integrity, leading to its exclusion. Similarly, there was not enough information to assess the structural stability of Van Noord Arena. These calculations are included in the project for future reference, pending confirmation of the roofs' stability.

Conclusions

The rooftop team identified six roofs to be included in the Calvin University Solar Array. These roofs were selected based on key factors such as structural stability, size, orientation, age, and overall condition. The Silfab SIL-430 QD solar panel was chosen as the most suitable option due to its optimal balance of weight, cost, and production capabilities, along with strong recommendations from industry professionals. Ultimately, the selected rooftops offer the best combination of feasibility and cost-effectiveness for Calvin University's solar panel installation, with top choices being the Venema Aquatic Center and Van Noord Arena.

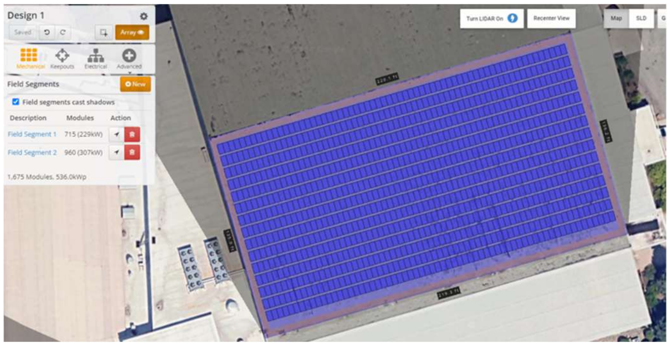
Figures & Tables

Figure 17. Roof locations for Calvin University solar array.

Figure 18. Helioscope model of Devos Building.

Figure 19. Helioscope model of Hekman Library and Hiemenga Hall.

Figure 20. Helioscope model of North Hall.

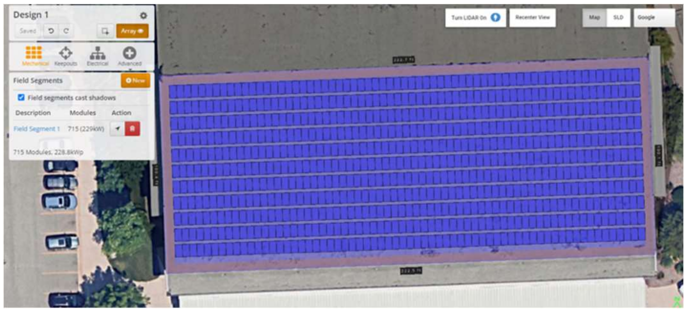


☑ Field segments cast shadows

Description	Modules	Action
Field Segment 1	715 (229kW)	
Field Segment 2	960 (307kW)	

1,675 Modules, 536.0kWp

Figure 21. Helioscope model of Van Noord Arena.



☑ Field segments cast shadows

Description	Modules	Action
Field Segment 1	715 (229kW)	

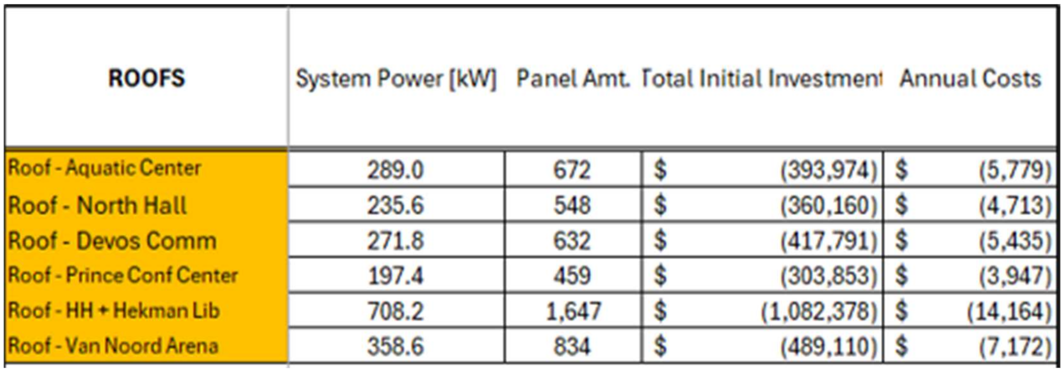
715 Modules, 228.8kWp

Figure 22. Helioscope model of Venema Aquatic Center.

Table 19. Internal cost determinations.

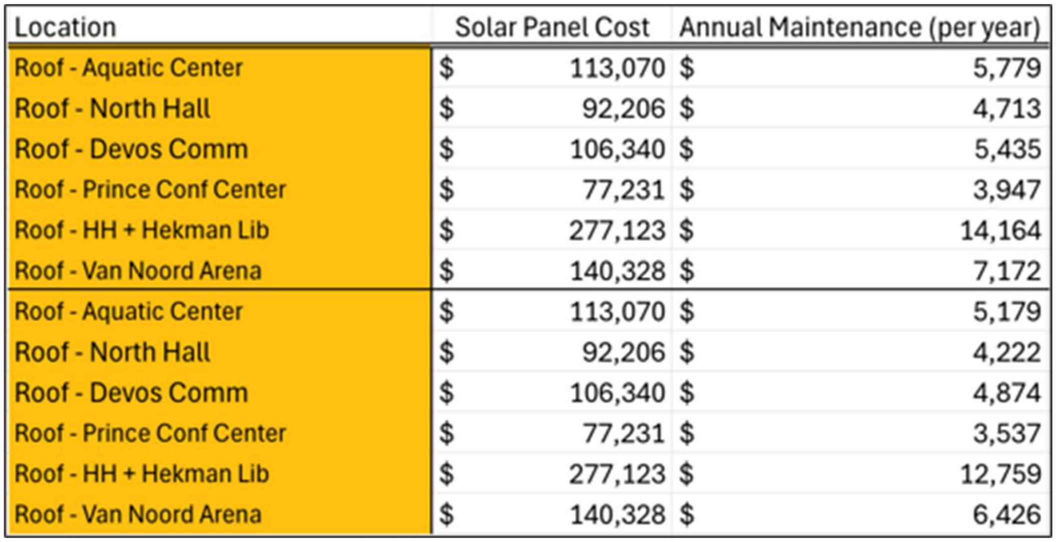
Cost type	.2 MW system costs per watt	.5 MW system	1 MW system
EPC/developer profit	$0.10	$0.10	$0.09
contingency (4%)	$0.04	$0.04	$0.04
Developer overhead	$0.30	$0.28	$0.27
Sales tax	$0.04	$0.04	$0.04
Permitting+inspectio	$0.09	$0.07	$0.06
EPC overhead	$0.16	$0.15	$0.15
Install+Labor	$0.15	$0.12	$0.11
Electrical BOS	$0.14	$0.13	$0.13
Structural BOS	$0.11	$0.10	$0.11
Inverter Only	$0.09	$0.09	$0.09
Total	$1.22	$1.12	$1.09

Table 20. Cost metrics.



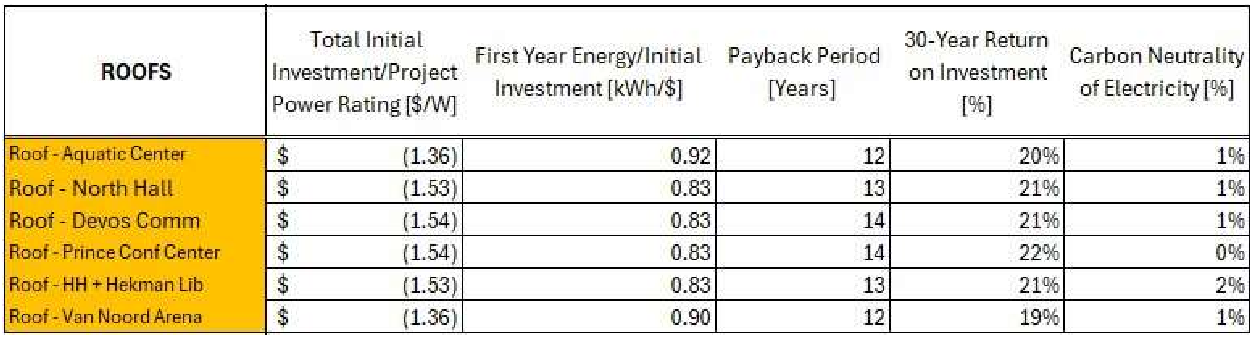
ROOFS	System Power [kW]	Panel Amt.	Total Initial Investment	Annual Costs
Roof - Aquatic Center	289.0	672	$ (393,974)	$ (5,779)
Roof - North Hall	235.6	548	$ (360,160)	$ (4,713)
Roof - Devos Comm	271.8	632	$ (417,791)	$ (5,435)
Roof - Prince Conf Center	197.4	459	$ (303,853)	$ (3,947)
Roof - HH + Hekman Lib	708.2	1,647	$ (1,082,378)	$ (14,164)
Roof - Van Noord Arena	358.6	834	$ (489,110)	$ (7,172)

Table 21. Calculation verification.



Location	Solar Panel Cost	Annual Maintenance (per year)
Roof - Aquatic Center	$ 113,070	$ 5,779
Roof - North Hall	$ 92,206	$ 4,713
Roof - Devos Comm	$ 106,340	$ 5,435
Roof - Prince Conf Center	$ 77,231	$ 3,947
Roof - HH + Hekman Lib	$ 277,123	$ 14,164
Roof - Van Noord Arena	$ 140,328	$ 7,172
Roof - Aquatic Center	$ 113,070	$ 5,179
Roof - North Hall	$ 92,206	$ 4,222
Roof - Devos Comm	$ 106,340	$ 4,874
Roof - Prince Conf Center	$ 77,231	$ 3,537
Roof - HH + Hekman Lib	$ 277,123	$ 12,759
Roof - Van Noord Arena	$ 140,328	$ 6,426

Table 22. Cost Metrics (cont.).



ROOFS	Total Initial Investment/Project Power Rating [$/W]	First Year Energy/Initial Investment [kWh/$]	Payback Period [Years]	30-Year Return on Investment [%]	Carbon Neutrality of Electricity [%]
Roof - Aquatic Center	$ (1.36)	0.92	12	20%	1%
Roof - North Hall	$ (1.53)	0.83	13	21%	1%
Roof - Devos Comm	$ (1.54)	0.83	14	21%	1%
Roof - Prince Conf Center	$ (1.54)	0.83	14	22%	0%
Roof - HH + Hekman Lib	$ (1.53)	0.83	13	21%	2%
Roof - Van Noord Arena	$ (1.36)	0.90	12	19%	1%

References

V. Ramasamy, D. Feldman, J. Desai, and R. Margolis, “U.S. Solar Photovoltaic System and Energy Storage Cost Benchmarks: Q1 2021,” 2021. Available: https://www.nrel.gov/docs/fy22osti/80694.pdf

Appendix E (Car Park)

Introduction

The Car Park team identified 14 parking lots, divided into 6 projects, that could sufficiently house Car Park style solar structures. The goal of this project is to reduce the peak power drawn by Calvin by integrating solar to help offset. This peak power charge accounts for a majority of the electricity bill, and in addition to contributing to Calvin's goal of being Carbon Neutral by 2057, this project would help decrease the power bill. Furthermore, the project-based division of integration enables Calvin to construct these projects in phases, rather than being faced with a large upfront cost if desired.

Methods

Sam Sands, Hunter Hicks, and Nick Henz formed the car park solar group. In order to maximize the space utilized in Calvin parking lots, the decision was made to focus on areas in the campus lots that had a centerline (i.e. a parking lot line with spots on either side of it, so no edge spaces were analyzed). This focus on the centerline maximizes the space we can use as well as accounts for trees, buildings, or other forms of shade that would hurt our power production. In addition, the team focused on parking lots that were feasible for solar. This feasibility was determined by overall shading of the lot, parking lot shape, parking lot size, and future campus plans (whether the lot will continue to exist).

Solar Panels were selected by comparing key features of several solar panels. A spreadsheet and table were made in order to compare factors such as Watts/Panel, Panel Efficiency, W/ft^2, and lb/ft^2. These factors helped the team make key decisions on which panel was best. Watts/Panel helps to examine the power capabilities of each panel. Panel Efficiency helps to see how effective each panel is. W/ft^2 helps to maximize the output with the available space, and lb/ft^2 allows for maximization of the output at the lightest weight. By comparing these factors, the team was able to choose a panel that balances being lightweight with producing a high wattage.

Selection of a structure introduces several factors that differentiate each one. Overall, selection comes down to which has the cheapest overall \$/W, including all construction, engineering, labor, and material cost for each project, as well as which structure can best deal with the weather in Michigan. To compare this, several structures were created using the MT Solar Auto designer tool and quoted. Additionally, a quote from Solar Mounts LLC through Agathon Solar was obtained and analyzed. All structures were designed to withstand up to 160 mph winds and 35 psf of snow load in accordance with typical Michigan weather conditions.

In order to model the output of the system, the Car Park team worked with the Infrastructure and Modeling team as well as creating a spreadsheet to model the outputs. The spreadsheet created modeled an ideal output in each lot, which allowed the team to quickly get estimates of outputs and optimize layouts from these values. The Infrastructure and Modeling team analyzed a detailed output, factoring in Michigan irradiance for a more realistic result. Cost calculations were conducted using a spreadsheet, encompassing every potential expense and breaking them down into $/W, allowing for cost interpolation for various projects. Optimizations could be analyzed via the $/W for efficient results.

Results

Firstly, 14 lots were selected and divided into 6 projects based on optimal solar conditions. Projects were organized as follows: Project 1 includes Lots 1-6, chosen for their numerous centerline spaces free from shading and ideal north-south orientation. Project 2 focuses on Lot 8 for its size and low shading, with a redesign required for optimal solar use. Project 3 comprises Lot 11, which is large and minimally shaded with north-south centerlines. Project 4 includes Lot 13, similar in size and shading with north-south centerlines. Project 5 covers Lots 14-17, chosen for their size and low shading, with most centerlines oriented north-south. Finally, Project 6 encompasses Lot 18, noted for its ideal centerlines and low shading.

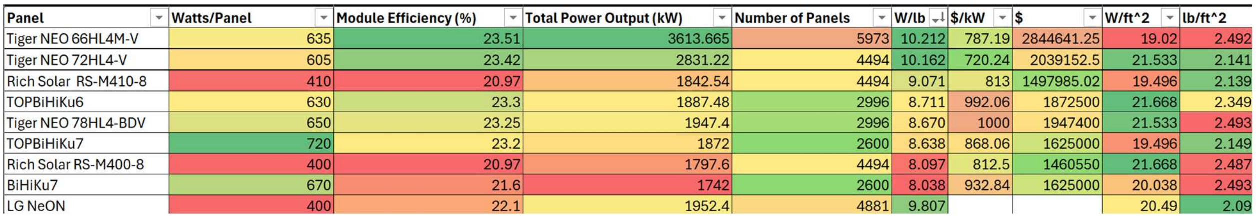
Panel selection was done by utilizing the table described in the methods, which is shown in Table E1. From this analysis, the Tiger NEO72HL4-V was selected, as it had a high efficiency, high power output, higher Watts/Panel, low W/lb, lowest $/kW, and highest W/ft^2 and lb/ft^2. The car park team performed a preliminary analysis on the various costs of structures. The first structure selected was a Y Frame from Solar Mounts LLC, with a $/W of $1.82 (including panels, materials, and labor). This was compared to the designs from MT Solar, which came in at $1.78 /W. While this is lower, the Solar Mounts LLC design allows for an additional 4,000 panels, which equates to almost double the power output for a similar $/W cost (6 MW vs 3.6 MW). These calculations were utilized to verify that calculations done by the Infrastructure and Modeling team were in the right ballpark. The Infrastructure and Modeling team found that the $/W was an average of $1.68/W across the parking lots, which is in the ballpark of the preliminary analysis.

Conclusions

In conclusion, the solar car park proposed produces an estimated 6,954 MWh at a cost of $1.68 per Watt. The industry standard for car park solar systems is about 3-4$/W before tax credit, so this system is well under that. Due to the outputs and costs, the system will be able to successfully accomplish our goal of decreasing the peak charges of the power bill as well as moving towards Carbon Neutrality by 2057.

Figures & Tables

Table 23. Decision Matrix for Solar Panel Selection for Rooftop & Car Park Mounted Panels.



Panel	Watts/Panel	Module Efficiency (%)	Total Power Output (kW)	Number of Panels	W/lb	$/kW	$	W/ft^2	lb/ft^2
Tiger NEO 66HL4M-V	635	23.51	3613.665	5973	10.212	787.19	2844641.25	19.02	2.492
Tiger NEO 72HL4-V	605	23.42	2831.22	4494	10.162	720.24	2039152.5	21.533	2.141
Rich Solar RS-M410-8	410	20.97	1842.54	4494	9.071	813	1497985.02	19.496	2.139
TOPBiHiKu6	630	23.3	1887.48	2996	8.711	992.06	1872500	21.668	2.349
Tiger NEO 78HL4-BDV	650	23.25	1947.4	2996	8.670	1000	1947400	21.533	2.493
TOPBiHiKu7	720	23.2	1872	2600	8.638	868.06	1625000	19.496	2.149
Rich Solar RS-M400-8	400	20.97	1797.6	4494	8.097	812.5	1460550	21.668	2.487
BiHiKu7	670	21.6	1742	2600	8.038	932.84	1625000	20.038	2.493
LG NeON	400	22.1	1952.4	4881	9.807			20.49	2.09

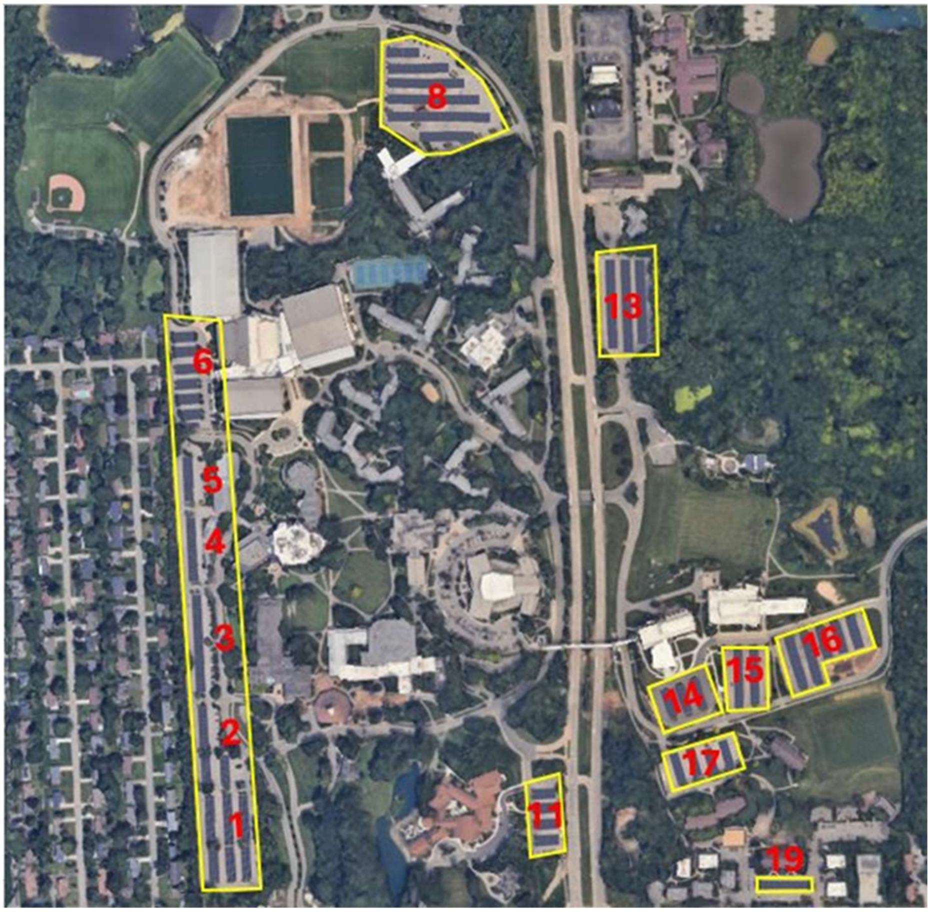
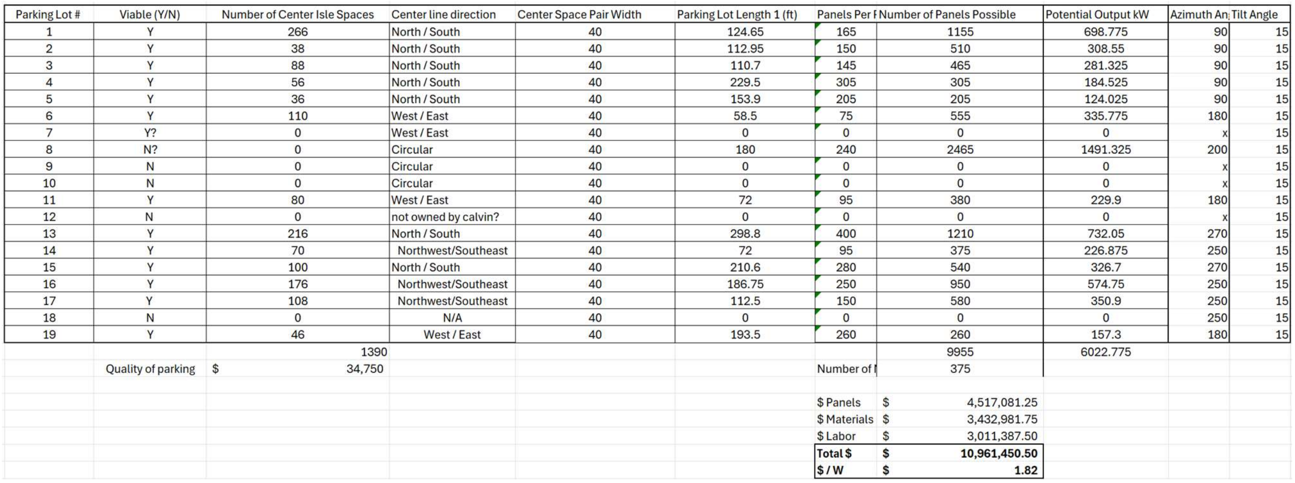


Figure 23. Map of Calvin University with all proposed car park solar.



Parking Lot #	Viable (Y/N)	Number of Center Isle Spaces	Center line direction	Center Space Pair Width	Parking Lot Length 1 (ft)	Panels Per	Number of Panels Possible	Potential Output kW	Azimuth An	Tilt Angle
1	Y	266	North / South	40	124.65	165	1155	698.775	90	15
2	Y	38	North / South	40	112.95	150	510	308.55	90	15
3	Y	88	North / South	40	110.7	145	465	281.325	90	15
4	Y	56	North / South	40	229.5	305	305	184.525	90	15
5	Y	36	North / South	40	153.9	205	205	124.025	90	15
6	Y	110	West / East	40	58.5	75	555	335.775	180	15
7	Y?	0	West / East	40	0	0	0	0	x	15
8	N?	0	Circular	40	180	240	2465	1491.325	200	15
9	N	0	Circular	40	0	0	0	0	x	15
10	N	0	Circular	40	0	0	0	0	x	15
11	Y	80	West / East	40	72	95	380	229.9	180	15
12	N	0	not owned by calvin?	40	0	0	0	0	x	15
13	Y	216	North / South	40	298.8	400	1210	732.05	270	15
14	Y	70	Northwest/Southeast	40	72	95	375	226.875	250	15
15	Y	100	North / South	40	210.6	280	540	326.7	270	15
16	Y	176	Northwest/Southeast	40	186.75	250	950	574.75	250	15
17	Y	108	Northwest/Southeast	40	112.5	150	580	350.9	250	15
18	N	0	N/A	40	0	0	0	0	250	15
19	Y	46	West / East	40	193.5	260	260	157.3	180	15
		1390					9955	6022.775		
	Quality of parking	$ 34,750				Number of	375			
						$ Panels	$ 4,517,081.25			
						$ Materials	$ 3,432,981.75			
						$ Labor	$ 3,011,387.50			
						Total $	**$ 10,961,450.50**			
						$ / W	**$ 1.82**			

Figure 24. Spreadsheet utilized to determine costs and potential outputs for each proposed car park.

Table 24. Car Park kWh/$ and Carbon Offsets by car park.

Location	Panel Used	# of Panels	System Power [kW]	Energy Produced [kWh]	Inverter Energy [kWh]	PEC kWh/$	Total kWh/$	Electric Carbon Offset	Total Carbon Offset
Lot 1	TigerNeo	1,155	698.8	1,010,843	792,501	1.29	0.68	3.6%	1.5%
Lot 2	TigerNeo	510	308.6	446,346	349,936	1.29	0.68	1.6%	0.7%
Lot 3	TigerNeo	465	281.3	406,963	319,059	1.28	0.67	1.5%	0.6%
Lot 4	TigerNeo	305	184.5	266,933	209,275	1.31	0.68	1.0%	0.4%
Lot 5	TigerNeo	205	124.0	179,414	140,660	1.27	0.67	0.6%	0.3%
Lot 6	TigerNeo	555	335.8	514,899	403,681	1.38	0.72	1.9%	0.8%
Lot 8	TigerNeo	2,465	1,491.3	2,286,894	1,792,925	1.37	0.72	8.2%	3.5%
Lot 11	TigerNeo	308	186.3	285,746	224,025	1.38	0.72	1.0%	0.4%
Lot 13	TigerNeo	1,210	732.1	1,058,547	829,901	1.29	0.67	3.8%	1.6%
Lot 14	TigerNeo	375	226.9	334,747	262,442	1.32	0.69	1.2%	0.5%
Lot 15	TigerNeo	540	326.7	472,409	370,369	1.30	0.68	1.7%	0.7%
Lot 16	TigerNeo	950	574.8	848,027	664,853	1.31	0.69	3.0%	1.3%
Lot 17	TigerNeo	580	350.9	517,743	405,910	1.31	0.69	1.9%	0.8%
Lot 19	TigerNeo	260	157.3	241,214	189,112	1.37	0.72	0.9%	0.4%

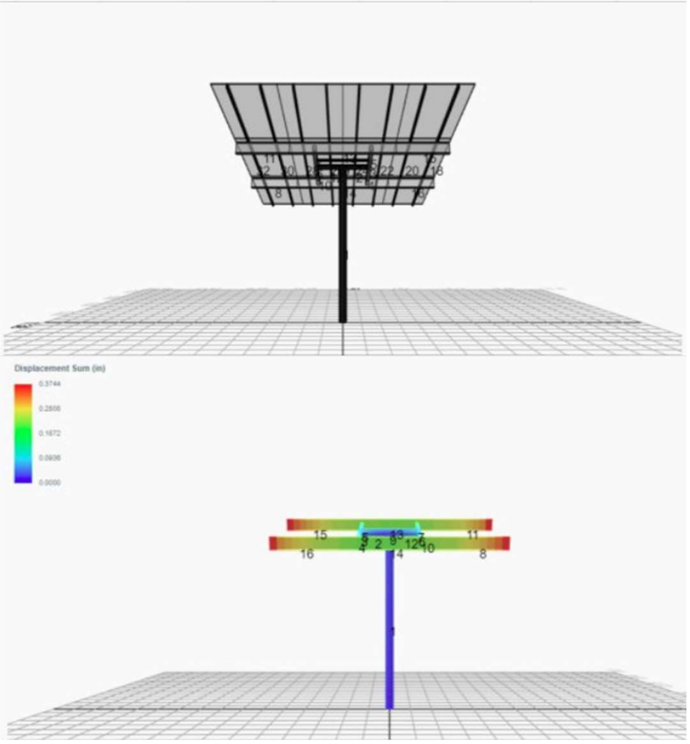


Figure 25. Car Park solar structure designed in MT Solar's Autodesigner.

Figure 26. Y-Frame Solar Car Park made by Solar Mounts LLC, like what would be proposed at Calvin.

References

Henderson, Michael. “Pole Mount Design and Quoting Tool - MT Solar AutoDesigner.” *MT Solar*, 15 Oct. 2024, www.mtsolar.us/autodesigner/. Accessed 19 Nov. 2024.

“Westchester Y-Frame Solar Carport.” *Solar Mounts LLC*, 19 Feb. 2024, solarmounts.com/projects/westchester/. Accessed 19 Nov. 2024.

“Jinko Solar-Tiger Neo.” *Jinkosolar.com*, 2020, www.jinkosolar.com/en/site/tigerneo. Accessed 19 Nov. 2024.

Appendix F (Physics 131)

Introduction

The physics 131 class provided with the following problem: “Given the attached datasheets for all proposed solar farm designs, A) determine the optimal tilt angle for adjustable designs, and calculate B) a projection of the monthly peak and overall power produced by each farm design throughout the year, C) a model of the impact made on Calvin's electrical billing during peak hours and throughout the year.”

Methods

To solve this problem, Professor Molnar created a program in python for the students to use during lab. The program included 4 main inputs: the orientation of the solar panels, the orientation of the sun, real weather data, and the electric bill data. The orientation of the panels was provided by ENGR 333 and included tilt and azimuth angles. There were some angles that were fixed and some angles that were varied to optimize the system. The orientation of the sun was input as vectors and used to determine extinction and how much sunlight would hit the solar panels. The real weather data was provided by Professor Molar from his personal solar system and was used to model as accurately as possible the weather conditions expected in western Michigan. These three inputs combined allowed the production of the solar farm to be modeled. Finally, the electric bill data was used to determine how much Calvin would save on electricity given the modeled production of the farm.

During the lab the students used this program to optimize the solar farm for maximum savings. To optimize the system, the students varied the azimuth and tilt angles that were not fixed. Once the max savings were found the results were given to the ENGR 333 class.

Results

Using the seven-step progression given by ENGR 333, a file was set up by Professor Molnar to calculate the deliverables. The progression can be found in Table 25, with the values shown as a [-1] able to be varied. This is found in Figure 27. From this progression, Figures 28-30 are created.

Figure 28 illustrates the daily electricity from grid for Calvin before and after implementation of the full progression. The graph depicts how in the middle of the day where the sun is above the panels, the energy Calvin produces can encompass its full need for a period.

Figures 29-30 show the peak kW purchased and billing information. The graphs are very similar as with a higher peak, the billing will increase, thus with a decrease in the peak of the peak kW shown well in the summer months, the billing will follow.

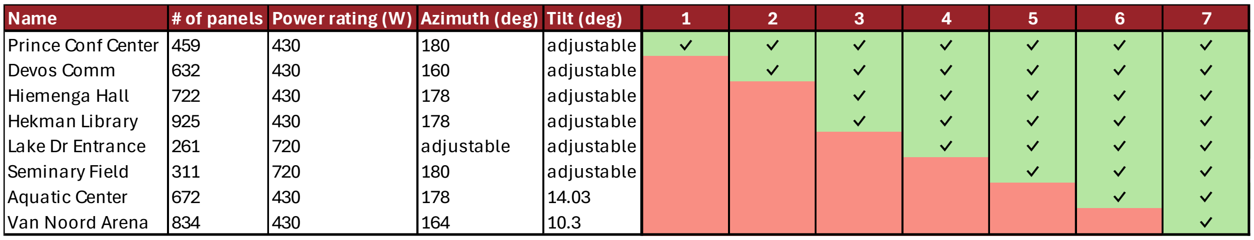
Table 26 is the summary table with the Energy produced, Savings in M$, and in GWh. The loss column also shows the efficiency to Calvin’s needs with a loss of only 0.001 throughout the entirety of the year.

Conclusion

The physics team was able to take part in the solar project in a major way, by taking on the role of energy production and savings from the energy bill. By using the code written by Professor Molnar and numbers optimized by the class, PHYS 131 delivered accurate and meaningful data to the ENGR 333 class to aid in the argument for and description of a Calvin solar farm.

Figures & Tables

Table 25. Full progression to calculate for deliverables.



Name	# of panels	Power rating (W)	Azimuth (deg)	Tilt (deg)	1	2	3	4	5	6	7
Prince Conf Center	459	430	180	adjustable	✓	✓	✓	✓	✓	✓	✓
Devos Comm	632	430	160	adjustable		✓	✓	✓	✓	✓	✓
Hiemenga Hall	722	430	178	adjustable			✓	✓	✓	✓	✓
Hekman Library	925	430	178	adjustable			✓	✓	✓	✓	✓
Lake Dr Entrance	261	720	adjustable	adjustable				✓	✓	✓	✓
Seminary Field	311	720	180	adjustable					✓	✓	✓
Aquatic Center	672	430	178	14.03						✓	✓
Van Noord Arena	834	430	164	10.3							✓

```
mytilt = 30. # Make your choice here for rooftop tilts
Panels.Tilt_deg[1] = mytilt
Panels.Tilt_deg[2] = mytilt
Panels.Tilt_deg[3] = mytilt
Panels.Tilt_deg[4] = mytilt


mytilt = 30. # Make your choice here for ground mounted tilts
myazi = 190. # Make your choice here for ground mounted azimuths.
Panels.Tilt_deg[6] = mytilt
Panels.Tilt_deg[7] = mytilt
Panels.Azi_deg[6] = myazi
```

Figure 27. Optimization interface.

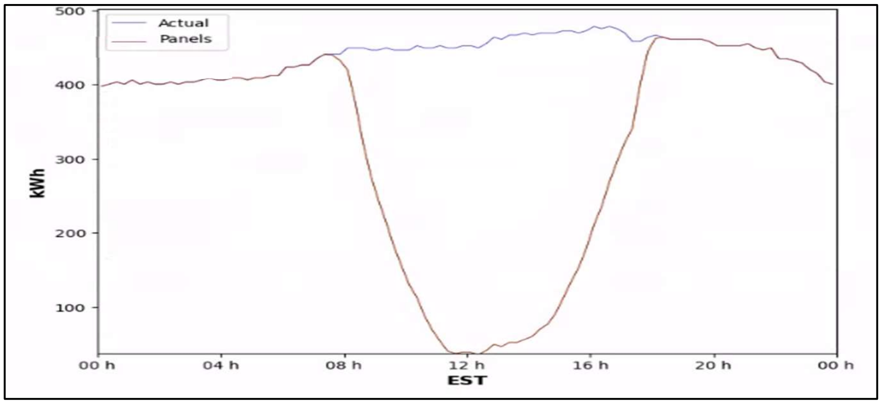


Figure 28. Daily energy need for Calvin.

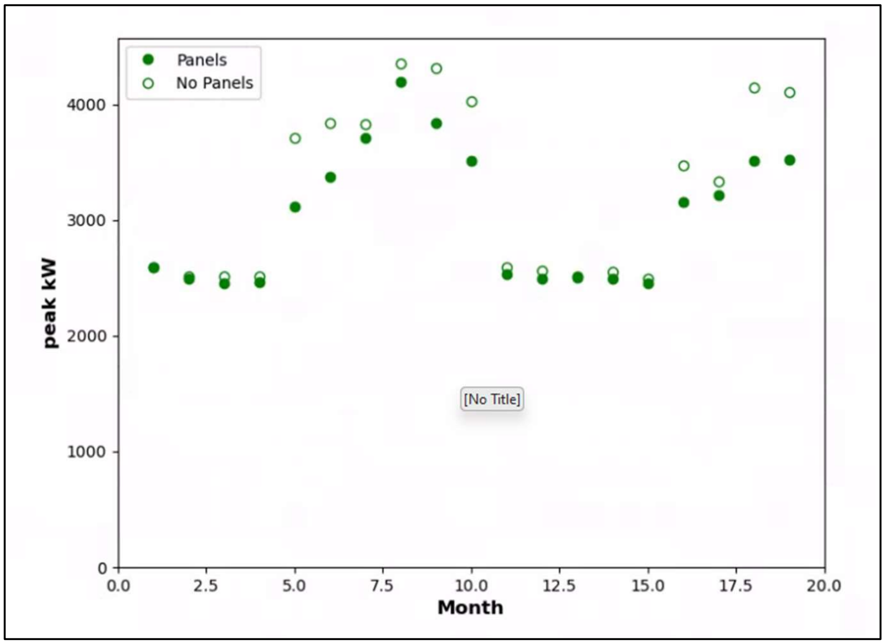


Figure 29. Peak kW Purchased per Month.

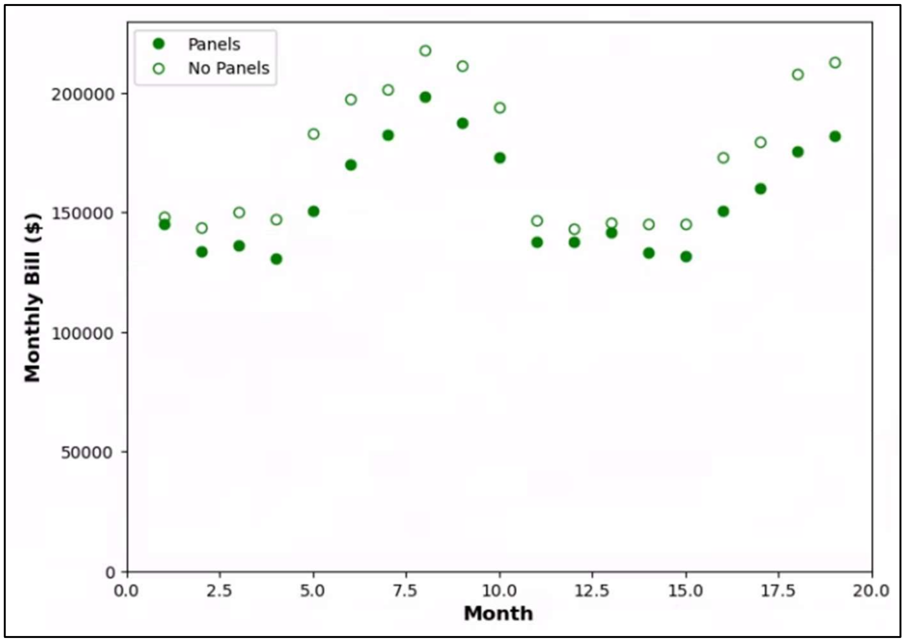


Figure 30. Calvin's monthly energy billing.

Table 26. Summary of final deliverables.

Summary Table				
Case	Power	Saving	Saving	Loss
	kW	M$	GWh	GWh
1	197	0.029	0.228	0.000
2	469	0.061	0.536	0.000
3	1177	0.125	1.355	0.000
4	1365	0.14	1.572	0.000
5	1589	0.159	1.832	0.000
6	1878	0.181	2.155	0.000
7	2237	0.209	2.562	0.001

Appendix G (Structural Engineering)

Full report starts on the next page.

Structural Capacity for Solar of Various Buildings on Campus

ENGR 327 Class, Fall 2024

MJ Van Antwerp, Catherine Grissom, Josh Gage, Reid Bentz, Annalise Holcomb, Leah Huizenga, Daniel Oyer, Josh Lundberg, David Bajwa, Nate Van Dyke, Garrett Schaaf

26 November 2024

Table of Contents

1 – Introduction

Calvin University is looking to reduce greenhouse gas emissions and upgrade the energy infrastructure. To do this, they have started to consider the impact of introducing solar photovoltaic panels to create a solar farm. Our class has been asked to analyze the structural capacity of roofs on campus to support solar panels. In order for each roof on these buildings to be considered, there must be a significant area facing south to maximize sunlight. Along with the correct direction these roofs must be without shade for most of the day, requiring little to no tree coverage.

Given these considerations, nine buildings on campus were selected for analysis. Our group selected some of the roofs, and others were added by request from the Mechanical Engineering class. Our class divided into three groups to conduct the structural analysis for nine roof structures across those nine buildings. Group A, consisting of MJ VanAntwerp, Reid Bentz, Catherine Grissom, and Josh Gage, analyzed the roof structures of the **Covenant Fine Arts Center (CFAC)** and the **Prince Conference Center**. Group B consisting of Annalise Holcomb, Daniel Oyer, Josh Lundberg, and Leah Huizenga analyzed the roof structures of **North Hall, Business Building,** and **Devos Communication Center**. A final group C consisted of David Bajwa, Garrett Schaaf, and Nate Van Dyke, and analyzed the roof structure of the **Aquatic Center, Van Noord Arena, Hekman Library**, and **Hiemenga Hall**.

All calculations for the structural capacity of buildings in this report were performed by students in the ENGR 327 class. Professor Leonard De Rooy served as an advisor for the project but was not involved in all of the calculations. If Calvin University decides to proceed with rooftop solar mounting, all work should be reviewed and approved by a licensed Professional Engineer in the state of Michigan.

The team has provided a file alongside this report with all of the extensive reference materials needed to support our findings. This zip file contains folders for each of the buildings that were analyzed. In those folders are all of the relevant structural plans, capacity calculations, load tables, and other reference materials used to compile this report.

2 – Executive Summary

The buildings in this analysis were assessed as potential candidates for the installation of photovoltaic panels according to the additional capacity supported by the existing structure. This report is limited in its application, as the load of the photovoltaic panel and its racking system differ depending on the type. Specified possible additional loading for each building is noted in each section of this report. A licensed Professional Engineer in the State of Michigan should review and approve the type according to the building and placement of the system.

The only building found to be structurally inadequate for solar panels in its current condition is the CFAC. The CFAC was divided into 5 roof sections in this analysis, and it was found that none can support the additional load in their current state. More detailed professional analysis and additional reinforcement in this building could make it a viable option.

The viable options for solar panel installation are as follows: Devos Communication Center, Business Building, Venema Aquatic Center, Van Noord Arena, Hekman Library, Hiemenga Hall, the circular area of North Hall, and part of the Prince Conference Center. Based on the calculations provided in this report, most of the buildings can support either type of ballasted or mechanically attached solar panels.

It is worth noting that while the Van Noord Arena is a feasible candidate, it is recommended that further analysis of the truss system is conducted with particular attention to the potential placement and load distribution of the photovoltaic system. Hiemenga Hall is another building in which further analysis is recommended, specifically with the type of photovoltaic system. The Prince Conference Center was divided into different roof sections, some which are viable and others which need further investigation due to lack of available documentation.

Overall, 8 out of 9 buildings in this report are able to support the possible additional load of a photovoltaic system. Once again, it is recommended that a licensed Professional Engineer conduct analyses on these systems and determine the appropriate type of photovoltaic system, along with the placement and structure of the solar panel racking on each roof.

Table 1 Summary of Findings of Structural Viability

Covenant Fine Arts Center	Not viable for solar panel mounting
Prince Conference Center & Hotel	Conference center viable, hotel unknown
North Hall	Likely viable
Devos Communications Center	Viable for solar panels
Business Building	Viable for solar panels mounted with a ballast system
Venema Aquatic Center	Viable for solar panels
Van Noord Arena	Likely viable
Hekman Library	Viable for solar panels
Hiemenga Hall	Viable for solar panels

3 – Covenant Fine Arts Center

The Covenant Fine Arts Center was analyzed for its feasibility as a site for rooftop solar. The five roofs shown below in Figure 1 were selected for structural analysis. Roof 1 was selected as a west and slightly south facing roof option to boost solar production in the afternoon. Roof 1 is structurally the same as the roof adjoining Roofs 2 and 3, but analysis was only performed north of the black line drawn, due to the requirement that all roof structures be facing at least slightly south. Roof 2 was chosen as it is south facing with no shade from nearby trees or structures. Roof 3 was selected as it is east and slightly south facing to allow for extra energy production in the mornings. Roof 4 was selected due to its large, flat, and shade free area. Roof 5 was selected because of its large south facing area with relatively little shade. The rest of the roof structures were rejected either because of the direction they face or because of shading from nearby roofs and trees. Full calculations and load tables used to support those calculations can be found in the zip file that was sent alongside this report.

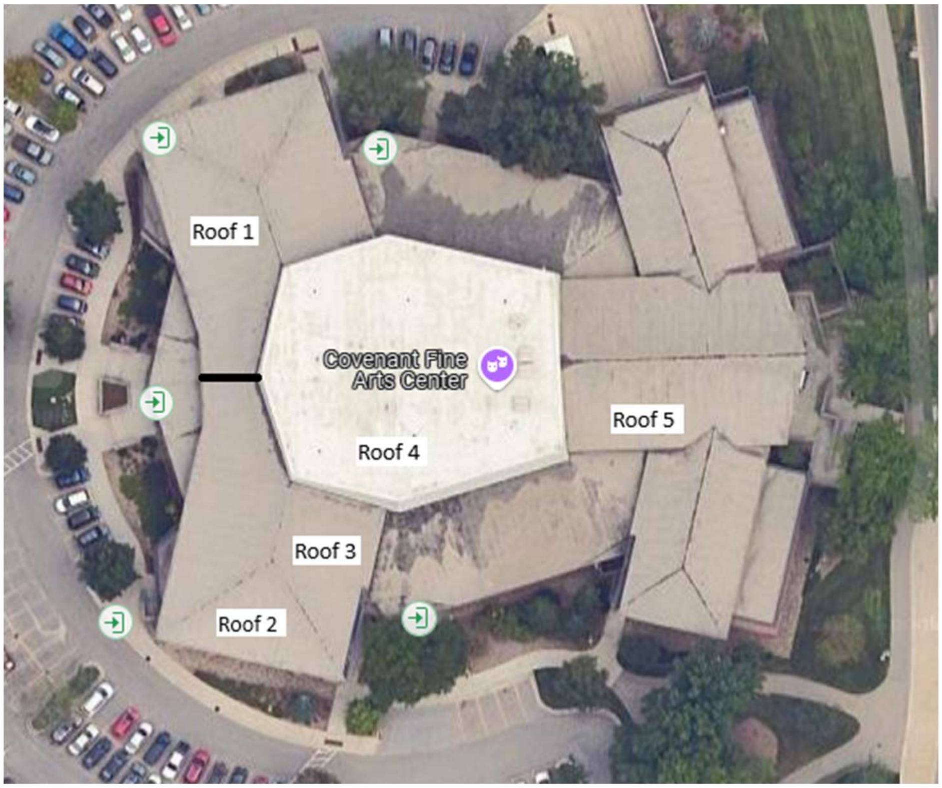


Figure 1. CFAC Roof Labels for Analysis.

3.1 – CFAC Roof 1

The east side of the Covenant Fine Arts Center has a large roof that spans from the north to the south end of the building. For our purposes, only the north half of this roof was analyzed, as the north half is slightly south facing. This roof structure consists of a mix of VS and K series joists, W beams, and custom trusses. Figure 2 below shows the roof section that was analyzed. The yellow lines show the roof area that was analyzed, the red lines show the VS series joists, the blue lines show the K series joists, the green lines show the custom trusses, the pink lines show the W beams, and the purple outlines a mechanical room.

Figure 2. Roof 1 of the CFAC with Specified Areas and Supports Highlighted.

The dead load of the roof over the mechanical room is higher than the typical roof deadload, due to extra equipment typically being mounted to the roof structure. The structural plans for the building call out a roof dead load of 35 psf (pounds per square foot) for mechanical rooms and 23 psf for other areas. Because of this higher dead load, the section of the roof over the mechanical room is not able to support solar panels. Additionally, the custom trusses (shown in green in Figure 2) were designed to support just the weight of the roof structure and snow load, and do not have extra capacity for solar panels according to the structural plans. The W beams, shown in pink, do have plenty of extra capacity, but that area is small and mostly not facing south at all, making it a poor location for solar panels.

It is possible that the custom trusses were built to have extra capacity outside of the standard safety factor, but in order to determine that, we would have to go measure the beams to get more information than is provided in the plans and inspect the welds. Based on the structural plans as shown and our calculations, we would **NOT** recommend this roof as an option for roof top solar. The full and unannotated structural plans and truss details for this roof, and our calculations can be found in the Appendix A and the attached zip files.

3.2 – CFAC Roof 2

Roof 2 in the CFAC is a south facing triangular shaped roof. It is symmetric with VS and KCS series joists spanning from the outside wall to the ridgeline. The ridgeline is formed by a custom truss, Truss M (shown in Appendix A). The joists extend past the outside wall, forming a cantilever section. This cantilever section was not analyzed, as the solar layout provided did not show the panels that close to the edge of the roof. The full structural plans for this section can be found in Appendix A and the attached files. For this section of roof, it was found that the joists could support solar panels. However, the joists are supported by Truss M. The structural plans show Truss M being designed to only hold the weight of the roof as it is. In order to determine if the truss was built with enough safety factor to hold solar panels, a much more extensive physical assessment of the truss and the roof structure would be required. That physical assessment is highly time consuming and would require an outside consultant to take detailed measurements and assess the welds. With those detailed measurements, the truss could be modeled in STAAD Pro. However, given the small size of the roof, the plethora of other options, and the resources required to conduct the analysis, our team decided to not pursue that avenue. Roof 2 of the CFAC is **NOT** recommended as a viable option to support solar panels.

3.3 – CFAC Roof 3

Roof 3 of the CFAC consists of VS and KCS series joists spanning from the outside wall to the diagonal ridgeline on the south portion, and custom trusses spanning the whole roof on the north portion. The ridgeline on the south portion is formed by a custom truss, Truss M. The trusses on the north portion are comprised of Truss L and Truss K. Full structural plans and truss details can be found in Appendix A. For this section of roof, it was found that the joists and Trusses L and K could support the weight of solar panels. However, the joists on the southern portion of the roof distribute their loads onto Truss M, which, as discussed in the Roof 2 section above, cannot support the load of solar panels. The section of roof comprised by Truss L and Truss K is small and faces east rather than south, making it an inefficient location on its own. Because of this, our team does **NOT** recommend Roof 3 as a viable option for solar panels.

3.4 – CFAC Roof 4

The fourth roof analyzed was the central section of the building with the white roof. This section of the roof is the oldest, built in 1964. The roof consists of five (5) trusses. The roof is a built-up roof, with a gypsum and bulb tees roof deck. Figure 3 below shows the structural drawings of Roof 4 and has the trusses that were analyzed highlighted. The structural drawings for Roof 4 display a total load on the trusses in the roof. Using the architectural drawings and the ASCE 7 code book, the deadload on the trusses was determined. Based on the LRFD (Load and Resistance Factor Design) method, the ultimate load was calculated to determine the extra capacity for each truss in Roof 4. On average, the trusses had an extra capacity of 4 psf, which is not enough to hold solar panels. Due to this, it is **NOT** recommended that solar panels be placed on Roof 4 of the CFAC. Full structural plans and calculations can be found in the attached files.

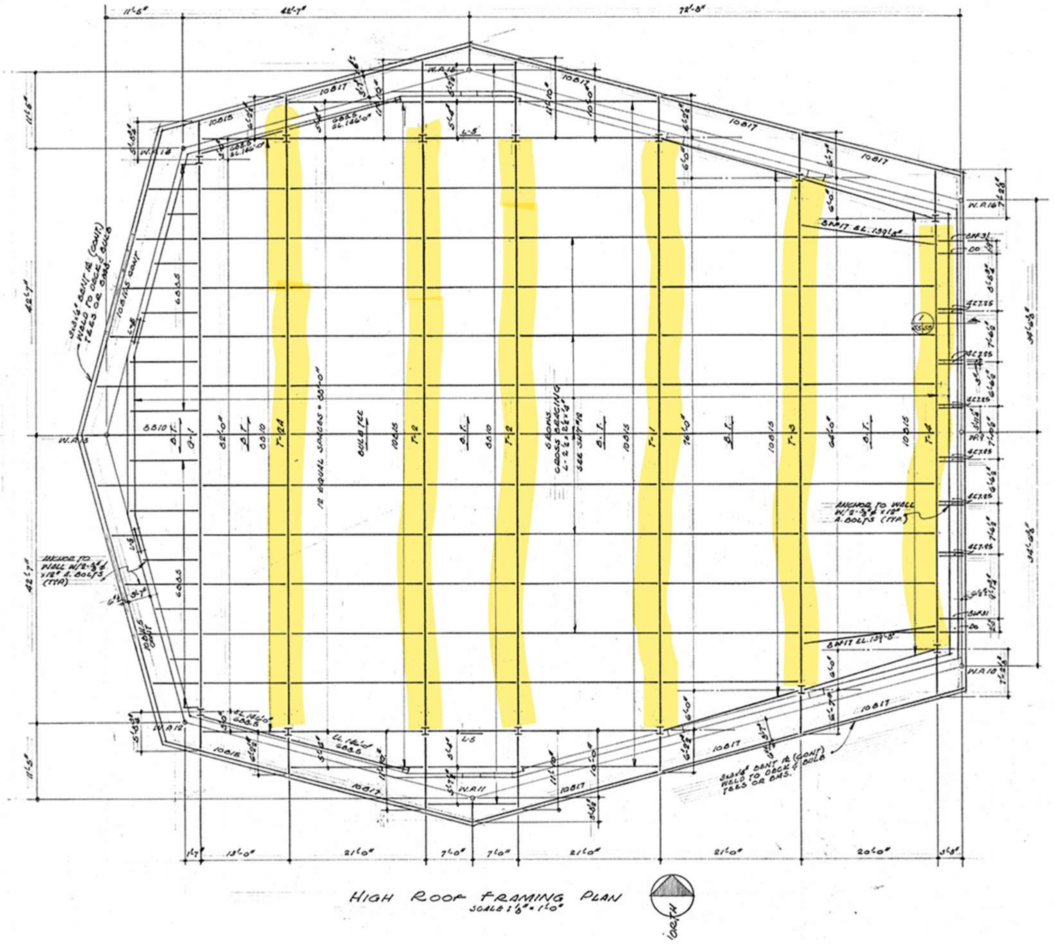


Figure 3. Roof 4 of the CFAC with Trusses Highlighted.

3.5 – CFAC Roof 5

This section of the CFAC was selected for analysis due to its large area and unobstructed south facing roof. The west section of the roof is comprised of a custom truss, Truss C, which spans the width of the roof. The east section of the roof is comprised of a custom framing plan, Frame D. Frame D is made up of a variety of W Beams connected to each other and supported perpendicularly by a larger W Beam with supports on some internal walls. The structural plans and truss details for this section of the roof can be found in Appendix A and in the attached files, and calculations can be found in the attached files.

The structural plans for Truss C show that the truss was only specified to support the weight of the roof and the anticipated snow load, with no extra capacity for solar panels. In order to assess if there is capacity for solar panels in the safety factors, a rigorous and detailed analysis of the truss would have to take place. This analysis would require information beyond what is in the structural plans and is highly time and resource intensive. It would require detailed measurements to be taken of the trusses, a thorough inspection of the welds and connections, and detailed modeling of the truss in STAADPro. Our team determined that given the other alternatives, the need for this rigorous analysis precludes this section of roof from viability for solar panels. Unless rigorous analysis is performed and overseen by licensed Professional Engineer in the state of Michigan, the western part of this roof is **NOT** recommended for solar panels.

The eastern half of the roof, supported by framing plan D, consists of a variety of W beams. It was found that the beams forming the framing plan (running north/south) do have the capacity to hold solar panels. However, these beams distribute their load onto a W18x50 running east/west, which does not have any extra capacity to support solar. Given the constraints with the cross-bracing beam on the eastern half of the roof and the custom truss on the western half, it was determined that this roof section is **NOT** viable for solar panels unless the girder was reinforced.

4 – Prince Conference Center and Hotel

The Prince Conference Center and Hotel were analyzed for their feasibility as a site for rooftop solar panels. The three roofs shown below in Figure 4 were selected for structural analysis. Roof 1 and Roof 2 are connected as part of the western portion of the Prince Conference Center. Roof 3 is the Hotel. These roofs were chosen because they are flat, relatively large, and could be connected to a larger system that includes the Business Building and carpark solar systems in Lots 14, 15, and 16 of Calvin's campus.

Full calculations and load tables used to support those calculations can be found in the zip file that was sent alongside this report.

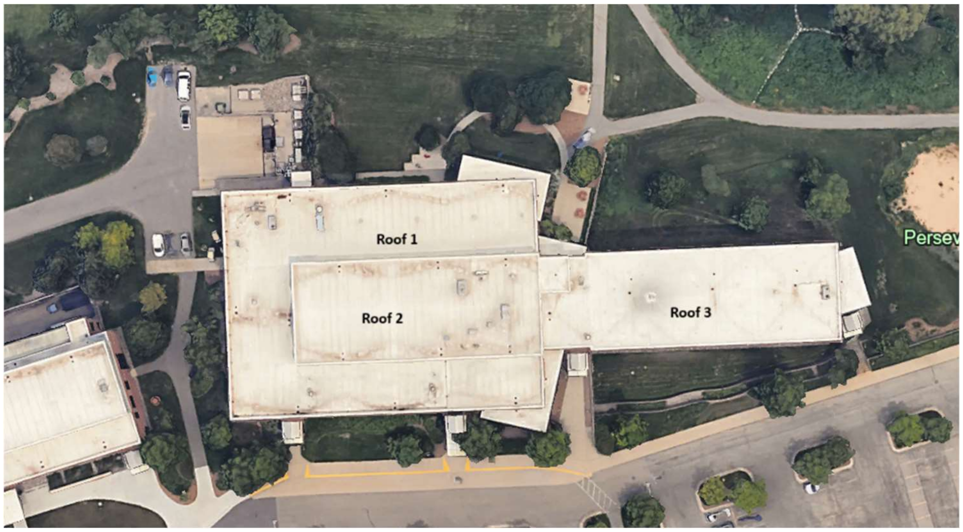


Figure 4. Prince Conference Center and Hotel Roof Labels for Analysis

4.1 – Prince Roof 1

Roof 1 is above the first floor of the western portion of the Prince Conference Center. The roof is made up of 20-gauge metal decking, two layers of rigid insulation, and a waterproof membrane. The roof consists of twelve types of beams and ten types of joists. The dead load of the roof was determined based on the ASCE 7 code book weights for the materials listed above. The live load on the roof was estimated to be 30 psf based on the snow loads found for other buildings on campus. The design capacities for the beams were found in the AISC Steel Construction Manual tables. The design capacities for the joists were found on various joist manufacturer websites. Full structural plans can be found in Appendix B and the attached files, and calculations can be found in the attached files. Upon analysis of Roof 1 it was determined that the beams and joists have **enough extra capacity to support a rooftop solar system**.

4.2 – Prince Roof 2

Roof 2 is the second story of the western portion of the Prince Conference Center. The roof is made up of 20-gauge metal decking, two layers of rigid insulation, and a waterproof membrane. The roof consists of one truss, eight types of beams, and three types of joists. The total load on the truss was found in the structural drawings. The dead load of the roof was determined based on the ASCE 7 textbook weights for the materials listed above. The live load on the roof was estimated to be 30 psf based on the live loads found in other buildings on campus. The design capacities for the beams were found in the AISC Steel Construction Manual tables. The design capacities for the joists were found on various joist manufacturer websites. Structural plans and calculations can be found in Appendix B and the attached files. Upon analysis of Roof 2 it was determined that the truss, beams, and joists have **enough extra capacity to support a rooftop solar system**.

4.3 – Prince Roof 3

Unfortunately, we were unable to locate any structural drawings of the hotel portion of the Prince Conference Center, in either the files shared to us by Professor De Rooy and facilities or in the physical construction plans located in the Physical Plant on campus. Due to this reality, **we cannot make any determination on the extra capacity of Roof 3 of the Prince Conference Center and therefore its ability to hold solar panels**.

5 – North Hall

When tasked with analyzing the structure of the North Hall, we decided to only focus on the northern circular part, as the other part would receive partial shade, and thus is not optimal for installing solar panels. The North Hall was analyzed in two sections. We analyzed beams and columns to check for strength. We knew that North Hall was built to be as cheap as possible, so it would likely not have significant additional strength. The roof construction includes metal decking, a 5-inch concrete slab, and waterproofing materials that are found in built up membrane roofs. The 5-inch concrete slab is atypical for buildings of this type and added 63 pounds per square foot of load. The cryptic and old-fashioned style of the plans also made analyzing beams precisely a challenge and obstructed the best level of accuracy

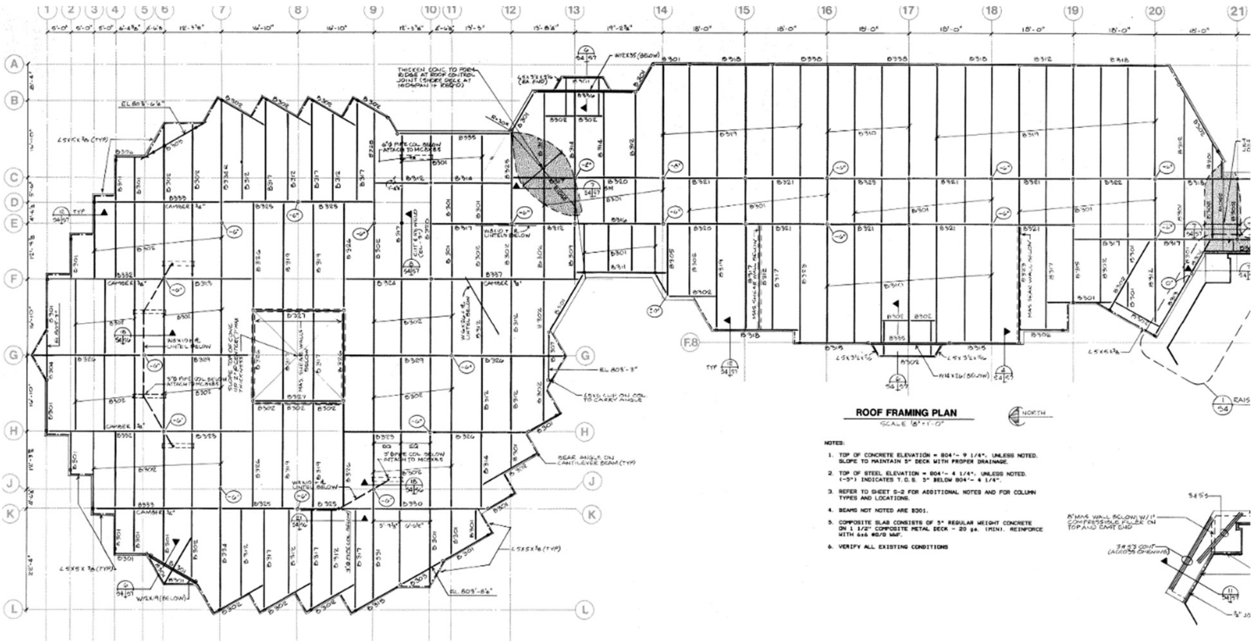
5.1 Beams

The roof beams were analyzed by finding the maximum actual moment in the building and comparing that to the maximum moment found in ASD 16th edition. The formula shown below was used to calculate the maximum moment experienced in a beam for most cases.

$$M_{max} = \frac{\omega L^2}{8}$$

The joists have a distributed load from the weight of the roof and thus used this formula to determine the maximum moment using the formula above. Girders and beams were analyzed on a case by case basis where point loads from other beams were added to distributed loads and analyzed in MD Solids. These moments were compared in a table to the maximum loads given for LRFD design in the ASD 16th edition. The roof framing plan can be found below in Figure 5, and full structural plans and calculations can be found in the attached files.

The results showed that for beams only, the first beam would fail once a uniform load greater than 11.5 pounds per square foot is applied. Due to the cryptic nature of the plans, they were not able to be analyzed in great detail, Thus the calculations were calculated in a manner that overestimated the load, so the roof likely has more strength than calculated, but we are **unable to verify any available capacity over 11.5 pounds per square foot**.



NOTES:

1. TOP OF CONCRETE ELEVATION = 804'- 9 1/4", UNLESS NOTED. SLOPE TO MAINTAIN 5" DECK WITH PROPER DRAINAGE.
2. TOP OF STEEL ELEVATION = 804'- 4 1/4", UNLESS NOTED. (-5") INDICATES T.O.S. 5" BELOW 804'- 4 1/4".
3. REFER TO SHEET S-2 FOR ADDITIONAL NOTES AND FOR COLUMN TYPES AND LOCATIONS.
4. BEAMS NOT NOTED ARE B301.
5. COMPOSITE SLAB CONSISTS OF 5" REGULAR WEIGHT CONCRETE ON 1 1/2" COMPOSITE METAL DECK - 20 ga. (MIN). REINFORCE WITH 6x6 #0/0 WWF.
6. VERIFY ALL EXISTING CONDITIONS

Figure 5. North Hall.

5.2 Columns

The North Hall column structure was spot-checked using 5 columns outlined in blue in Figure 6 below. These columns were chosen for the varying location and loads.

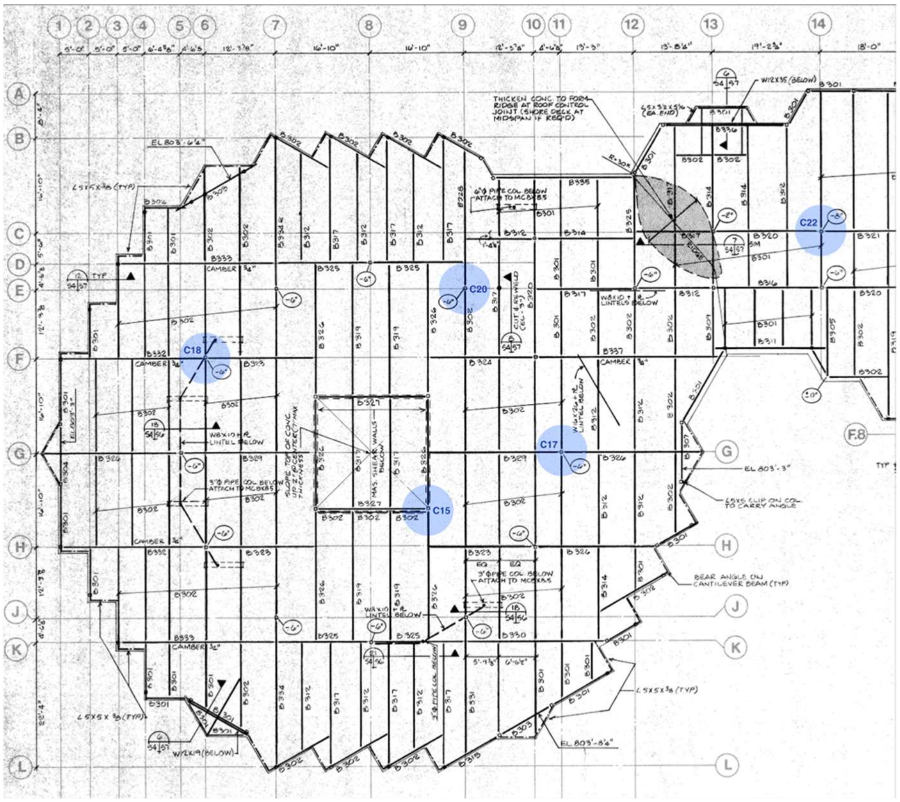


Figure 6. North Hall Spot Column Selection

Each column has a pinned-pinned connection type, indicating a k value of k = 1. The lengths of the columns analyzed extended only from the 2nd floor to the roof, for a length of 154" according to the North Hall Column Schedule. The values of the radius of gyration (r_y) and area were supplied by the AISC 16th edition according to the column type. At the time that this building was constructed, the value $F_y = 43{,}000$ psi was used for the grade of steel in the columns.

This analysis was based on flexural buckling and aimed to find the potential additional load capacity of each column. The critical load (F_{cr}) calculator in Appendix B. The critical capacity (psi) was then multiple by the area of the column to find the critical load value. The LRFD factored reaction forces of the beams were then applied to each column, providing the additional load capacity for each column. At this point in the analysis, it became clear that there is a significant difference in capacity between different areas in the building. The columns in the circular section of North Hall are able to support the additional uniform load of 11.5 psf along any beam. However, the columns in the section of North Hall which is rectangular and connects the circular end section to the Science Building have much lower additional load capacity, which cannot support the additional load of solar panels. Calculations can be found in Appendix C and the attached files.

Therefore, North Hall is likely to support the additional weight of the photovoltaic system in the circular area of the building, but it is recommended that the existing structure and potential implementation of the system is professionally assessed before installation.

6 – DeVos Communication Center

The roof of the Devos Communication Center was also considered (Figure 2). The sections that were analyzed are highlighted in Figure 7 below; for the lower section of the roof, only the part highlighted in yellow was analyzed because this section of the lower roof receives maximum sunlight. Figure 8 below shows a side view of the building roofs.

Figure 5. Roof Sections of Devos Communication Center.

The roof is a built-up membrane roof consisting of a membrane on top of two 2.5” sections of polisocyanurate insulation on top of a 20-gage 1 ½” metal decking. The loading information that was used to perform our calculations for each section is shown in Table 2.

Table 2. Loading information used in Devos Communications Center Calculations.

Original Loading Information		
Live Load	**35**	**psf**
Solar Panel System	5	psf
Snow Load [4]	30	psf
dead load:	**12**	**psf**
Membrane [1]	0.5	psf
0.5" recovery board	0.5	psf
2.5" polisocyanurate insulation [2]	4.5	psf
2.5" polisocyanurate insulation [2]	4.5	psf
metal decking (20-gage) 1 1/2") [3]	2	psf

1. The specific membrane for the roof was also not specified, most membranes I found online weigh 0.5psf.
2. 1" Polisocyanurate insulation weighs 1.5-2psf. A 2.5" section then weighs about 4.5psf
3. Taken from 31-S301-DC.
4. Taken from ASCE 7-10, snow loads.

Figure 6. Side View of Communications Building Roof.

To find the weight of solar panels that each roof could sustain, the roof was split into sections based on their respective members and were analyzed using ASD (allowable stress design) methodology. Our method of analysis started by finding the ultimate moment for each section under the current loading configuration and comparing that to the allowable moment. The difference between the ultimate moment and the allowable moment can be expressed as a weight per square foot, which is the allowable weight of solar panels that each roof can sustain in its current condition. Our analysis found that the Devos Communications Center would be a **suitable building to fit with solar panels**.

6.1 – Lower Roof

The section of the lower roof that was analyzed was split into four separate sections based on the structural members of the roof. The four sections are shown in Figure 9 below.

Figure 7. Sections of lower roof. Section 2 is ignored.

Our calculations determined that sections 1, 3, and 4 can hold solar panels with each section having an allowable weight for the panels shown in Table 1. Section 2 in Figure 9 was ignored because it will not receive as direct of sunlight as sections 1, 3, and 4. Table 3 below summarizes our findings for this section of the roof.

Table 3. Allowable weights for solar panels, Lower Roof.

Section	Additional Weight for Panels (psf)
1	58
2	ignore
3	58
4	78

6.2 – Penthouse of Communications Center

The penthouse was split into two sections for analysis based on the structural members that constitute each section (Figure 10).

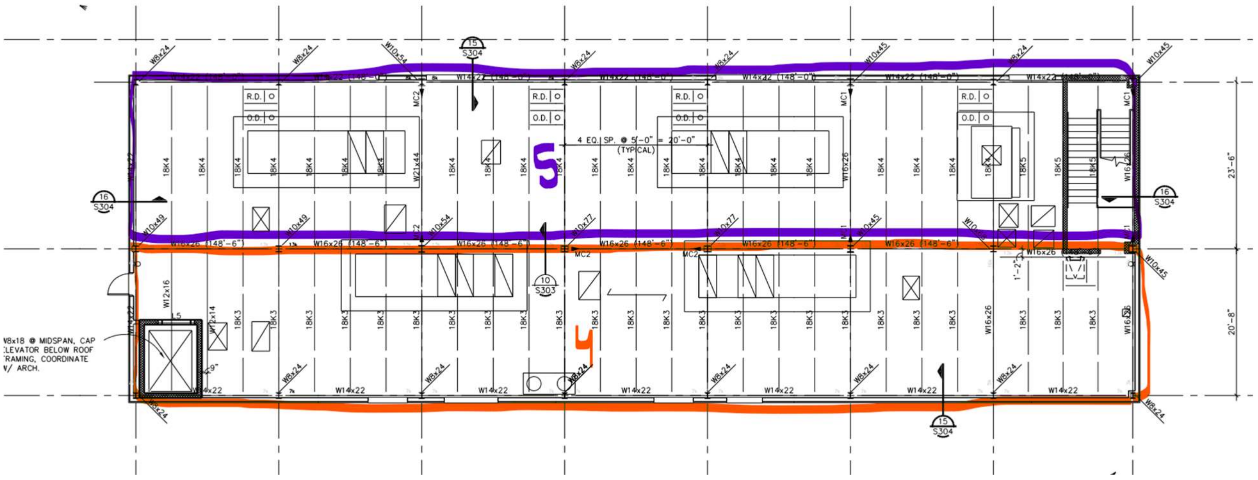


Figure 80. Sections of Penthouse Roof.

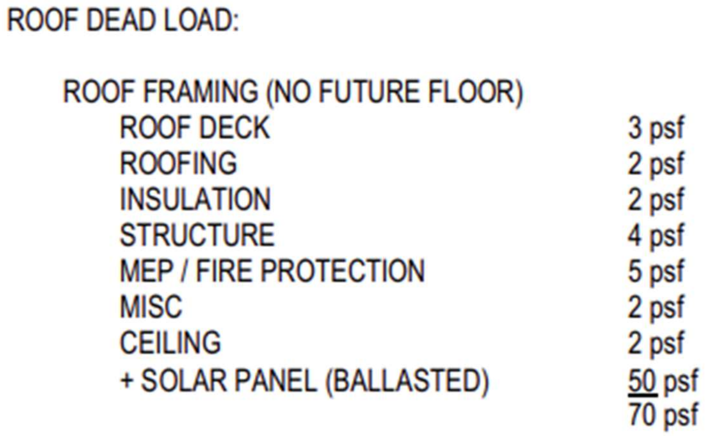
Our calculations show that each roof can sustain an allowable weight for solar panels shown in Table 4. The calculations are shown in Appendix D.

Table 4. Allowable Weight for Solar Panels, Penthouse Roof.

Section	Allowable Weight for Panels (psf)
4	43
5	33

7 – Business Building

The Business Building was a recent addition to Calvin University and was therefore built with many considerations for the future. The roof is built with a new, modern membrane with a warm roof construction. It was coated with a lap sealant and flashing to waterproof the edges. The proposed attachment for the solar panels is through a ballast system which would involve penetration of the roof. The roof was designed to support a ballast system with solar panels of 50 pounds per square foot, found in Figure 11. Since the building was designed with intentions to eventually install solar panels, there were no calculations required. The Business Building **CAN** support solar panels.



ROOF DEAD LOAD:

ROOF FRAMING (NO FUTURE FLOOR)

ROOF DECK	3 psf
ROOFING	2 psf
INSULATION	2 psf
STRUCTURE	4 psf
MEP / FIRE PROTECTION	5 psf
MISC	2 psf
CEILING	2 psf
+ SOLAR PANEL (BALLASTED)	50 psf
	70 psf

Figure 11. Roof Deadload for the Roof Framing Plan.

8 – Venema Aquatic Center

STAAD Pro modelling was used to determine if the roof trusses of the Venema Aquatic Center could safely support the extra load. Safely supporting the extra load required the deflection of the trusses in the y-direction (in inches) to be less than the length of the span (in inches) divided by 240 (L/240) as per specification in the AISC manual.. The Venema Aquatic center roofing structure was primarily composed of eleven (11) identical roof trusses. This truss was modelled in STAADPro (see Fig. 12), after hand calculations and consultation of the building structural plans (please see Appendix E for hand calcs and truss details).

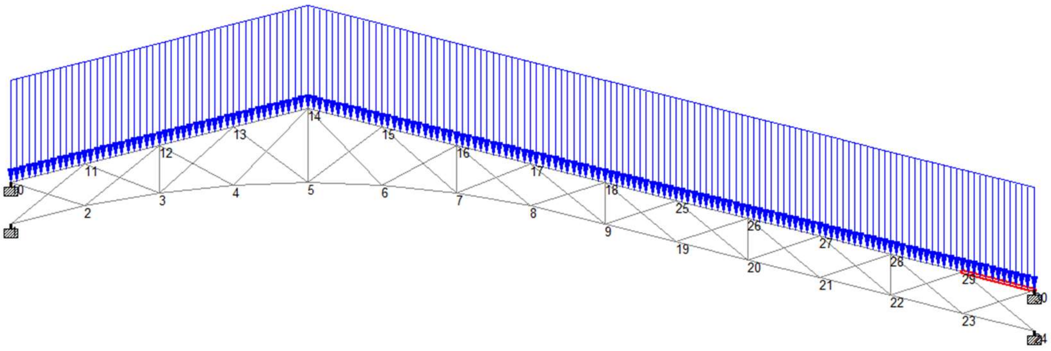


Figure 12. Venema Truss with Loads.

The ends of the truss were assumed to be fixed (as they ran into the wall). Loading was found to be 1.84 kips/ft. This was determined by multiplying the live and dead loads (47 psf combined) by the area of the roof (40,000 sf), after which the solar panel load (63,504 kg or 140,002.35 lbs.) was added. The total load for the whole roof was determined to be 2,020,002.35 pounds. This number was divided by eleven (11), to give the average loading for each individual truss – 252,500.294 pounds or 253 kips. The load was then divided by the length of the truss (127.82 ft) to give the load in kips/ft (1.84). This load was applied to the truss modeled in StaadPro. STAADPro analysis (please see the Venema Reference Items for analysis results) determined that under these loading conditions, the truss deflected only 1.47 inches. The maximum allowable deflection was determined to be 6.2 inches, using the length of the truss span in inches (L = 1,488 in) divided by 240. Given the analysis done in STAADPro, we determined that this **truss can easily support the additional weight of the solar panels.**

9 – Van Noord Arena

The Van Noord Arena was split up into different sections of trusses. The analysis was first started by dividing up the areas that each truss type would experience loading from, using the given number of 21.3 kg per panel. The area of the roof is nearly split in half with a triangular shaped truss and more bridge looking truss, named Arena Truss C and Arena Truss B, respectively (See these in Appendix F). There is a similar truss to Truss B that is called Arena Truss D, which has one extra member in it. After finding the load each section would experience, we started modeling Truss C. After modeling, a report is generated by the program and can be seen in the provided project folder, labeled as 'Truss C Report'. We found that the deflection shown in the report is significantly below the calculated allowable deflection. This was found using the equation L/240, which ends up giving an allowable deflection of 3.2 inches. Because of this knowledge, we can go on to assume that Truss C is **able to hold the load of the new solar panels.**

At this point, the analysis got a little murky. Truss B and D are very similar and ended up with similar results post-modeling. It can be found in the provided project folder labeled as 'Truss B Report' that it is assumed that Truss B is to deflect about 7 inches, while the allowable was only 5.5 inches. This does not make much sense. Our team deduced that Truss C is experiencing a higher load than Truss B, due to the area distribution. For this reason, we believe that this building can support solar panels. However, given that the Mechanical class requested a structural response weeks earlier than initially planned, we didn't have enough time to obtain a more professional assessment of potential inaccuracies in the model. Once again, Truss C contains more solar panels than Truss B and Truss C was successful. Therefore, we would cautiously like to assume that the model has a discrepancy and that the Van Noord Arena is capable of withstanding the addition of solar panels.

10 – Hekman Library

Hekman Library was initially only a four-story building, and in 1994 a fifth story was completed. This roof is a simply supported steel beam section, that has the necessary capacity to add the required number of panels (see attached spreadsheet in the zip folder). The capacity was found using LRFD method. After finding the additional moment capacity, the additional allowable psf was found, and Hekman library **<u>will be able to hold the extra capacity</u>**. These numbers range from about 17.5 psf to 25 psf.

11 – Hiemenga Hall

The first section of Hiemenga Hall was built in 1961, and an additional section was built in the late eighties. The first building was built using a simply supported steel beam section, that has plenty of additional capacity. Drawings are a bit unclear in quite a few spots, especially weak on the dimensioning side, which led our group to assume worst case scenario, and even in worst case scenario, this **building has the necessary capacity**. In the attached excel (found in the zip folder), equations are given. The addition in Hiemenga, which completed the block and gives that area its courtyard, was built using concrete slaps. It was again found there was plenty of additional capacity for solar panels. An exact analysis of available loading in pounds per square foot is available on the excel in the zip file, but the figures are smallest at about 30 psf, with a rather large uncertainty due to unclear sheet plans and poor dimensioning.

Appendix A: CFAC

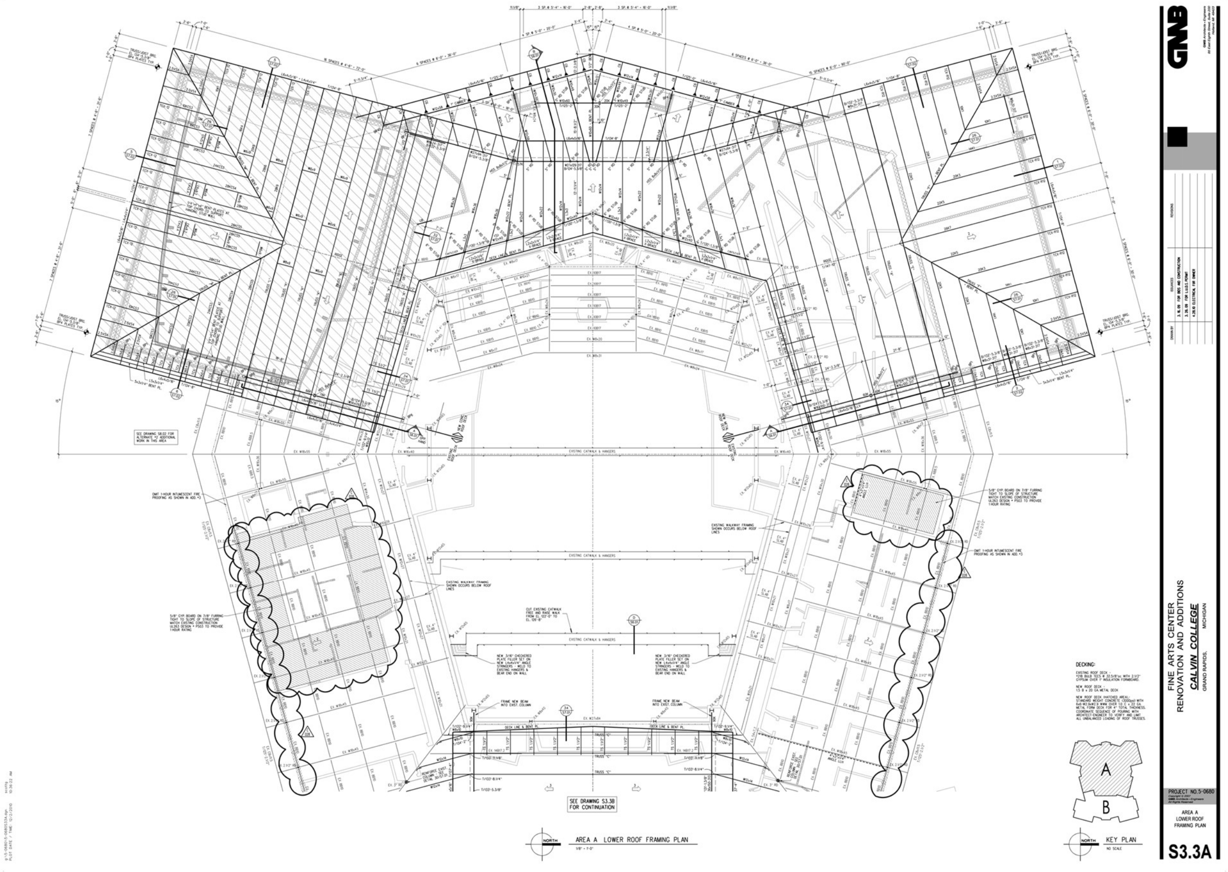


Figure 93. CFAC Structural Plans for Roofs 1,2,3.

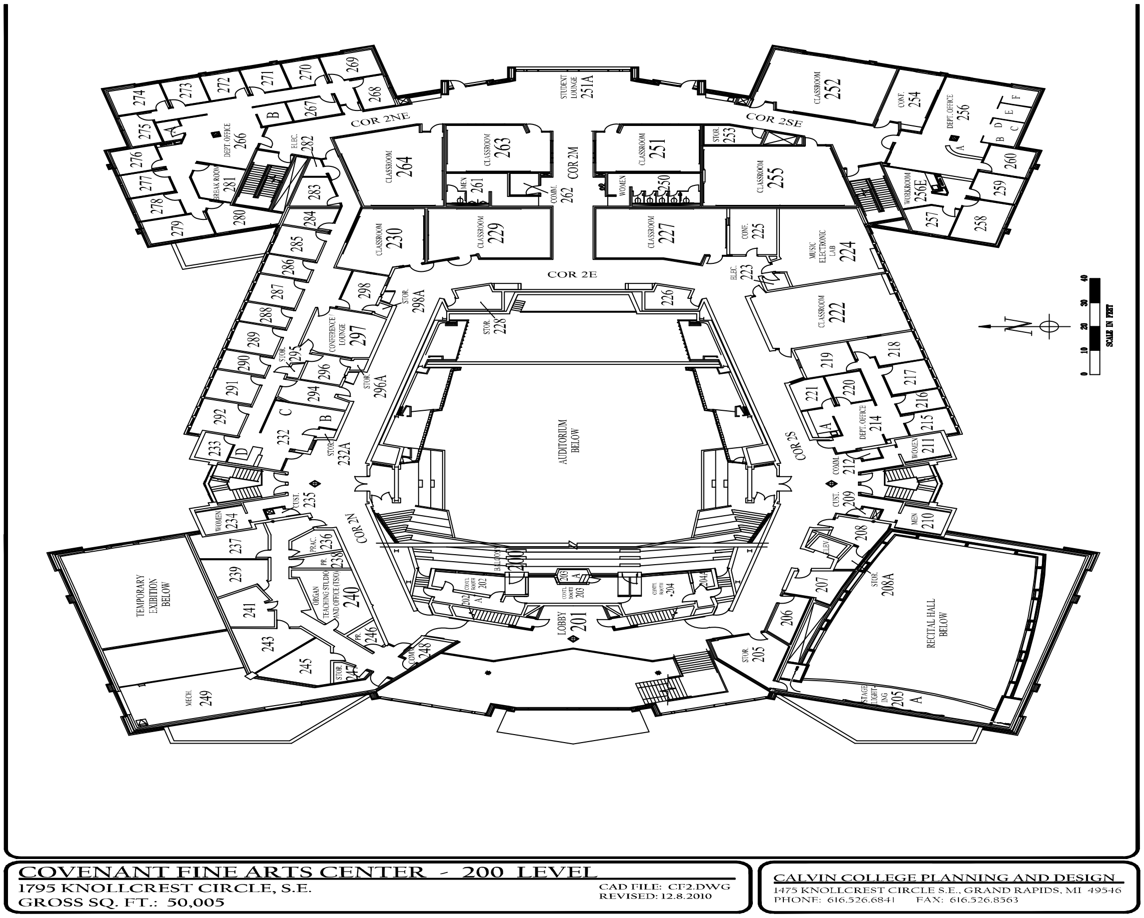


Figure 104. CFAC Upper-Level Floor Plan Roofs 1, 2,3.

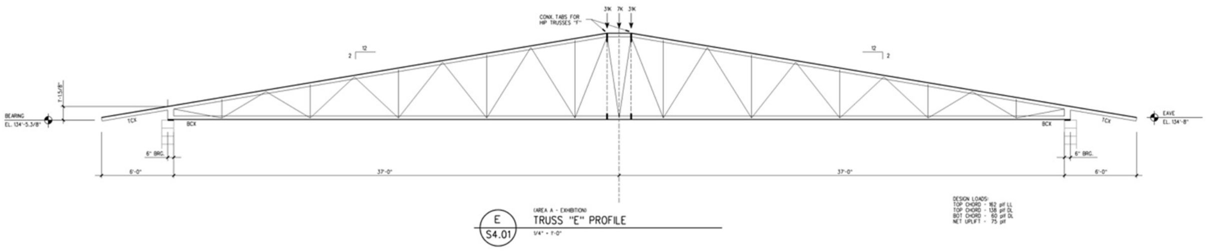


Figure 115. Truss E Profile from CFAC Roof 1.

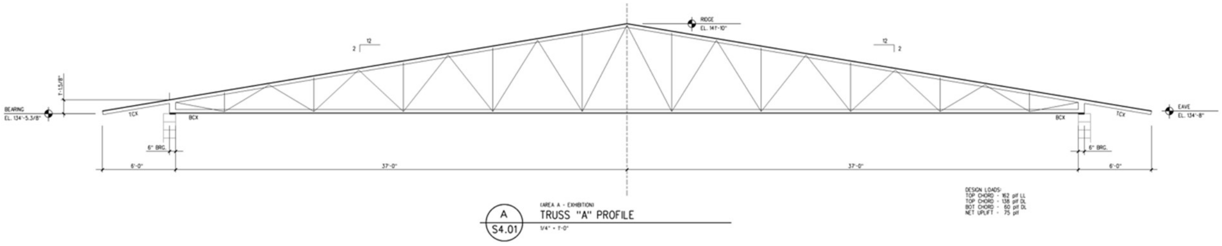


Figure 126. Truss A Profile from CFAC Roof 1.

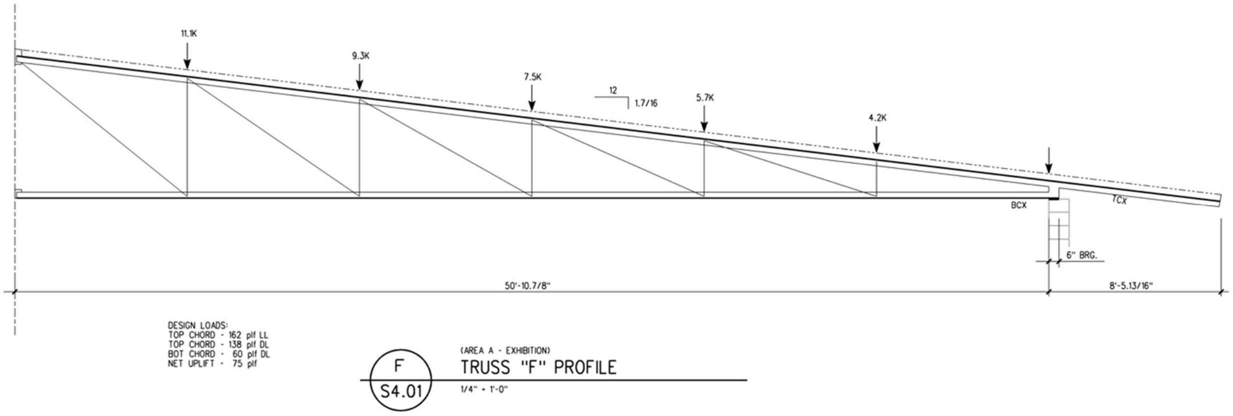


Figure 137. Truss F Profile from CFAC Roof 1.

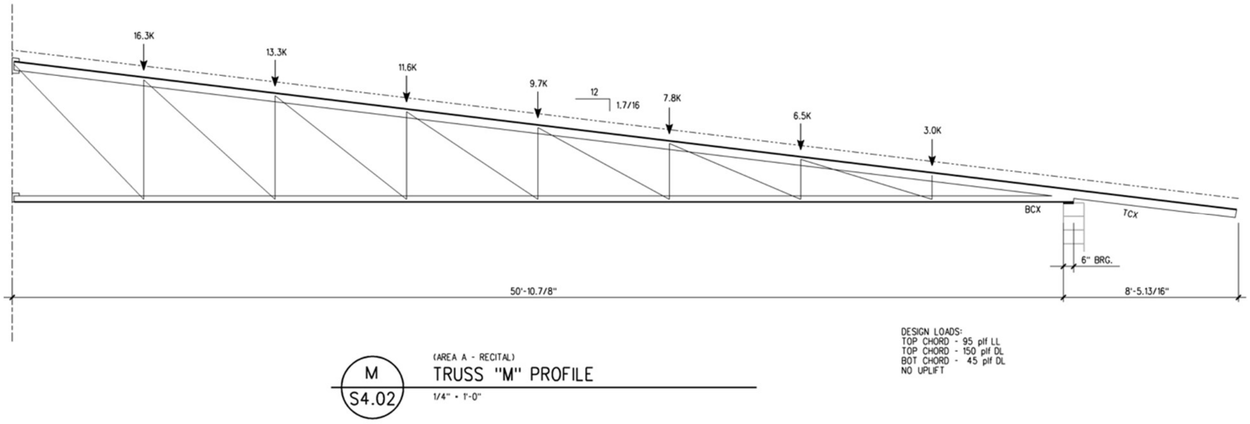


Figure 148. Truss M Profile from CFAC Roofs 2 and 3.

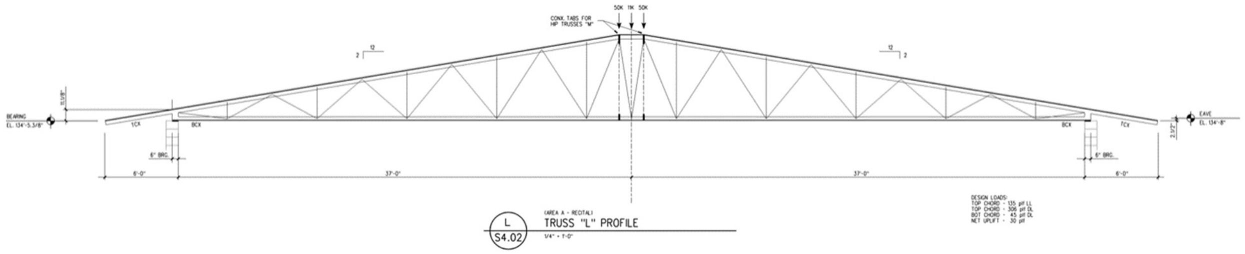


Figure 159. Truss L Profile from CFAC Roof 3.

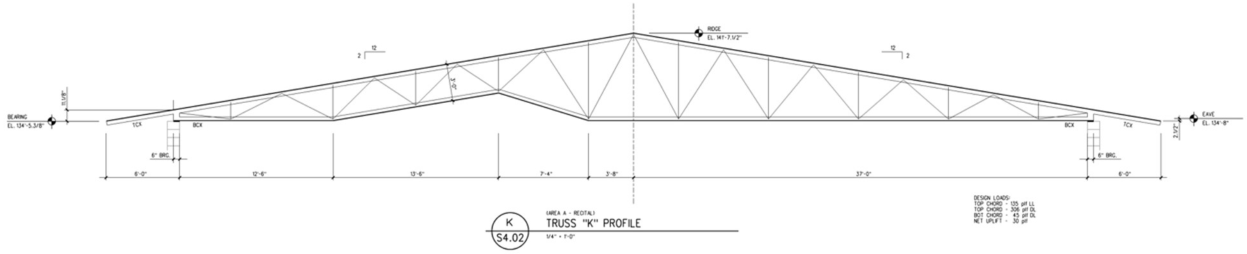


Figure 160. Truss K Profile from CFAC Roof 3.

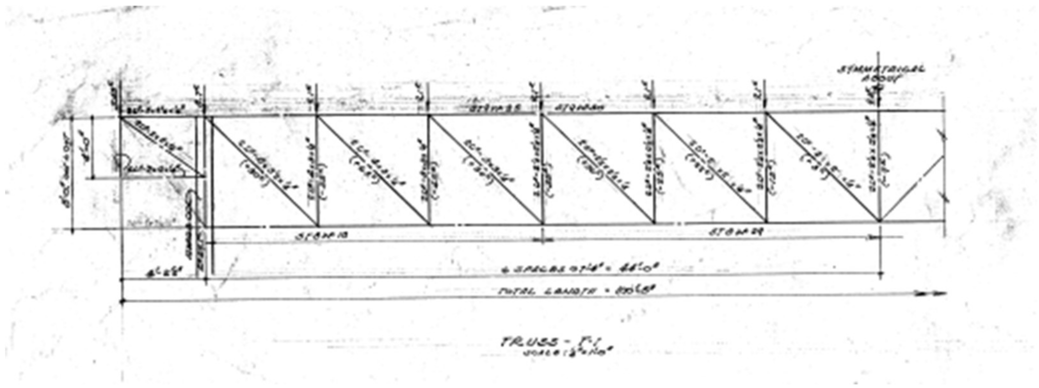


Figure 171 Truss T-1 Profile from CFAC Roof 4.

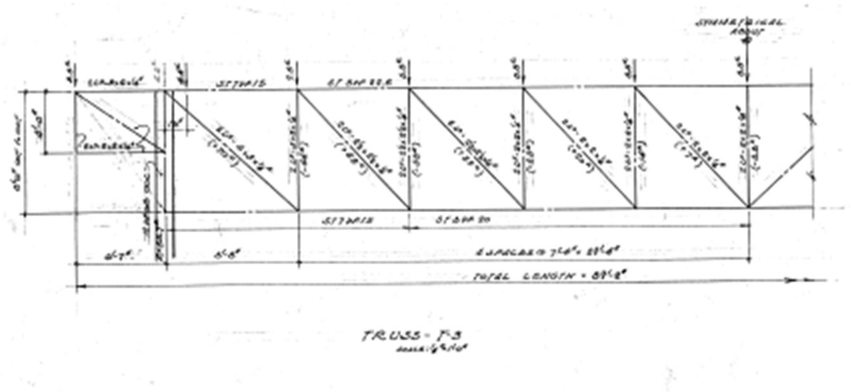


Figure 182. Truss T-3 Profile from CFAC Roof 4.

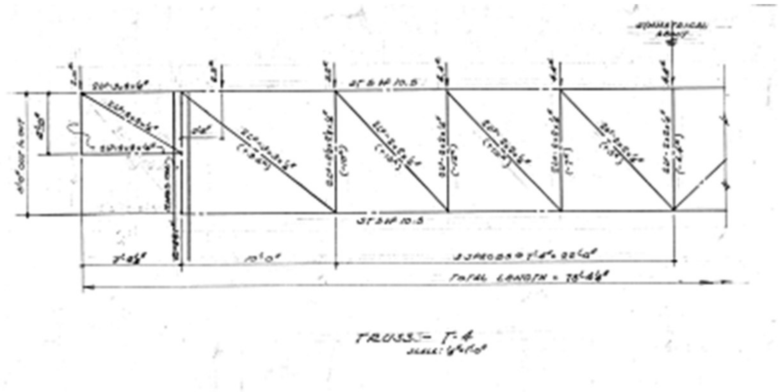


Figure 193. Truss T-4 Profile from CFAC Roof 4.

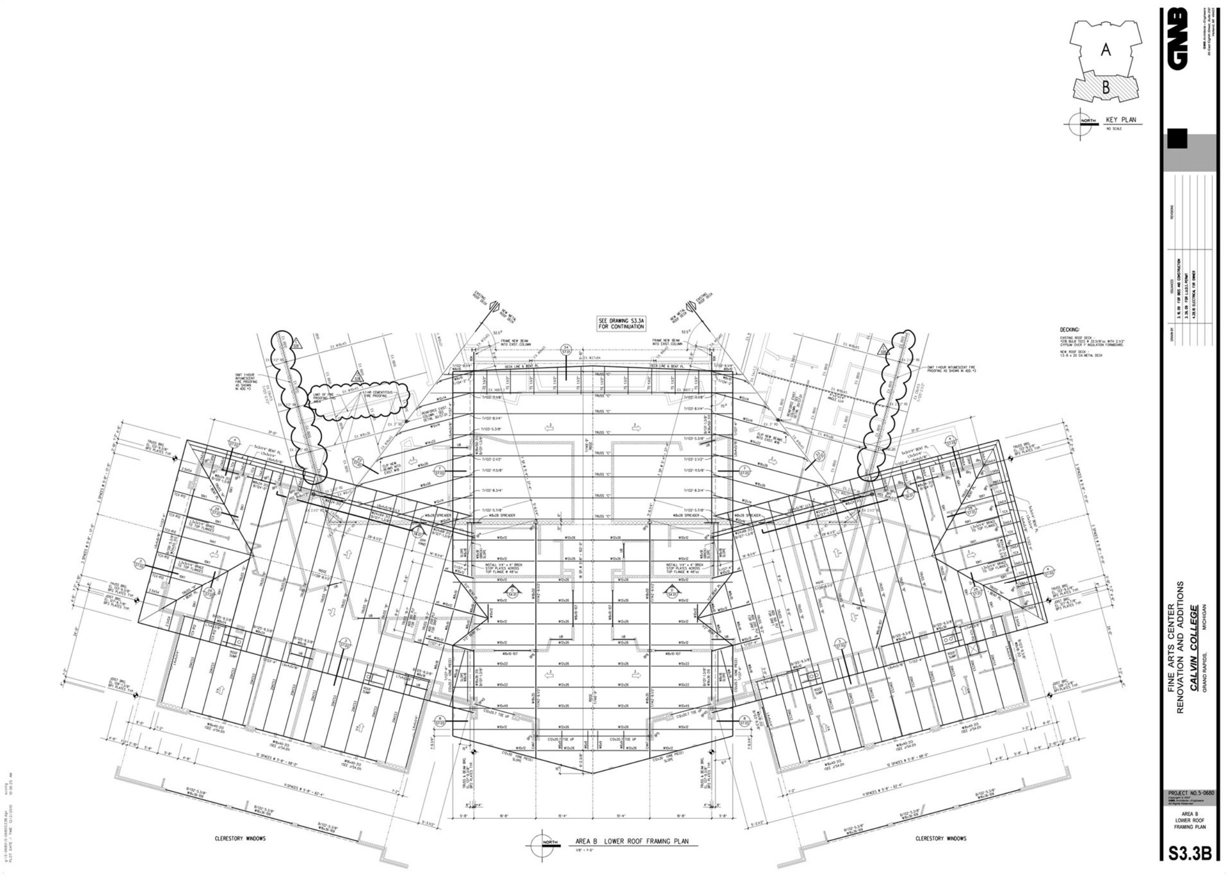


Figure 204. CFAC Structural Plans for Roof 5.

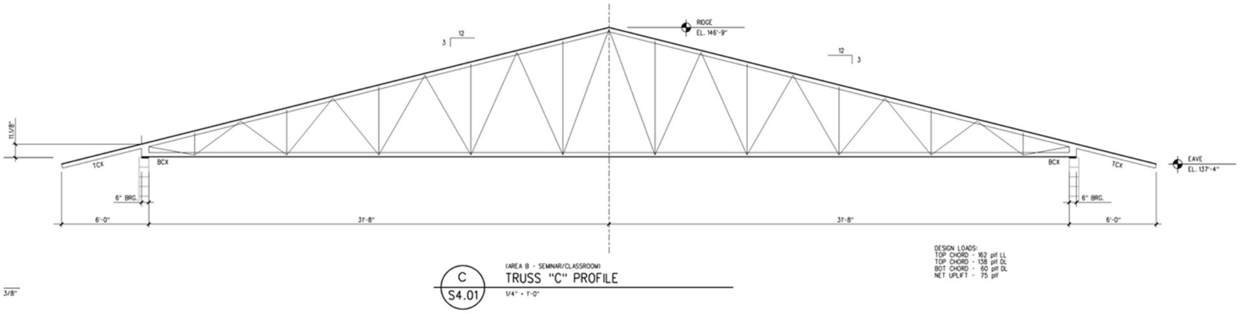


Figure 215. Truss C Profile for CFAC Roof 5.

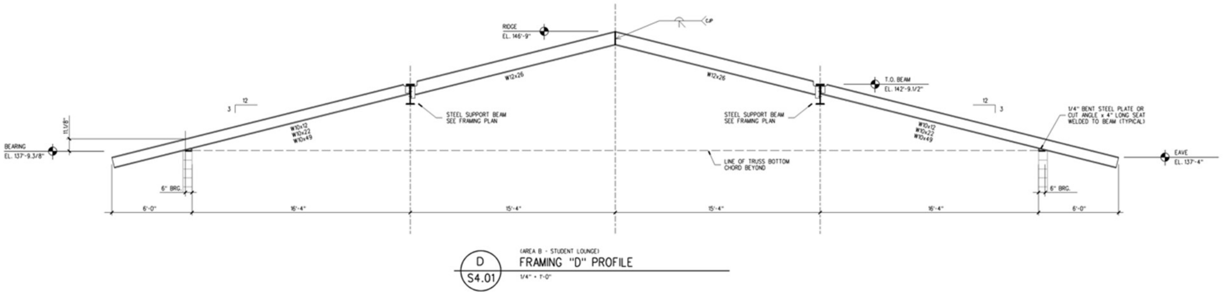


Figure 226. Framing Plan D Profile for CFAC Roof 5.

Appendix B: Prince Conference Center and Hotel

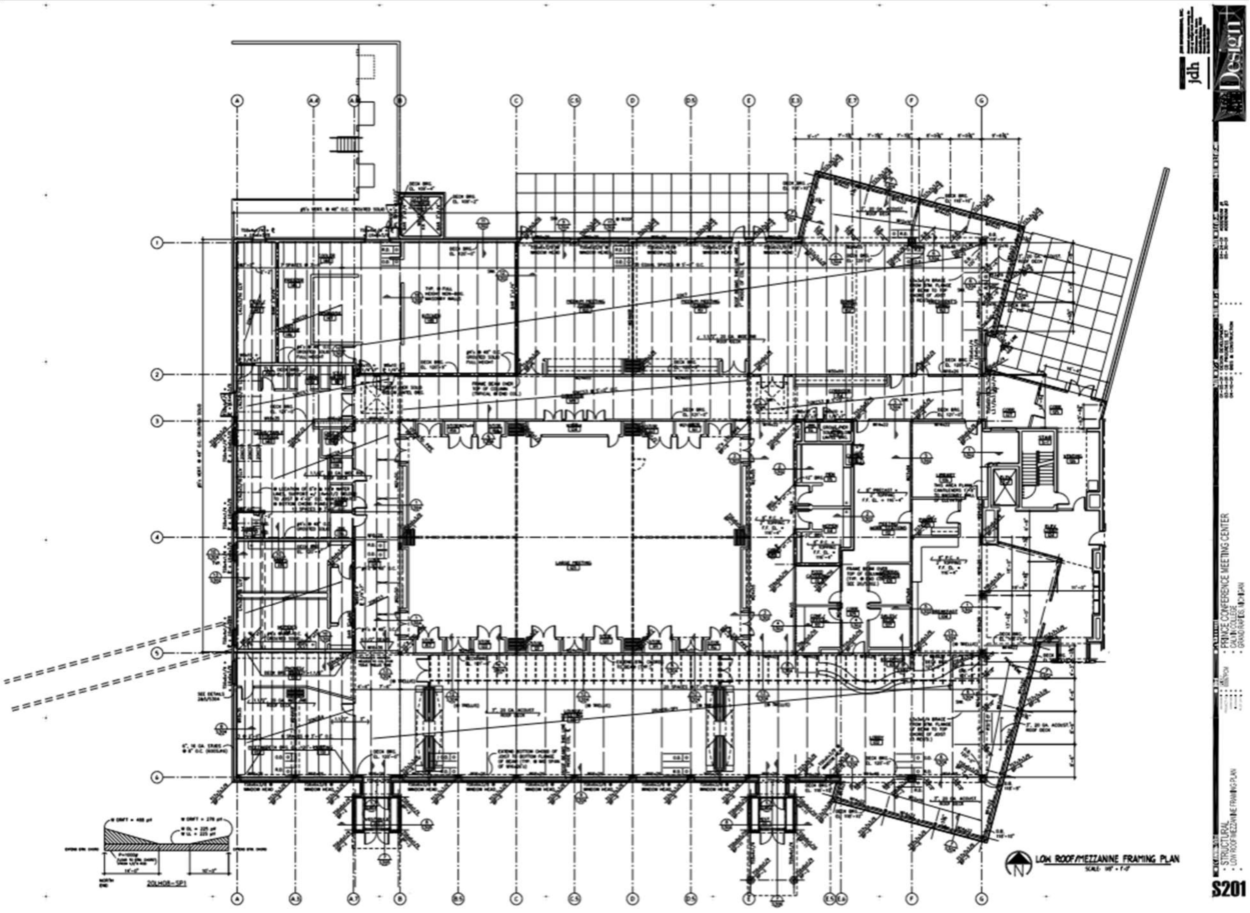


Figure 27. Prince Conference Center Roof 1 Framing Plan.

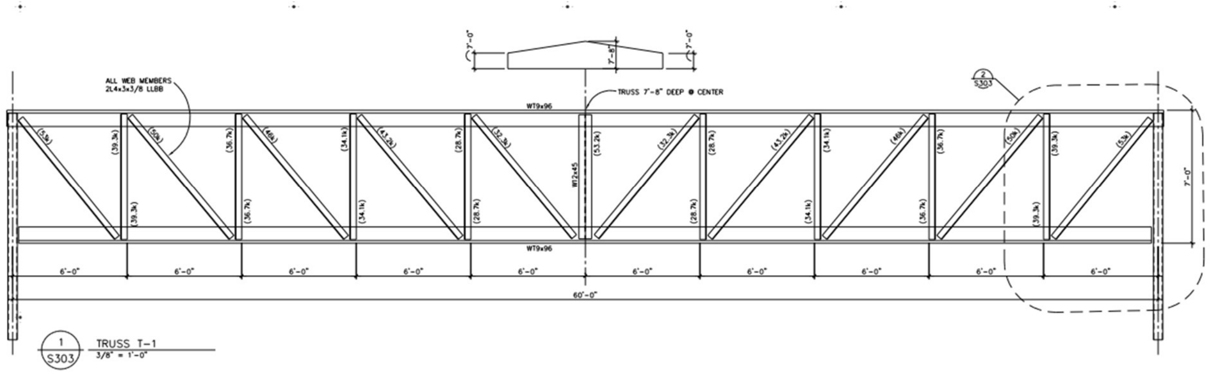


Figure 28. Truss T-1 Profile for Prince Conference Center Roof 1.

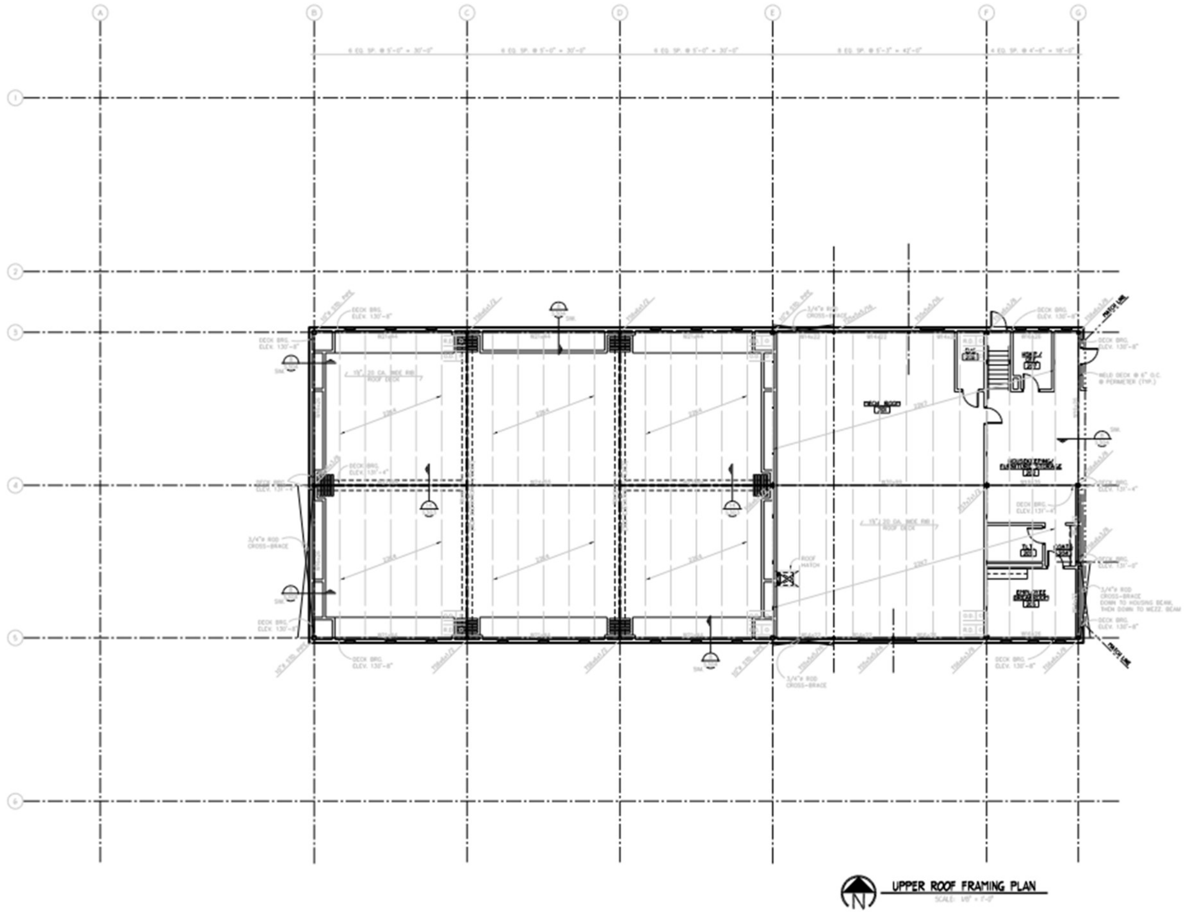
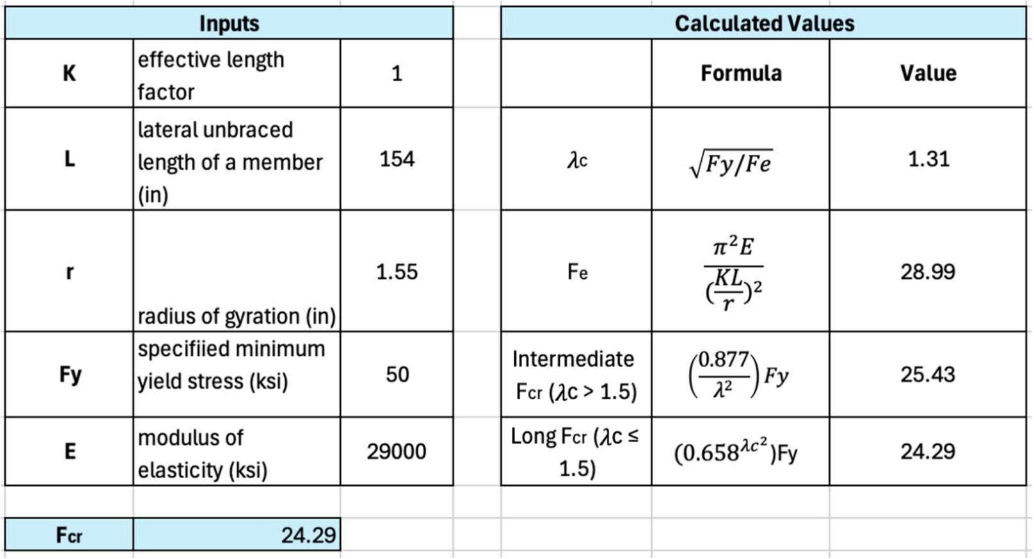


Figure 29. Prince Conference Center Roof 2 Framing Plan.

Appendix C: Column Calculator for North Hall

Table 4 – Column Limit State of Flexural Buckling (F_{cr}) Calculator



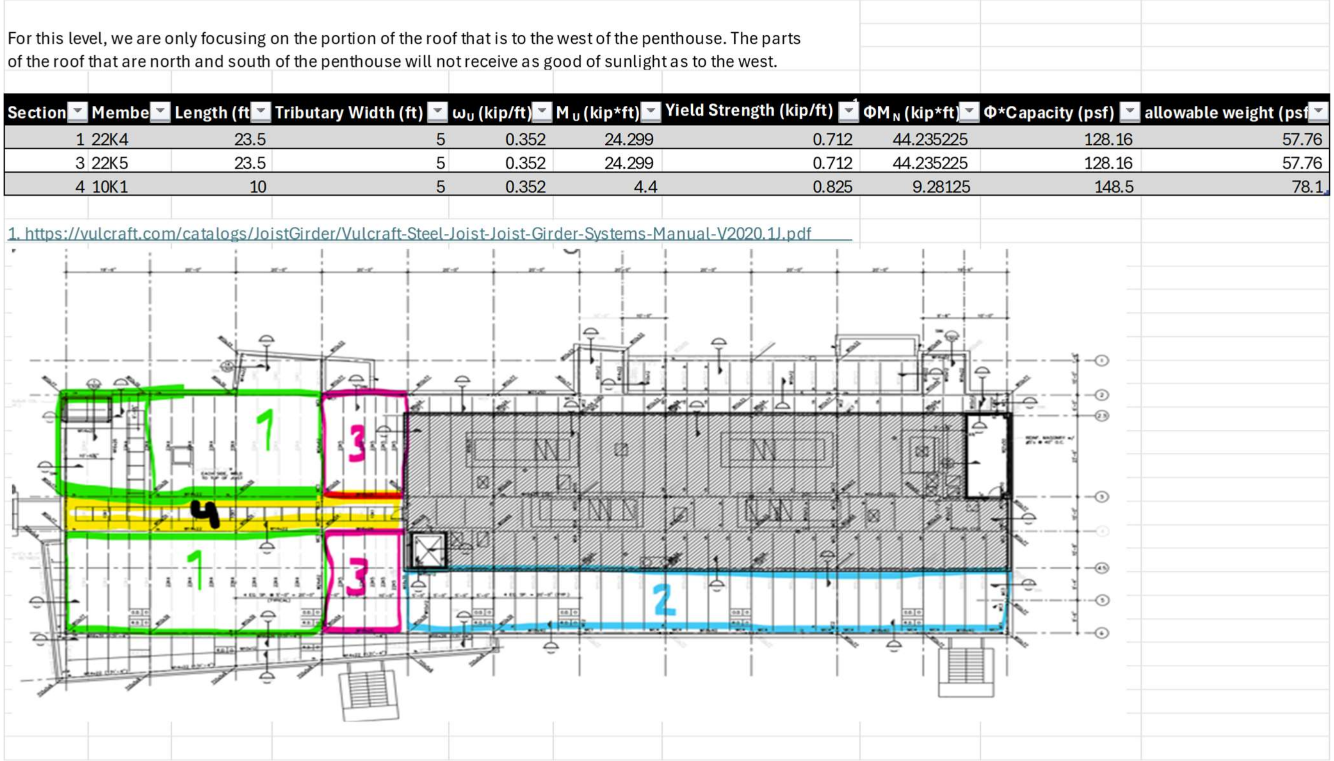
Inputs		
K	effective length factor	1
L	lateral unbraced length of a member (in)	154
r	radius of gyration (in)	1.55
Fy	specifiied minimum yield stress (ksi)	50
E	modulus of elasticity (ksi)	29000
Fcr	24.29	

Calculated Values		
	Formula	**Value**
λc	$\sqrt{Fy/Fe}$	1.31
Fe	$\frac{\pi^2 E}{(\frac{KL}{r})^2}$	28.99
Intermediate Fcr ($\lambda c > 1.5$)	$\left(\frac{0.877}{\lambda^2}\right)Fy$	25.43
Long Fcr ($\lambda c \leq 1.5$)	$(0.658^{\lambda c^2})$Fy	24.29

Table 5 – Column Additional Capacity Calculations

Column Calculations								
Column No.	**Size**	**Area (in^2)**	**Ry (in)**	**Slenderness Ratio L_c/r_y**	**Calculated F_{cr} (ksi)**	**Load Capacity (kips)**	**Load from Reactions at Top of Column (kips)**	**Additional Capacity (kips)**
C20	HSS 4x4x3/16	2.58	1.55	8.3	24.29	62.6682	29.96	32.71
C18	HSS 5x5x3/16	3.28	1.96	6.5	31.84	104.4352	84.13	20.30
C17	HSS 5x5x3/16	3.28	1.96	6.5	31.84	104.4352	57.46	46.98
C15	HSS 6x6x3/16	3.98	2.37	5.4	36.72	146.1456	39.39	106.76

Appendix D: Calculations for Devos Communications Center

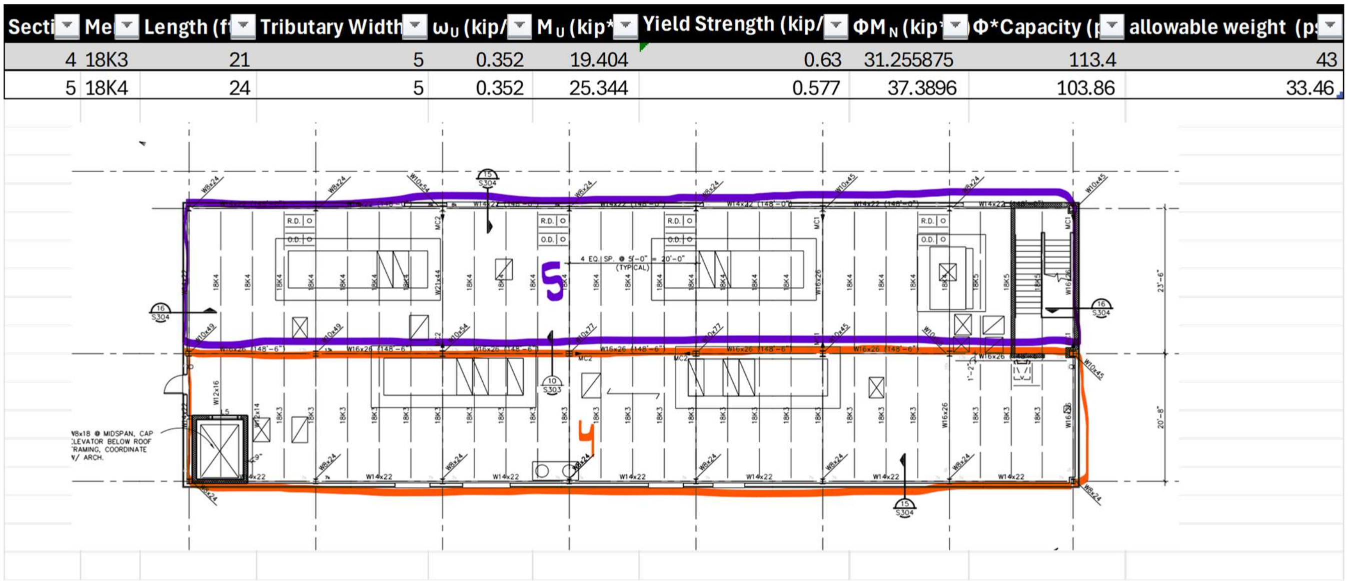


For this level, we are only focusing on the portion of the roof that is to the west of the penthouse. The parts of the roof that are north and south of the penthouse will not receive as good of sunlight as to the west.

Section	Membe	Length (ft	Tributary Width (ft)	ω_U (kip/ft)	M_U (kip*ft)	Yield Strength (kip/ft)[1]	ΦM_N (kip*ft)	Φ*Capacity (psf)	allowable weight (psf
1	22K4	23.5	5	0.352	24.299	0.712	44.235225	128.16	57.76
3	22K5	23.5	5	0.352	24.299	0.712	44.235225	128.16	57.76
4	10K1	10	5	0.352	4.4	0.825	9.28125	148.5	78.1

1. https://vulcraft.com/catalogs/JoistGirder/Vulcraft-Steel-Joist-Joist-Girder-Systems-Manual-V2020.1J.pdf

Figure 30 Calculations for Devos Communication Center



Secti	Me	Length (f	Tributary Width	ω_U (kip/	M_U (kip*	Yield Strength (kip/	ΦM_N (kip*	Φ*Capacity (p	allowable weight (p
4	18K3	21	5	0.352	19.404	0.63	31.255875	113.4	43
5	18K4	24	5	0.352	25.344	0.577	37.3896	103.86	33.46

Figure 31. Calculations for Devos Communications Center

Appendix E: Venema Aquatic Center

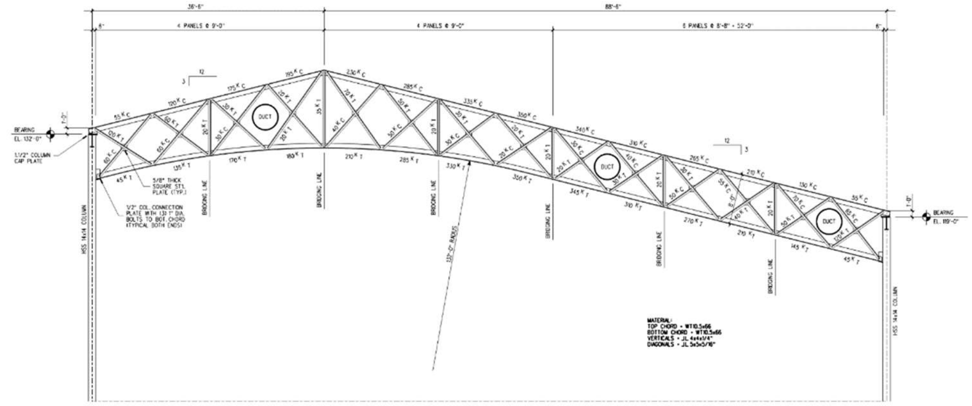
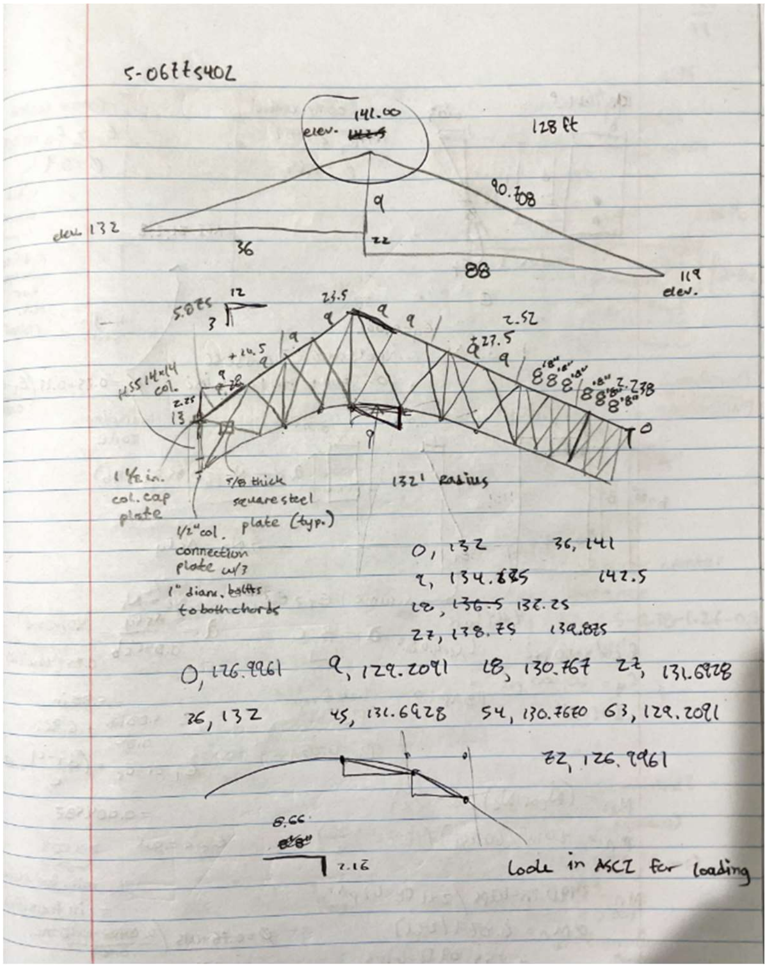


Figure 32. Venema Aquatic Center Truss



0, 132 36, 141

9, 134.875 142.5

18, ~~136.5~~ 132.25

27, 138.75 139.875

0, 126.9961 9, 129.2091 18, 130.767 27, 131.6928

36, 132 45, 131.6928 54, 130.7670 63, 129.2091

72, 126.9961

Code in ASCE for loading

Figure 33. Venema Aquatic Center Hand Calculations

Appendix F: Van Noord Arena

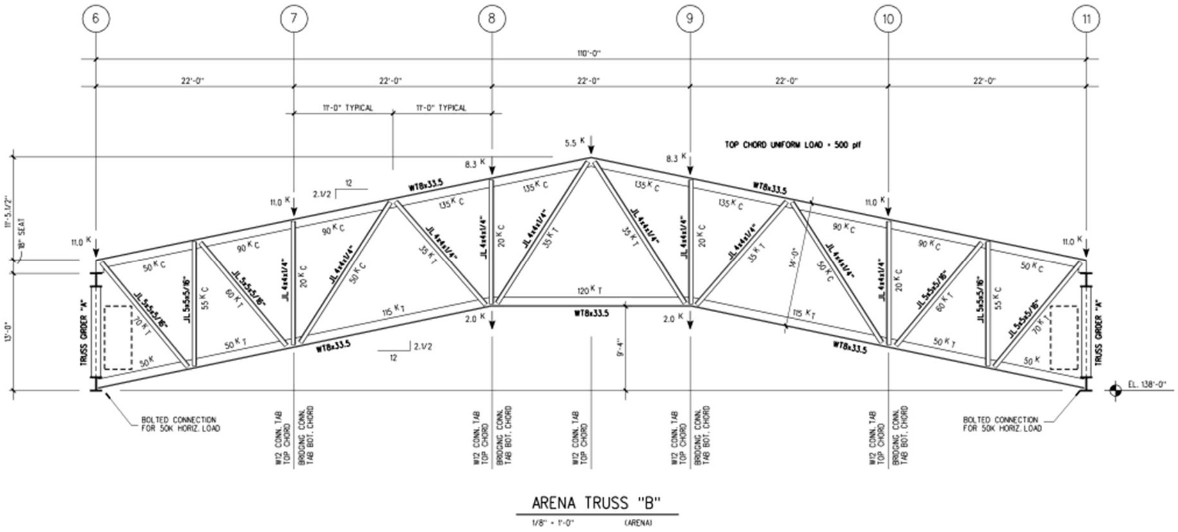


Figure 34. Van Noord Arena Roof Truss B

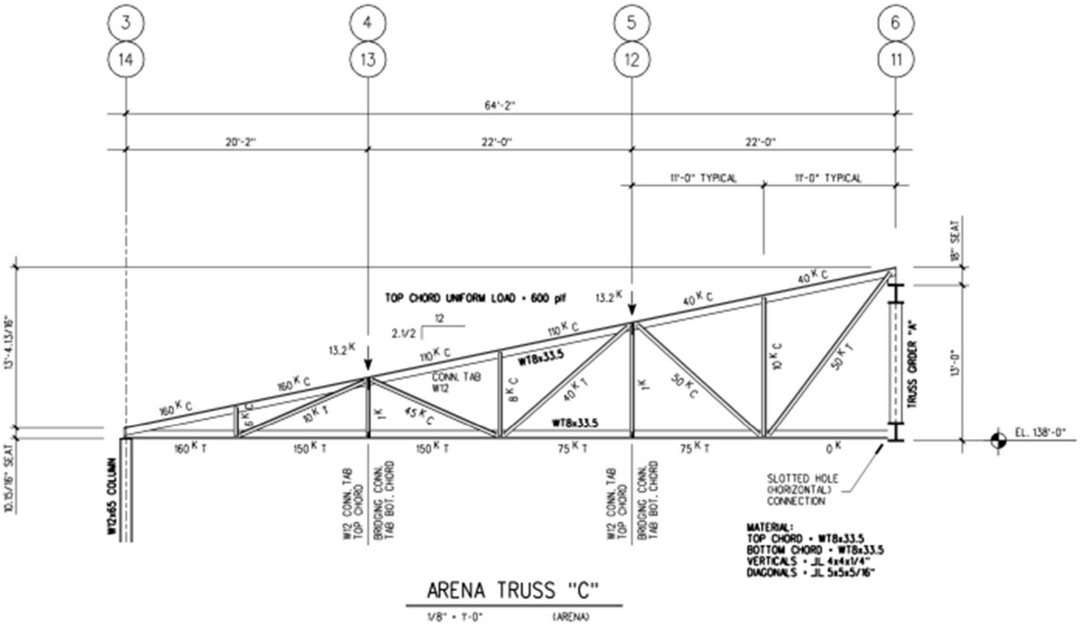


Figure 35. Van Noord Arena Truss C