Renewable Energy Generation Project

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Engineering 333B: Thermal Systems Design

December 18, 2018

Introduction

What is the largest possible reduction in Calvin College's annual energy costs from a $5M initial investment in renewable energy? Renewable energy systems are essential for Calvin College to reduce greenhouse gas emissions and achieve carbon neutrality to meet the Carbon Commitment that President Le Roy signed in December 2017. Also, a significant cost reduction could be a positive result of transitioning to renewable energy sources such as geothermal, wind, solar, and biomass. Four renewable energy sources were studied throughout the semester to determine a feasible renewable energy plan for Calvin with a $5M investment.

Method

Initially, the large team was split into sub-groups to cover each of the renewable energy sources, with a management team to cover finances, CO_2 emissions, and coordination of the other four teams. As renewable energy sources were deemed infeasible, disbanded group members were allocated to other energy sources or tasks for the remaining weeks in the semester.

The solar team studied the feasibility of adding a solar panel system to Calvin's campus. This required research on the annual sunlight rates for the Grand Rapids area and the distribution of sunlight throughout the year. Various solar panel technologies and locations were discussed as shown in Appendix A.

The geothermal team began with research on increasing the efficiency of the various heating and cooling systems on campus with a supplementary geothermal system. The underground loops act as a heat pump system using water to transfer heat. In the heating mode, the fluid is circulated through the earth's surface to absorb heat from the ground to be used to supplement the system. In cooling mode, the fluid discharges heat into the earth's surface. A geothermal system can be feasible due to the extreme air temperature differences and the approximately constant ground temperature. More on the feasibility of a geothermal system can be found in Appendix B.

Next, the wind team researched the feasibility and cost savings of implementing a variety of wind turbines on Calvin's campus. This team studied the annual wind rate experienced in the Grand Rapids area and the zoning requirements to add such a large turbine in a suburban area. These feasibility and specifications of this energy source is found in Appendix C.

The biomass team researched the technologies available for energy production from a biomass incinerator or an anaerobic digester. The biomass team consulted the dining hall staff and the physical plant to determine Calvin's annual food waste. Project feasibility was verified on an economic and fuel availability basis based on the energy production on a per mass basis of Calvin's food waste. Further information on the feasibility of implementing a biomass system on Calvin's campus can be found in Appendix D.

Results and Alternative Solutions

Following thorough research on each of these energy sources, the team determined that a solar panel system supplemented with additional renewable energy sources would be the best use of a $5M investment into Calvin's commitment to reducing greenhouse gas emissions and becoming carbon neutral. The proposed $3.68M solar panel system is comprised of 5889 solar panels spanning roof tops throughout campus. This system will result in annual savings of $183,750 and has a pay-back period of 16 years. This system will provide Calvin with approximately 10% of its yearly energy usage or 2.12 GWh/year.

This system is limited by the roof space availability that is suitable to withstand the weight of numerous solar panels. Therefore, this system is maxed out at $3.68M. The remaining $1.32M can be invested into a series of alternatives summarized below and discussed in detail in Appendix E.

The first option, Alternative A, is comprised of a 75 hp geothermal system in Commons Lawn. This will supplement the aging Kewanee Boilers, which currently have a 65% efficiency rate. Implementation of a geothermal system will provide a total estimated annual savings of $11,195.

Alternative B encompasses either the placement of a single 335 kW turbine and/or a series of smaller 1.5 kW turbines placed around campus. These smaller turbines would only cost about $1,500 each and would pay themselves back in approximately 19 years. The downside to this system is the lengthy payback period that presents potential financial infeasibility and the constraint of space.

Finally, Alternative C consists of using the remaining $1.32M to purchase carbon credits for approximately $10/ton to negate Calvin's carbon emissions for approximately 5.25 years when implemented in addition to a solar panel system. This would be a short-term solution to reduce Calvin's carbon footprint but would not reduce energy cost.

Conclusion

Given a $5 million investment in renewable energy, meant to save on energy costs while reducing the carbon footprint at Calvin College, the maximum annual savings is $183,750. The most efficient investment is in solar panels, which have the highest annual energy savings per dollar spent of any of the technologies that were studied. Unfortunately, this would require rooftop mounting of the panels, and there is currently not enough rooftop space to invest the entire budget into solar. The maximum amount that can be invested in solar is $3.7 million, and several proposals for using the remaining $1.3 million were developed; investing in wind, geothermal, and carbon credits. Wind and geothermal would provide a marginal additional cost savings, while carbon credits would be purchased solely to offset Calvin's carbon footprint.

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Appendix A: Solar Renewable Energy Source

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Engineering 333B: Thermal Systems Design

Dr. Matthew Heun: Calvin College Engineering Department

December 18, 2018

Introduction

Solar power is energy from the sun that can be converted into electricity. The solar market has grown quickly in the last few years, becoming one of the most common forms of renewable energy. Calvin College would benefit from the installation of photovoltaic solar panels, not only because of the savings in electricity costs, but because it emphasizes Calvin College's commitment towards becoming more carbon neutral.

Method

To determine feasibility of spending the $5M budget on solar, a spreadsheet was created that considered the cost of solar panels, racking, inverters, installation, labor, utility connection, and a federal rebate. These calculations can be found in Appendix A1.

The spreadsheet uses a variety of inputs, such as the number of solar panels, number of strings, efficiencies, labor cost and time, panel specifications, and inverter specifications. These inputs are used to calculate the effective area of the panels, total required area, system power, string power, number of inverters and system costs.

To determine the electricity produced by the solar panel system, the incident radiation for every hour of every day for an entire year was calculated. These radiation calculations require the geographical location of the system and include weather reduction coefficients. The radiation equations provided the electricity production in watt-hours per meter squared. Multiplying by the effective solar panel area of the system, the solar panel efficiency, inverter efficiency, wiring and other module efficiencies provides the electricity produced for each hour. This can then be summed to find daily, monthly, and yearly electricity production. Some of the equations used can be found in Appendix A2, with the rest being found in the solar radiation resources.

From the annual electricity production, the annual savings can be found using the effective yearly rate at which Calvin College purchases electricity from the grid. Considering the increasing cost of electricity, solar panel degradation, and maintenance, the payback period for the capital investment and the lifetime savings can be found. The equations and calculations can be found in Appendix A2 and A3.

Case studies from Northwestern University and Princeton University, which have similar climate patterns to Calvin College, were used to validate the calculations. The energy produced in their systems and the costs were scaled to the proposed budget of $5M. The System Advisor Model, or SAM, was also used as a tool to validate the numbers calculated from the Excel spreadsheet the solar team created. It incorporates geographical location, taxes, and all system costs, and provides information such as annual energy usage, payback period area, and total cost. This system yielded similar values to the spreadsheet model. Also, using the solar map data from NREL (National Renewable Energy Laboratory), the annual electricity production was verified. The NREL data was provided in $kWh/m^2/day$, multiplied by the effective solar panel area, efficiencies, and the days per year.

Solar Panel Selection

The panel type was selected based on its efficiency when compared to the cost. Polycrystalline, monocrystalline and thin solar panels were compared using the website Wholesale Solar. Appendix A4 shows a cost per watt and area per watt comparison between the best solar panel option found for each type. Thin solar panels are the cheapest option, but they have a short lifespan and a low efficiency rate, so they were not used. Monocrystalline panels have a longer lifetime and a high efficiency rate of 20%, but they are the most expensive option. Polycrystalline are cheaper but have a slightly lower lifetime and an efficiency of 15%. For this project, Polycrystalline was selected, because the price per watt of electricity produced was cheaper. The exact solar panel recommended and used in the calculations is the CS6K-275P from Canadian Solar. The Canadian Solar panel specification sheet is shown in Appendix A8.

Inverter Selection

The type of inverter was selected from a list of possible industrial inverters found through company websites. The necessary criteria for the inverters were that it had an output voltage of 240 VAC and an input voltage of 200-400 VDC. Because the standard voltage in the United States is 120 VAC, a transformer will be needed to convert the 240 VAC from the inverter into a useable voltage. The selection was made based on the price of the inverter, the maximum wattage it was able to process, and its weight. The four best inverters, two from Sunny Boy and two from SolarEdge, were selected and compared. As shown in Appendix A5, when comparing the different options, the Sunny Boy Model SMA 7.7kW has the best cost/watt, $0.009 better than the next best, however, the cost/pound is $4.70 more expensive than the next best. Because of this, the Sunny Boy Model SMA 6.0kW was chosen and used in calculations. The specification sheet for this inverter is shown in Appendix A8.

Location

The placement of solar panels was determined by considering the rooftop space on the buildings at Calvin College. The buildings chosen must be able to hold the required weight capacity and, ideally, have rooftops that are at optimal angles for receiving sunlight with little tree coverage. Through talking to Professor Leonard De Rooy, it was determined that the dorms and the Track and Tennis Center cannot be used because they are not strong enough to hold the required load. Many of the dorms are also surrounded by trees, so this would not be an ideal location even if the rooftops could withstand the load. The Venema Aquatic Center and Van Noord Arena are the best options for solar panels because of their large open roofs that face south, allowing for the optimal amount of power generation. The Hekman Library, Covenant Fine Arts Center, new Commons building, North Hall, DeVries Hall, DeVos Communication Center, and Prince Conference Center were also determined as possible locations. These locations and rooftop areas are shown in Appendix A6. The areas of the rooftops were determined using a Google Maps area calculator tool. Free standing structures in the parking lots were also considered but were not pursued in this project because of the expense and the problems with snow removal. The Prince Conference Center parking lot is set up at the optimal angle for free standing structures, but it is not used enough to make the cost worth it.

Racking

There are various options for solar panel racking, including non-rotational fixed tilt racking, 1 axis tracking, and 2 axis tracking. Due to the cost per watt at the time of studying solar tracking racking systems, the non-rotational fixed racking was chosen.

After discussing this topic with Professor De Rooy, the distance between roof beams on the buildings capable of handling the additional load is 6.75 ft. Using this information, along with the number of panels and placement of the panels, racking was accomplished using the online application IronRidge Racking. Chosen panel manufacturer, model, and orientation (portrait vs landscape) were selected in the application as well as zip code, snow load, wind speed, building height, configuration of panels (sub arrays, tilt angle), and attachment span were entered so the application would yield racking cost, weight, watts and $/watt to verify the number previously calculated. A screenshot of the application can be found in Appendix A7.

CO_2 Emissions for Solar Power Generation System

A study was done on the CO_2emissions associated with the proposed solar power generation system. This study investigated the CO_2emissions from the life cycle of a mono-crystalline silicon PV panel as well as the racking and installation associated. A study by Fthenakis wrote that the amount of electricity required to produce $1m^2$ of mono-crystalline silicon solar panel is approximately 250kWh (this includes the mining and production of mono-crystalline silicon, wafer, cell, and module). The solar power generation system proposed to install approximately 5889 panels with the total area of 9658m^2. The total CO_2emission from manufacturing the solar panels were calculated to be 4,442,903 lbs. of CO_2, with the assumption that the solar panels were manufactured using the electricity from Consumer's with their CO_2 emission rate of 1840 lbs. of CO_2/MWh. The CO_2 emission from the racking of the solar panels was also calculated based on the total amount of aluminum used. The proposed system required 19.8 metric tons of aluminum. Gautam cited that the average aluminum production (also includes the mining and processing of aluminum) consumes 14.65 MWh/tons of aluminum. Assuming again that the aluminum was produced using Consumer's electricity, the total emissions from the racking would be approximately 533,939 lbs. of CO_2. The total CO_2 emission from all sources associated with the solar panel system was then calculated to be 4,976,843 lbs. of CO_2.

The "payback" period for the embodied CO_2 emissions of the solar panels and the racking system was also calculated. The proposed solar power generation system had the capacity to produce approximately 2100MWh/year, which is equivalent to a savings of 3,864,210 lbs. of CO_2 per year. It was then determined that the time to payback the CO_2 emission is approximately 1.3 years. Figure A10.1 shows the tonnes of CO_2 emission saved per year. Year zero shows the embodied CO_2 of the system.

Feasibility and Recommendation

The maximum rooftop area available on campus is 5.00 acres as shown in Appendix A6, of which 4.94 acres is used. Utilizing this area would allow for 5889 solar panels and produce 2.115 GWh/yr of electricity, which is approximately 10% of Calvin's annual electricity consumption. This would cost a total of $3,700,000 in 2018$, which factors in installation, racking, and utility connection cost. Since this doesn't use the entire $5M budget, the remaining funds could be used for geothermal, wind, carbon credits, or investments to be used in the future. The estimated payback period for this system would be approximately 16 years, which is less than the 30-year life of the solar panels. The total savings in electricity would be $183,750 annually.

Conclusion

Utilizing the 5.00 acres of available rooftop area on Calvin's Campus is recommended, because it yields the most savings and the system can be paid back within its lifetime. As the plans for the new Commons building are determined, it is recommended that solar panels are incorporated into these plans so that the roof is designed and oriented correctly for solar panel usage. Having solar panels on buildings where they can be seen, such as the Venema Aquatic Center, is important because potential students, alumni, and visitors can see that Calvin is making a step towards renewable energy sources and becoming more carbon neutral, something that is going to become more and more important in the coming years.

Appendix A1: Solar System Implementation Cost

Table A1.1: System Implementation Costs and Weight

Location	Total Cost [2018$]	Racking Cost [2018$]	Decl. Dist. Weight [PSF]	Weight/Attach [lbs]	Weight [lbs]
Devos Center	$ 334,948.31	$ 40,228.44	3.10	47.50	25879
Gym Overhang	$ 204,663.74	$ 17,571.96	3.10	44.30	13441
Prince Conference	$ 243,711.18	$ 23,476.00	3.10	47.4	17010
Van Noord Arena	$ 458,479.60	$ 50,035.00	3.10	45.40	36490
Venema Aquatic Roof	$ 439,209.84	$ 46,957.00	3.10	47.20	34820
Venema Aquatic Overhang	$ 117,947.73	$ 7,402.00	3.10	44.90	5378
North Hall	$ 328,275.22	$ 34,577.88	3.10	47.40	24884
Library Roof Upper	$ 511,813.10	$ 57,385.00	3.10	47.40	41571
Devries Hall	$ 243,897.85	$ 23,871.85	3.10	47.40	17103
CFAC	$ 226,065.75	$ 21,499.00	3.10	44.00	15371
Commons	$ 573,148.20	$ 64,371.75	3.10	44.00	47284
Total System	**$ 3,682,160.52**	**$ 387,375.88**	**-**	**-**	**279231**

*Weight includes racking, clamps, wiring, inverters, and solar panels. Declared distributed weight is given in pounds per square foot.

Table A1.2: System Specifications

Location	Number of Panels	Columns	Number of Strings	Number of Inverters
Devos Center	525	25	21	3
Gym Overhang	285	15	19	2
Prince Conference	360	12	30	1
Van Noord Arena	775	25	31	3
Venema Aquatic Roof	740	20	37	2
Venema Aquatic Overhang	114	19	6	2
North Hall	525	7	75	1
Library Roof Upper	880	16	55	2
Devries Hall	360	12	30	1
CFAC	325	13	25	2
Commons	1000	20	50	2
Total System	**5889**	**184**	**379**	**21**

Table A1.3: System Outputs and Requirements

Location	Electricity Produces (GW-hr/yr)	Effective Panel Area (Acres)	Required Area (Acres)	Actual Rooftop Area (Acres)
Devos Center	0.189	0.213	0.44	0.45
Gym Overhang	0.102	0.115	0.239	0.24
Prince Conference	0.129	0.146	0.302	0.31
Van Noord Arena	0.278	0.314	0.65	0.65
Venema Aquatic Roof	0.266	0.3	0.62	0.62
Venema Aquatic Overhang	0.041	0.046	0.096	0.1
North Hall	0.189	0.213	0.44	0.44
Library Roof Upper	0.316	0.357	0.738	0.75
Devries Hall	0.129	0.146	0.302	0.31
CFAC	0.117	0.132	0.272	0.28
Commons	0.359	0.4052	0.838	0.85
Total System	**2.115**	**2.3872**	**4.937**	**5**

Appendix A2: Equations

To calculate the incident radiation on each solar panel for every hour of every day for an entire year, the following equations were used. The first step in these calculations is knowing the latitude, longitude, Greenwich mean time, local time zone, and the surface angles. With this information, the declination angle, equation of time, solar altitude, zenith, and azimuth angles can be calculated. The angles determine the intensity of the radiation on the surface.

$$I_{DN} = A \cdot 0.7^{X^{0.678}} \quad \textbf{(A2.1)}$$

$$A = 1367.2\left(1 + 0.033 \cdot \cos\left(\frac{360(d-2)}{365}\right)\right) \quad \textbf{(A2.2)}$$

$$X = \frac{1}{\cos(\theta_H)} + (0.50572 \cdot |96.07995 - \theta_H|)^{-1.6364} \quad \textbf{(A2.3)}$$

$$I_{Direct} = I_{DN}\cos(\theta_{incident}) \quad \textbf{(A2.4)}$$

$$I_{Diffuse} = I_{DN}\cos(\theta_H)\frac{1 + \cos(\theta_{surface})}{2} \quad \textbf{(A2.5)}$$

$$I_{reflected} = \rho_{GND} I_{DN}\cos(\theta_H)\frac{1 + \cos(\theta_{surface})}{2} \quad \textbf{(A2.6)}$$

$$I_{total} = I_{Direct} + I_{Diffuse} + I_{Reflected} \quad \textbf{(A2.7)}$$

A represents the varying intensity of solar radiation with respect to the day (***d***) of the year. ***X*** represents the air mass ratio, which accounts for the shift in the solar rays after they hit the atmosphere and compensates for the curvature of the earth. When the air mass is positive, there is sunlight and when its negative, it is night. To determine the electricity produced for each hour of every day, the effective solar panel (or string) area and efficiencies were multiplied by the total radiation.

$$E_i = \varepsilon_{i,total} \cdot A_{effective,i} \cdot I_{total} \quad \textbf{(A2.8)}$$

$$A_{effective,i} = \#panels \cdot A_{panels} \quad \textbf{(A2.9)}$$

These values were summed to find the monthly and yearly electricity production. From this the annual electricity savings can be found.

$$Savings = \frac{1.98\ [M\$/yr]}{22.08\ [GWh/yr]} * E_i \quad \textbf{(A2.10)}$$

Based in inflation and interest rates, as well as the increase in cost to produce electricity, the payback period was found by finding the integer number of years until the savings equaled the total capital investment. The before rebate cost was found using the following equations.

$$Cost_{BR} = C_{Eval} + C_{permit} + C_{insp} + C_{PI} + C_L + C_{bal} + C_{UC} + C_{Rack} \quad \textbf{(A2.11)}$$

$$C_{Eval} = \text{if } 1500 \cdot A_{required} < 2000,\ then\ 2000,\ otherwise\ 1500 \cdot A_{required} \quad \textbf{(A2.12)}$$

$$C_{permit} = \$72 + \frac{\$6.25}{\$1000} \cdot C_{panels} \cdot \#panels \quad \textbf{(A2.13)}$$

$$C_{PI} = \left(P_{panels} \cdot \#panels\right) + \left(P_{Inverter} \cdot \#inverters\right) \quad \textbf{(A2.14)}$$

$$C_L = (P_{labor} \cdot t_{labor} \cdot \#panels) + (P_{labor} \cdot t_{labor} \cdot \#inverters \quad \textbf{(A2.15)}$$

$$C_{bal} = 37.52(\#panels) + 68{,}686 \quad \textbf{(A2.16)}$$

$$C_{UC} = P_{labor} t_{labor} \#panels \quad \textbf{(A2.17)}$$

$$C_{Rack} = 64.885(\#panels) - 513.25 \quad \textbf{(A2.18)}$$

Considering the federal rebate of 30% of the total costs of the renewable energy system and contingency costs of 15%, the following equation provides the final cost of the system.

$$Cost_{final} = C_{contingent} + C_{BR} - 0.3 \cdot C_{BR} \quad \textbf{(A2.19)}$$

Appendix A3: Cost Savings Graphs

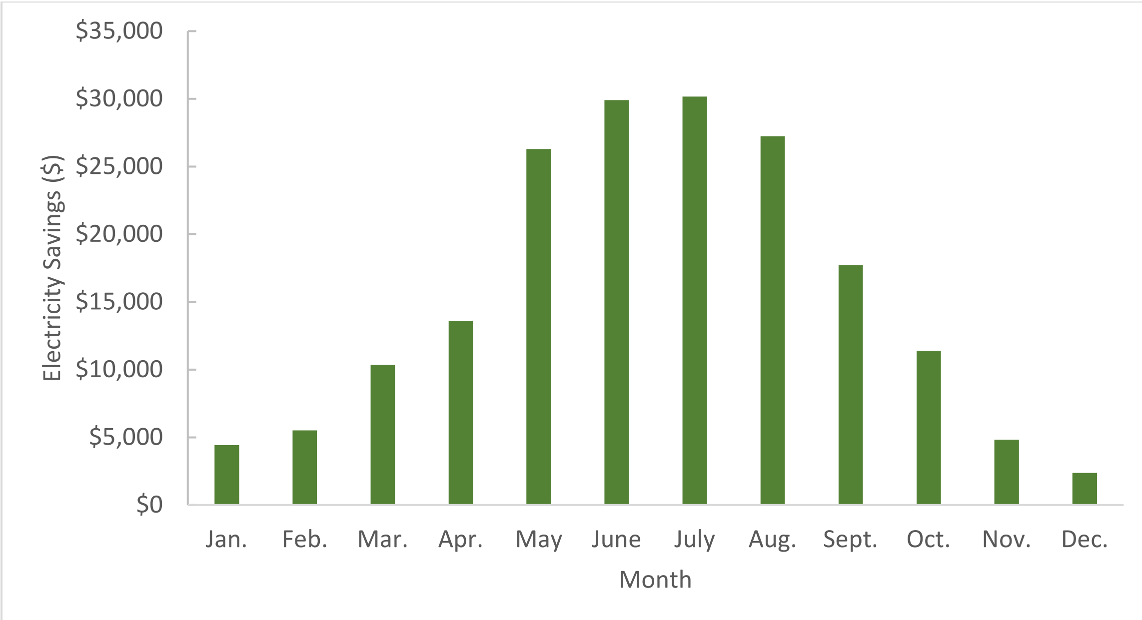


Figure A3.1: Solar System Cost Savings Per Month

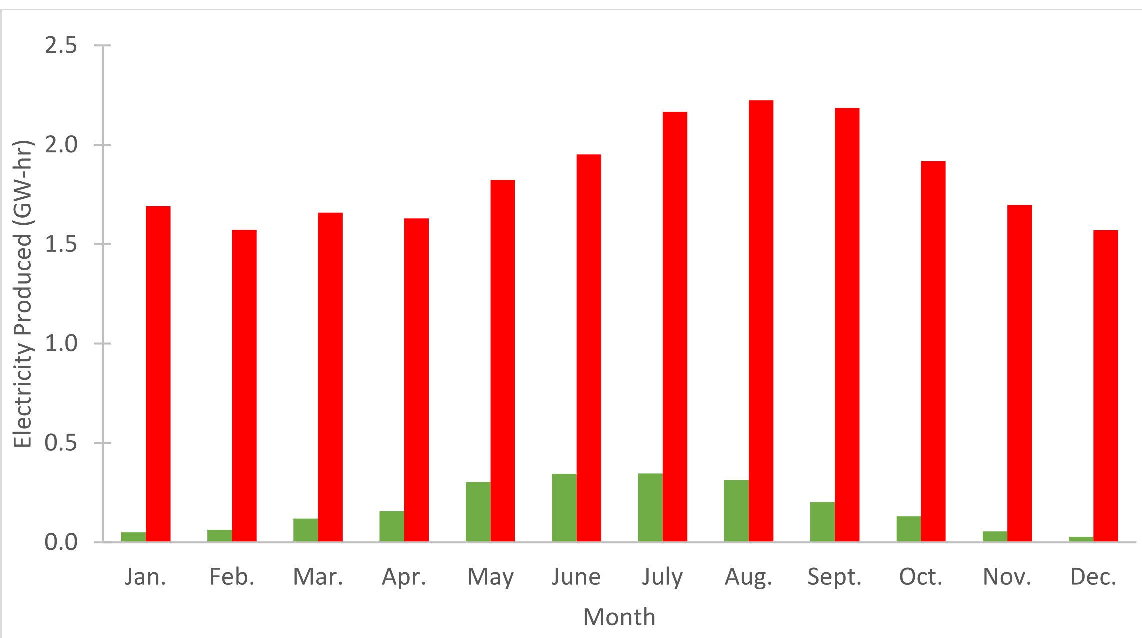


Figure A3.2: Monthly Electricity Produced from Solar System vs. Calvin Electricity Load

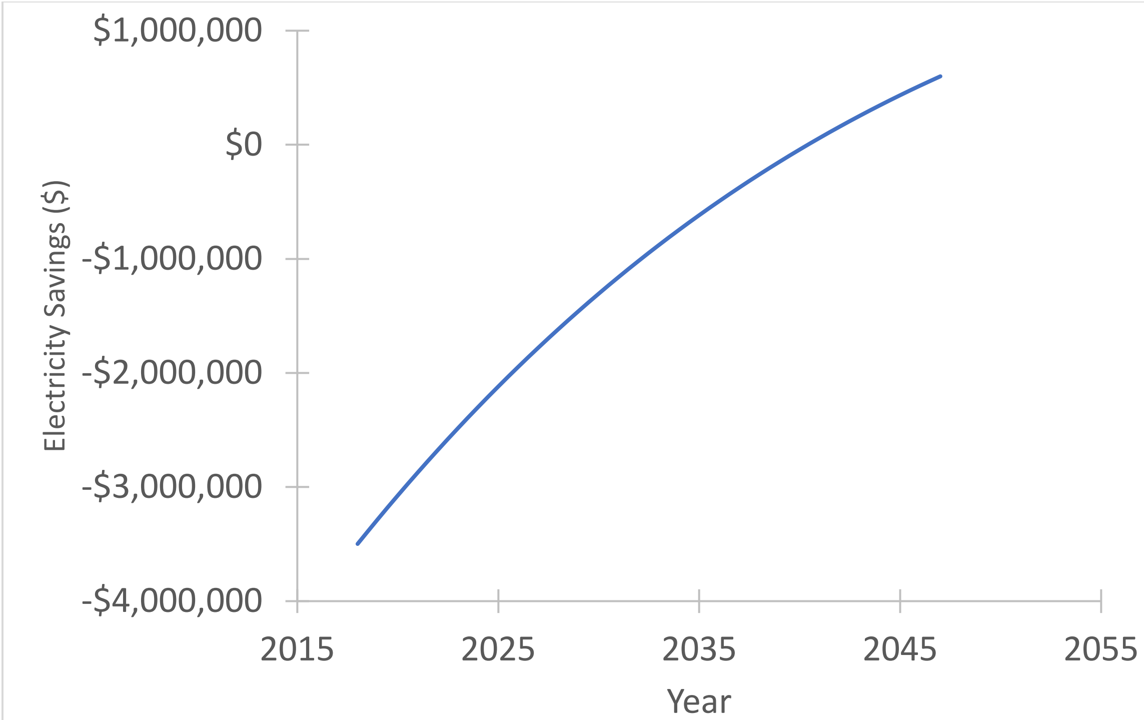


Figure A3.3: Solar Panel System Payback Period

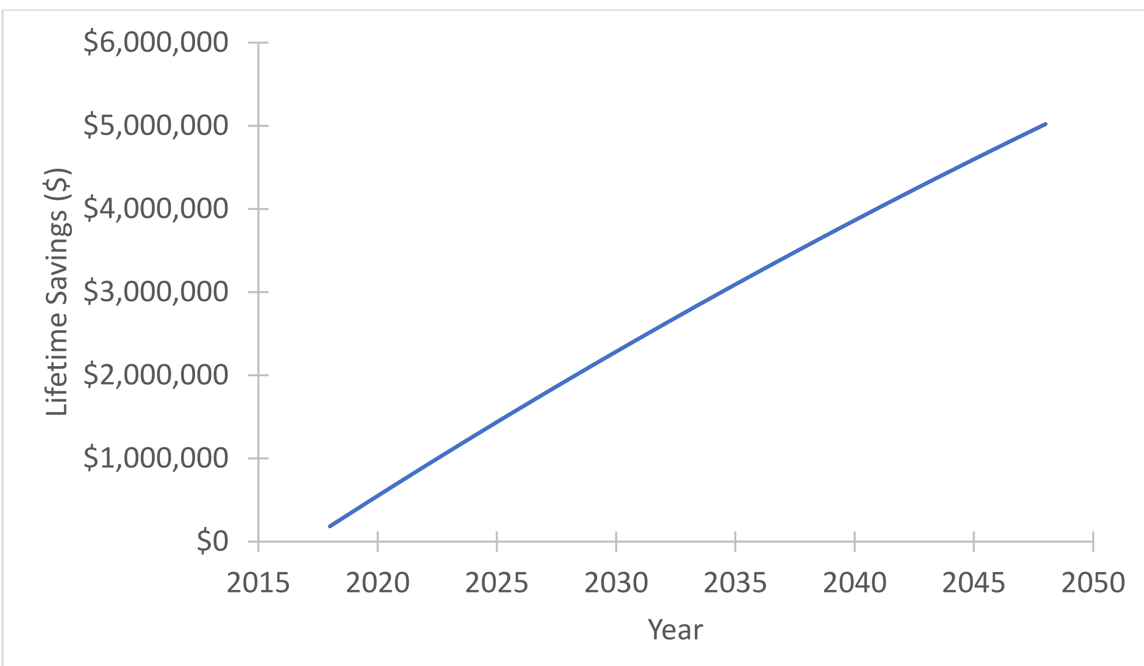


Figure A3.4: Lifetime Savings from Solar Panel System

Appendix A4: Solar Panel Comparison

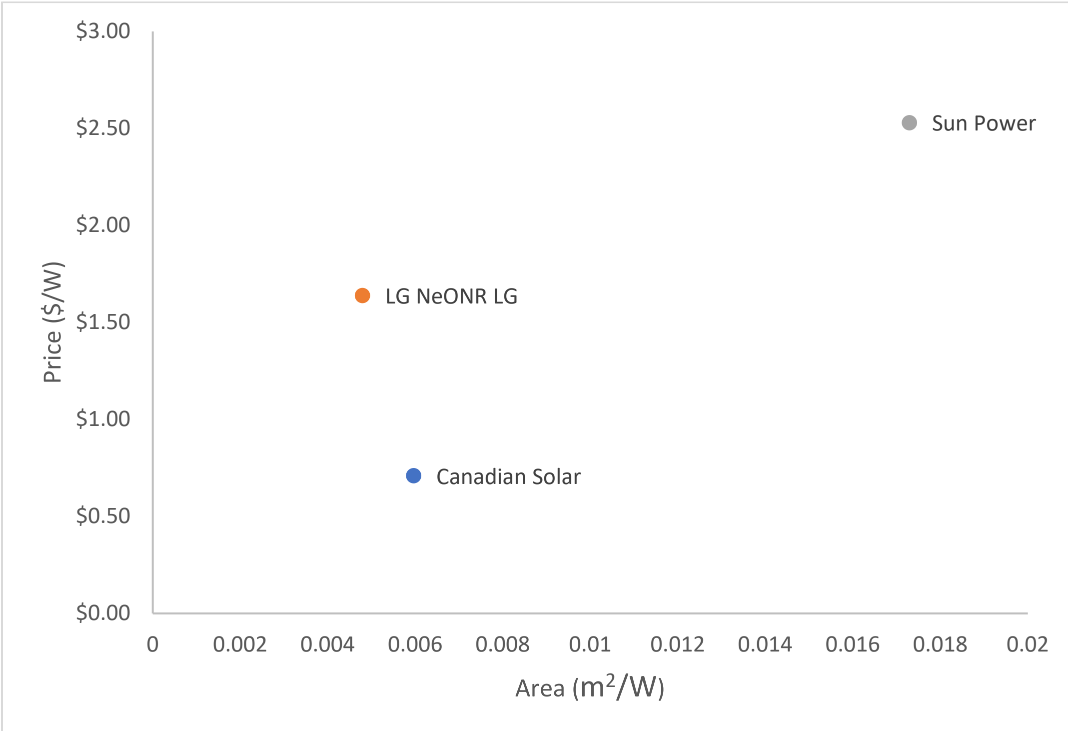


Figure A4.1: Comparison of Solar Panel Types

Table A4. 1: Solar Panel Property Chart

Manufacturer	**Canadian Solar (Polycrystalline)**	**LG NeONR LG (Monocrystalline)**	**Sun Power (Thin)**
Panel Model	CS6K-275P	260Q1C-A5	SPR-R-Flex-100
Power Output [W]	275	360	100
Price [$]	195	590	253
Area [m^2]	1.640	1.727	1.734
Price per Watt [$/W]	0.71	1.64	2.53
Area per Watt [m^2/W]	0.0059625	0.00479784	0.0173

Appendix A5: Inverter Comparison

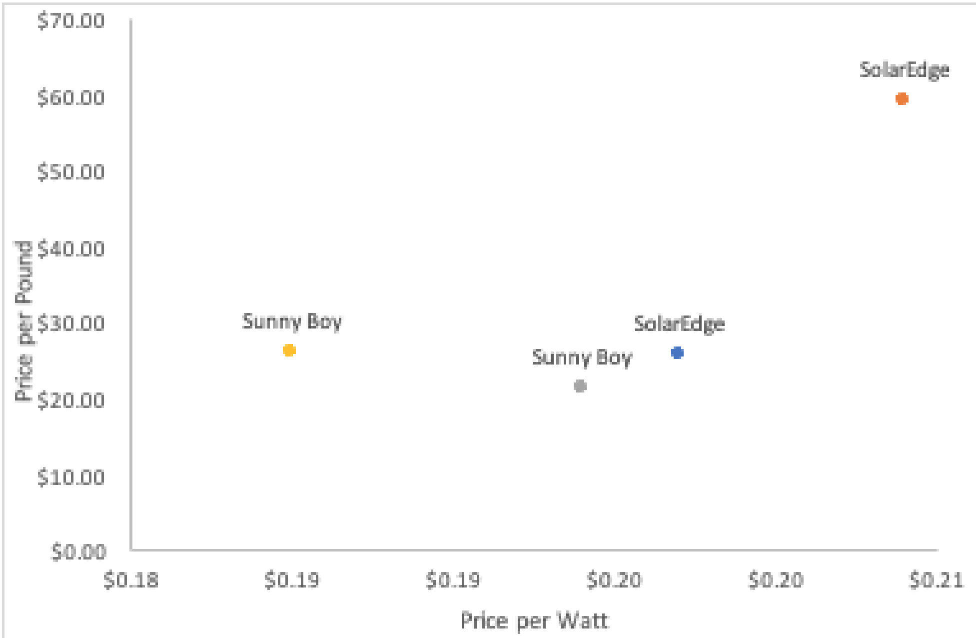


Figure A5.1: Comparison of Solar Inverter Options

Table A5.1: Solar Inverter Property Table

	Inverter Manufacturer	Inverter Model	Max Wattage (W)	
	SolarEdge	SE11400A	11400	
	SolarEdge	SE7600H	7600	
	Sunny Boy	SMA 6.0kW	6200	
	Sunny Boy	SMA 7.7kW	7950	
Weight (lb)	Price	Price/Watt ($/W)	Price/lb ($/lb)	Watt/Pound (W/lb)
88.4	$2,250.00	$0.197	$25.45	128.959276
26.2	$1,550.00	$0.204	$59.16	290.0763359
57	$1,201.41	$0.194	$21.08	108.7719298
57	$1,469.62	$0.185	$25.78	139.4736842

Appendix A6: Locations and Areas

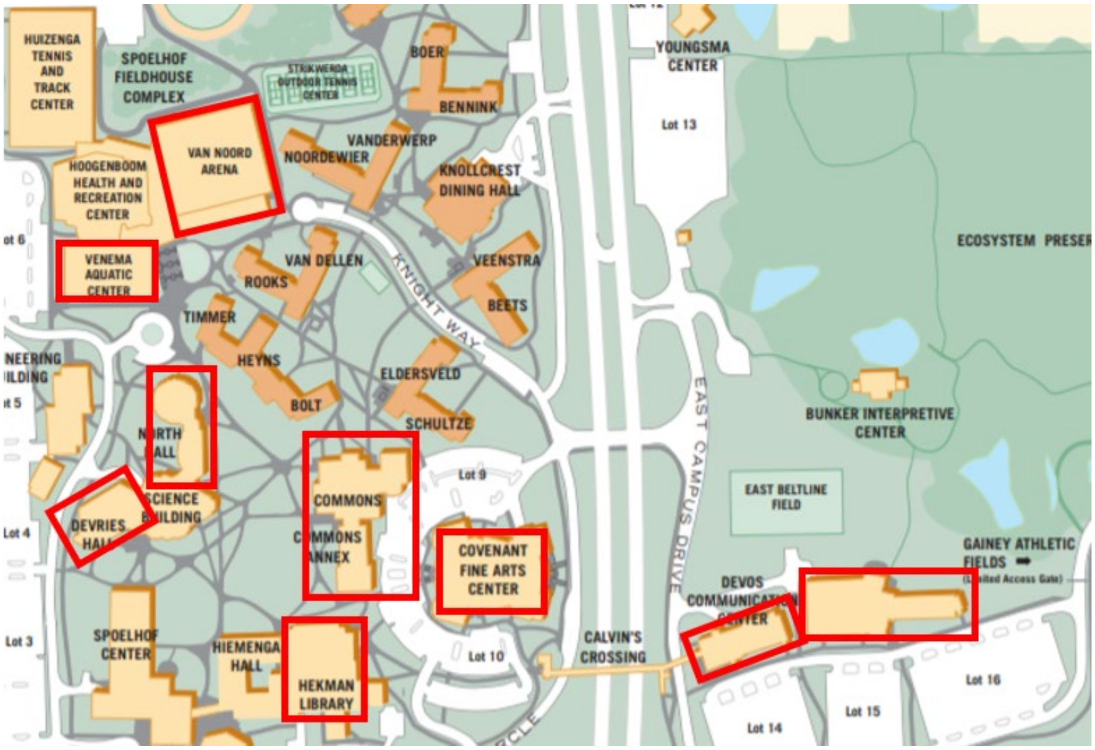


Figure A6.1: Rooftops Utilized on Calvin College's Campus

Table A6.1: Rooftop Areas of Calvin College's Campus

Location	Actual Rooftop Area (Acres)
Devos Center	0.45
Gym Overhang	0.24
Prince Conference	0.31
Van Noord Arena	0.65
Venema Aquatic Roof	0.62
Venema Aquatic Overhang	0.10
North Hall	0.44
Library Roof Upper	0.75
Devries Hall	0.31
CFAC	0.28
Commons	0.85
Total	**5.00**

Appendix A7: IronRidge Racking Application

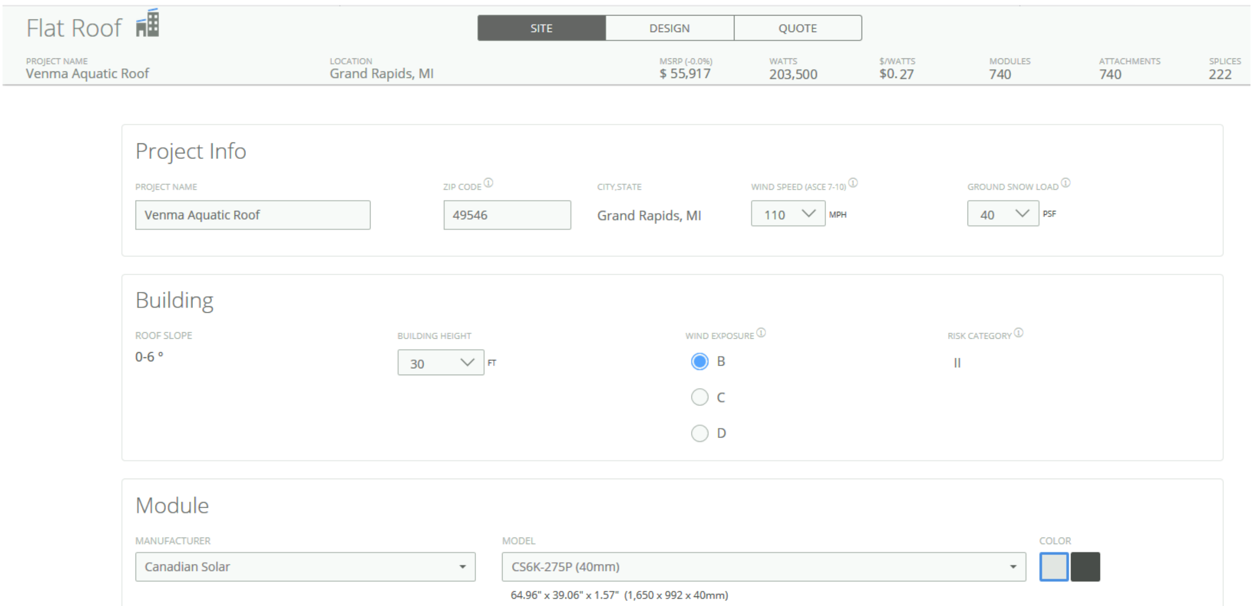


Figure A7.1: The Iron Ridge Application

Appendix A8: Solar Panel Specification Sheets

CanadianSolar

CS6K-265|270|275|280P

Canadian Solar's modules use the latest innovative cell technology, increasing module power output and system reliability, ensured by 15 years of experience in module manufacturing, well-engineered module design, stringent BOM quality testing, an automated manufacturing process and 100% EL testing.

*Black frame product can be provided upon request.

25 years linear power output warranty

10 years product warranty on materials and workmanship

KEY FEATURES

- Excellent module efficiency of up to: 17.11 %
- High PTC rating of up to: 92.14 %
- Outstanding low irradiance performance of up to: 96.5 %
- IP68 junction box for long-term weather endurance
- Heavy snow load up to 6000 Pa, wind load up to 4000 Pa *

MANAGEMENT SYSTEM CERTIFICATES*

ISO 9001:2008 / Quality management system
ISO 14001:2004 / Standards for environmental management system
OHSAS 18001:2007 / International standards for occupational health & safety

PRODUCT CERTIFICATES*

IEC 61215 / IEC 61730: VDE /TÜV-Rheinland / CE / MCS / CEC AU / INMETRO / CQC
UL 1703 / IEC 61215 performance: CEC listed (US) / FSEC (US Florida)
UL 1703: CSA / IEC 61701 ED2: VDE / IEC 62716: VDE
UNI 9177 Reaction to Fire: Class 1
IEC 60068-2-68: SGS
Take-e-way

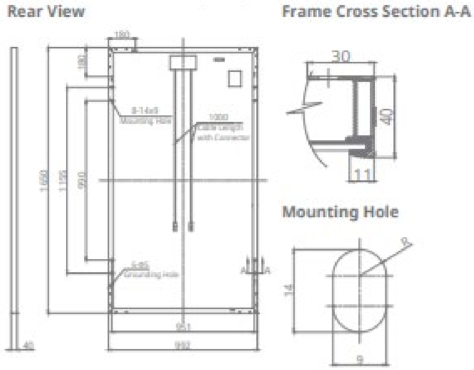
* Please contact your local Canadian Solar sales representative for the specific product certificates applicable in your market.

CANADIAN SOLAR INC. is committed to providing high quality solar products, solar system solutions and services to customers around the world. As a leading PV project developer and manufacturer of solar modules with over 21 GW deployed around the world since 2001, Canadian Solar Inc. (NASDAQ: CSIQ) is one of the most bankable solar companies worldwide.

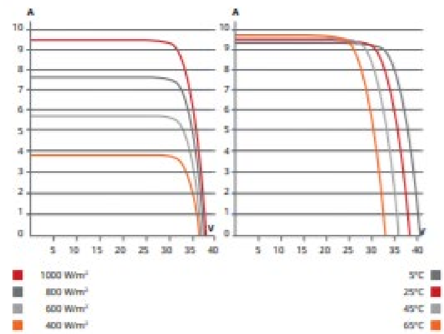
*For detailed information, please refer to the Installation Manual.

CANADIAN SOLAR INC.
545 Speedvale Avenue West, Guelph, Ontario N1K 1E6, Canada, www.canadiansolar.com, support@canadiansolar.com

ENGINEERING DRAWING (mm)



CS6K-280P / I-V CURVES



ELECTRICAL DATA | STC*

CS6K	265P	270P	275P	280P
Nominal Max. Power (Pmax)	265 W	270 W	275 W	280 W
Opt. Operating Voltage (Vmp)	30.6 V	30.8 V	31.0 V	31.3 V
Opt. Operating Current (Imp)	8.66 A	8.75 A	8.88 A	8.95 A
Open Circuit Voltage (Voc)	37.7 V	37.9 V	38.0 V	38.2 V
Short Circuit Current (Isc)	9.23 A	9.32 A	9.45 A	9.52 A
Module Efficiency	16.19%	16.50%	16.80%	17.11%
Operating Temperature	-40°C ~ +85°C			
Max. System Voltage	1000 V (IEC) or 1000 V (UL)			
Module Fire Performance	TYPE 1 (UL 1703) or CLASS C (IEC 61730)			
Max. Series Fuse Rating	15 A			
Application Classification	Class A			
Power Tolerance	0 ~ + 5 W			

* Under Standard Test Conditions (STC) of irradiance of 1000 W/m², spectrum AM 1.5 and cell temperature of 25°C.

MECHANICAL DATA

Specification	Data
Cell Type	Poly-crystalline, 6 inch
Cell Arrangement	60 (6×10)
Dimensions	1650×992×40 mm (65.0×39.1×1.57 in)
Weight	18.2 kg (40.1 lbs)
Front Cover	3.2 mm tempered glass
Frame Material	Anodized aluminium alloy
J-Box	IP68, 3 diodes
Cable	4.0 mm² (IEC), 12 AWG (UL), 1000 mm (39.4 in)
Connector	T4 series
Per Pallet	27 pieces, 538 kg (1186.1 lbs)
Per Container (40' HQ)	756 pieces

ELECTRICAL DATA | NMOT*

CS6K	265P	270P	275P	280P
Nominal Max. Power (Pmax)	195 W	198 W	202 W	206 W
Opt. Operating Voltage (Vmp)	28.2 V	28.3 V	28.5 V	28.8 V
Opt. Operating Current (Imp)	6.92 A	7.00 A	7.08 A	7.14 A
Open Circuit Voltage (Voc)	35.1 V	35.3 V	35.4 V	35.6 V
Short Circuit Current (Isc)	7.45 A	7.53 A	7.63 A	7.69 A

* Under Nominal Module Operating Temperature (NMOT), irradiance of 800 W/m², spectrum AM 1.5, ambient temperature 20°C, wind speed 1 m/s.

TEMPERATURE CHARACTERISTICS

Specification	Data
Temperature Coefficient (Pmax)	-0.41 % /°C
Temperature Coefficient (Voc)	-0.31 % /°C
Temperature Coefficient (Isc)	0.05 % /°C
Nominal Module Operating Temperature (NMOT)	43 ± 2 °C

PERFORMANCE AT LOW IRRADIANCE

Outstanding performance at low irradiance, with an average relative efficiency of 96.5 % for irradiances between 200 W/m² and 1000 W/m² (AM 1.5, 25°C).

PARTNER SECTION

The aforesaid datasheet only provides the general information on Canadian Solar products and, due to the on-going innovation and improvement, please always contact your local Canadian Solar sales representative for the updated information on specifications, key features and certification requirements of Canadian Solar products in your region.

Please be kindly advised that PV modules should be handled and installed by qualified people who have professional skills and please carefully read the safety and installation instructions before using our PV modules.

Appendix A9: Inverter Specification Sheets

SUNNY BOY
3.0-US / 3.8-US / 5.0-US / 6.0-US / 7.0-US / 7.7-US

SMA

Value-Added Improvements

- Superior integration with SMA's MLPE Power+ Solution
- World's first Secure Power Supply* now offers up to 2,000 W
- Full grid management capabilities ensure a utility-compliant solution for any market

Reduced Labor

- New Installation Assistant with direct access via smartphone minimizes time in the field
- Integrated disconnect simplifies equipment stocking and speeds installation

Unmatched Flexibility

- SMA's proprietary OptiTrac™ Global Peak technology mitigates shade with ease
- Multiple independent MPPTs accommodate hundreds of stringing possibilities

Trouble-Free Servicing

- Two-part enclosure concept allows for simple, expedited servicing
- Enhanced AFCI technology reduces false tripping while improving sensitivity in real arcs

SUNNY BOY
3.0-US / 3.8-US / 5.0-US / 6.0-US / 7.0-US / 7.7-US

Reduce costs across your entire residential business model

The residential PV market is changing rapidly. Your bottom line matters more than ever—so we've designed a superior residential solution to help you decrease costs at every stage of your business operations. The Sunny Boy 3.0-US/3.8-US/5.0-US/6.0-US/7.0-US/7.7-US join the SMA lineup of field-proven solar technology backed by the world's #1 service team, along with a wealth of improvements. Simple design, improved stocking and ordering, value-driven sales support and streamlined installation are just some of the ways that SMA helps your business operate more efficiently. And, Sunny Boy's superior integration with the innovative Power+ Solution means installers have even more flexibility in addressing their toughest challenges.

www.SMA-America.com

Technical data	Sunny Boy 3.0-US		Sunny Boy 3.8-US		Sunny Boy 5.0-US	
	208 V	240 V	208 V	240 V	208 V	240 V
Input (DC)						
Max. usable DC power	3100 W	3100 W	3450 W	4000 W	5150 W	5150 W
Max. DC voltage	600 V					
Rated MPP voltage range	155 - 480 V		195 - 480 V		220 – 480 V	
MPPT operating voltage range	100 – 550 V					
Min. DC voltage / start voltage	100 V / 125 V					
Max. operating input current per MPPT	10 A					
Max. short circuit current per MPPT	18 A					
Number of MPPT tracker / string per MPPT tracker	2/1				3 / 1	
Output (AC)						
AC nominal power	3000 W	3000 W	3330 W	3800 W	5000 W	5000 W
Max. AC apparent power	3000 VA	3000 VA	3330 VA	3800 VA	5000 VA	5000 VA
Nominal voltage / adjustable	208 V / ●	240 V / ●	208 V / ●	240 V / ●	208 V / ●	240 V / ●
AC voltage range	183 – 229 V	211 – 264 V	183 – 229 V	211 – 264 V	183 – 229 V	211 – 264 V
AC grid frequency	60 Hz / 50 Hz					
Max. output current	14.5 A	12.5 A	16.0 A	16.0 A	24.0 A	24.0 A
Power factor (cos φ)	1					
Output phases / line connections	1 / 2					
Harmonics	< 4 %					
Efficiency						
Max. efficiency	97.2 %	97.6 %	97.2 %	97.5 %	97.2 %	97.5 %
CEC efficiency	96 %	96.5 %	96.5 %	96.5 %	96.5 %	97 %
Protection devices						
DC disconnect device	●					
DC reverse polarity protection	●					
Ground fault monitoring / Grid monitoring	●					
AC short circuit protection	●					
All-pole sensitive residual current monitoring unit (RCMU)	●					
Arc fault circuit interrupter (AFCI)	●					
Protection class / overvoltage category	I / IV					
General data						
Dimensions (W / H / D) in mm (in)	535 x 730 x 198 (21.1 x 28.5 x 7.8)					
Packaging dimensions (W / H / D) in mm (in)	600 x 800 x 300 (23.6 x 31.5 x 11.8)					
Weight / packaging weight	26 kg (57 lb) / 30 kg (66 lb)					
Operating temperature range	– 25°C ...+60°C					
Noise emission (typical)	39 dB(A)					
Internal power consumption at night	< 5 W					
Topology	Transformerless					
Cooling concept	Convection					
Features						
Ethernet ports	2					
Secure Power Supply	●*					
Display (2 x 16 characters)	●					
WLAN	●					
Sensor module / External WLAN antenna	○ / ○					
Warranty: 10 / 15 / 20 years	● / ○ / ○					
Certificates and approvals	UL 1741, UL 1998, UL 1699B, IEEE1547, FCC Part 15 (Class A & B), CAN/CSA V22.2 107.1-1					
Type designation	SB3.0-1SP-US-40		SB3.8-1SP-US-40		SB5.0-1SP-US-40	

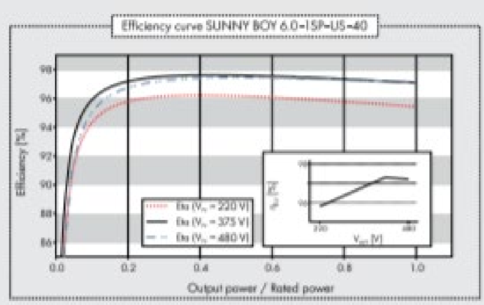
● Standard features ○ Optional features – Not available Data at nominal conditions NOTE: US inverters ship with gray lids. * Not functional with Power+ Solution

Accessories


Sensor module
MD.SEN-US-40


External WLAN antenna
EXTANT-US-40


SMA Rooftop
Communication Kit
ROOFCOMMKIT-P1-US



Technical data	Sunny Boy 6.0-US		Sunny Boy 7.0-US		Sunny Boy 7.7-US	
	208 V	240 V	208 V	240 V	208 V	240 V
Input (DC)						
Max usable DC power	5400 W	6200 W	6900 W	7200 W	6900 W	7950 W
Max. DC Voltage	600 V					
Rated MPP Voltage range	220 - 480 V		245 - 480 V		270 - 480 V	
MPPT operating voltage range	100 - 550 V					
Min. DC voltage / start voltage	100 V / 125 V					
Max. operating input current per MPPT	10 A					
Max. short circuit current per MPPT	18 A					
Number of MPPT tracker / string per MPPT tracker	3 / 1					
Output (AC)						
AC nominal power	5200 W	6000 W	6660 W	7000 W	6660 W	7680 W
Max. AC apparent power	5200 VA	6000 VA	6660 VA	7000 VA	6660 VA	7680 VA
Nominal voltage / adjustable	208 V / ●	240 V / ●	208 V / ●	240 V / ●	208 V / ●	240 V / ●
AC voltage range	183 - 229 V	211 - 264 V	183 - 229 V	211 - 264 V	183 - 229 V	211 - 264 V
AC grid frequency	60 Hz / 50 Hz					
Max. output current	25.0 A	25.0 A	32.0 A	29.2 A	32.0 A	32.0 A
Power factor (cos φ)	1					
Output phases / line connections	1 / 2					
Harmonics	< 4 %					
Efficiency						
Max. efficiency	97.2 %	97.6 %	97.1 %	97.5 %	97.1 %	97.5 %
CEC efficiency	96.5 %	97 %	96.5 %	97 %	96.5 %	97 %
Protection devices						
DC disconnect device	●					
DC reverse polarity protection	●					
Ground fault monitoring / Grid monitoring	●					
AC short circuit protection	●					
All-pole sensitive residual current monitoring unit (RCMU)	●					
Arc fault circuit interrupter (AFCI)	●					
Protection class / overvoltage category	I / IV					
General data						
Dimensions (W / H / D) in mm (in)	535 x 730 x 198 (21.1 x 28.5 x 7.8)					
Packaging Dimensions (W / H / D) in mm (in)	600 x 800 x 300 (23.6 x 31.5 x 11.8)					
Weight / packaging weight	26 kg (57 lb) / 30 kg (66 lb)					
Operating temperature range	- 25°C ...+60°C					
Noise emission (typical)	39 dB(A)		45 dB(A)			
Internal power consumption at night	< 5 W					
Topology	Transformerless					
Cooling concept	Convection		Fan			
Features						
Ethernet ports	2					
Secure Power Supply	●*					
Display (2 x 16 characters)	●					
WLAN	●					
Sensor module / External WLAN antenna	○ / ○					
Warranty: 10 / 15 / 20 years	●/○/○					
Certificates and approvals	UL 1741, UL 1998, UL 1699B, IEEE1547, FCC Part 15 (Class A & B), CAN/CSA V22.2 107.1-1					
● Standard features ○ Optional features – Not available	Data at nominal conditions NOTE: US inverters ship with gray lids. * Not functional with Power+ Solution					
Type designation	SB6.0-1SP-US-40		SB7.0-1SP-US-40		SB7.7-1SP-US-40	

POWER+ SOLUTION

The SMA Power+ Solution combines legendary SMA inverter performance and intelligent DC module-level electronics in one cost-effective, comprehensive package. This means that you can achieve maximum solar power production for your customers while also realizing significant installation savings.

Unlike conventional microinverter and DC optimizer systems, Power+ is faster to install, provides more flexibility, boasts logistical advantages, and reduces service risk.

Visit www.SMA-America.com for more information.

SIMPLE, FLEXIBLE DESIGN

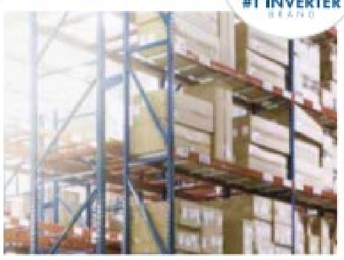
Speed the completion of customer proposals and maximize the efficiency of your design team with the Sunny Boy-US series, which provides a new level of flexibility in system design by offering:

- Hundreds of stringing configurations and multiple independent MPPTs
- SMA's proprietary OptiTrac™ Global Peak shade mitigation technology
- Diverse application options including on- and off-grid compatibility

VALUE-DRIVEN SALES ENABLEMENT

SMA wants to enable your sales team by arming them with an abundance of feature/benefit support. Show your customers the value of the Sunny Boy-US series by utilizing:

- Secure Power Supply, now with 2,000 W of opportunity power in the event of a grid outage, as an increased value-add or upsell opportunity
- SMA's 35 year history and status as the #1 global inverter manufacturer instills homeowners with peace of mind and the long-term security they demand from a PV investment
- An economical solution for shade mitigation and the challenges of complex roofs



IMPROVED STOCKING AND ORDERING

Ensure that your back office business operations run smoothly and succinctly while mitigating potential errors. The Sunny Boy-US series can help achieve cost savings in these areas by providing:

- An integrated DC disconnect that simplifies equipment stocking and allows for a single inverter part number
- All communications integrated into the inverter, eliminating the need to order additional equipment

STREAMLINED INSTALLATION AND COMMISSIONING

Expedite your operations in the field by taking advantage of the new Sunny Boy's installer-friendly feature set including:

- Direct access via smartphone and utilization of SMA's Installation Assistant, which minimizes time/labor spent in the field and speeds the path to commissioning
- Improved communication—no need to install additional equipment
- Integrated DC disconnect that simplifies onsite logistics and eliminates the need to install a separate disconnect unit, speeding overall installation time

SUPERIOR SERVICE

SMA understands the factors that contribute to lifetime PV ownership cost, that's why the Sunny Boy-US series was designed for maximum reliability and backstopped by an unmatched service offering. Benefit from:

- The new Sunny Boy's two-part enclosure concept that separates the connection unit from the power unit, which allows for simple, expedited servicing
- The #1 service team in the PV industry, as recognized by IMS research, with experience servicing an installed base of more than 55 GW

Appendix A10: CO_2 Emissions

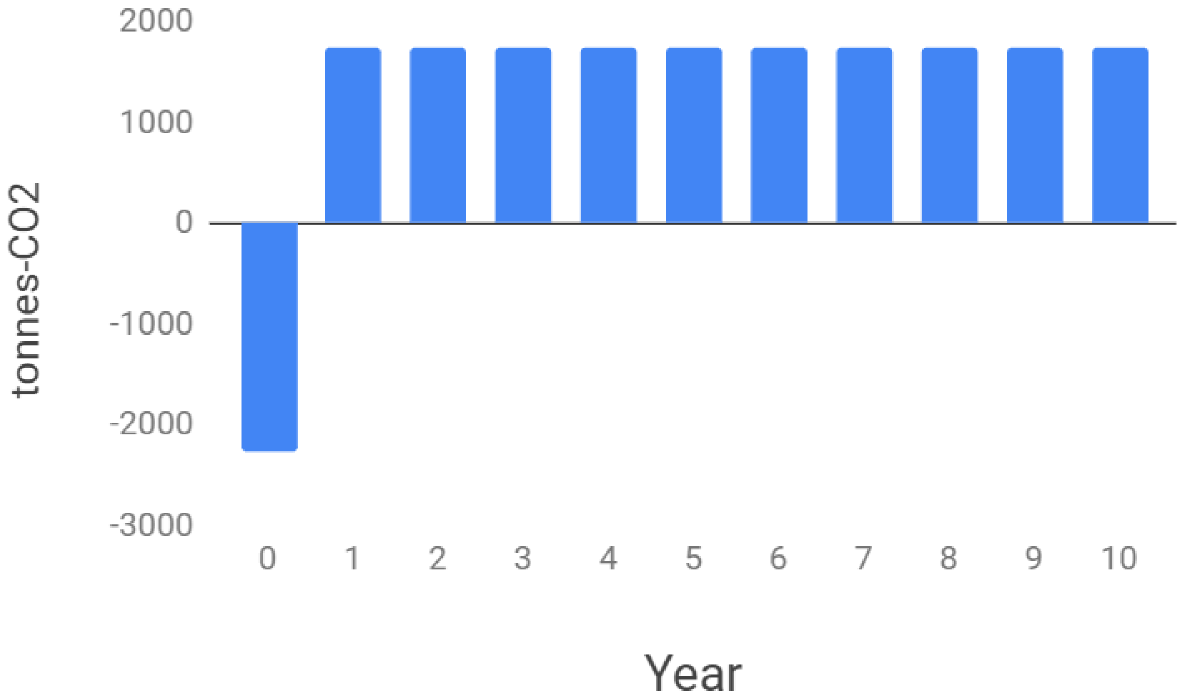


Figure A10.1: CO2 Tonnes of CO2 Emissions Saved per Year

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Appendix B: Geothermal Renewable Energy Source

Alec DeJonge, Timothy Dykhuis, Breanna Kooiman, and Samuel Olson

Engineering 333B: Thermal Systems Design

Dr. Matthew Heun: Calvin College Engineering Department

December 18, 2018

Introduction

Geothermal systems can broadly be split into two categories, power-producing systems and geothermal heat pump systems. Geothermal heat pumps are the most common type of system as they rely on the relatively constant temperature of the earth to heat or cool a building. A system diagram using a ground source heat pump can be seen in Appendix B1 through Figure B1.1. These systems can be further broken down into two types, closed and open loop systems. Closed loop systems utilize loops of water-filled plastic piping buried in the ground through either horizontal trenches or vertical bores, much like the coils on the back of a refrigerator or freezer. The fluid in the coils never interacts directly with the environment. Open loop systems use one or more wells where water is pumped into and removed from an underground reservoir. The water is free to mix with the environment as it is warmed or cooled by the earth.

In a geothermal heating system, a refrigeration cycle is used to concentrate the low temperature heat into more usable high temperature heat. Because refrigeration cycles are designed to transfer thermal energy from one place to another, rather than generating thermal energy, geothermal systems may be more efficient than other heating or cooling options.

Method

To determine the approximate size of a $5M geothermal system, case studies from nineteen other colleges that had implemented geothermal systems were examined. The projects ranged in cost from $350,000 to $78M. From the case studies, it was determined that the most common systems were closed-loop systems with most utilizing vertical bores. Others used horizontal bores or a combination of both. A difference was found in the cost of small-scale projects and that of campus size projects. From these case studies, models for each of these cases were formed by graphing the cost of installation for the systems vs. the square footage of the buildings in which they were implemented, as seen in Figure B2.1. Note that the point for Calvin College on Figure B2.1 is the cost of a geothermal system that would heat and cool the whole campus. The small-scale case study can be seen in Figure B2.2 in Appendix B2.

Calvin College Cost Model

These cost models were then adapted for Calvin. The cost of a campus-wide geothermal system was divided by the heating and cooling capacities of Calvin to find an equivalent cost of heating or cooling with geothermal on a $/hp or $/ton basis, which is seen in Table B4.3 in Appendix B4. Once this was known, a system could easily be sized for a $5M investment. Using the efficiency of the geothermal heat pumps, the price to run them at the current electric rates was found. This cost was compared with the current cost to run the existing chillers using electricity and the cost to run the current boilers with natural gas for Calvin, which can be seen in Figure B3.2 and Figure B3.3 in Appendix B3 as well as Tables B4.5 and B4.6 in Appendix B4. The difference was understood as the savings.

After sizing the geothermal system for $5M, it was determined that the system could supply 16% of Calvin's heating capacity and 20% of Calvin's cooling capacity using the small-scale model. The reason for the difference in capacities is that Calvin heats the buildings for a longer part of the year. In addition, when Calvin is cooling the buildings, classes are often not in session, which results in fewer bodies in the building and less equipment being run, i.e. computers and lighting. The given cost for heating Calvin was $888,000 per year in natural gas and estimated as $405,473 for cooling. Using the small-scale cost model for Calvin, a net savings of around $14,500 per year would be achieved.

Varied Cost Case Studies

There were two main cost case studies conducted. The first was using the small-scale cost model. This case study assumed that it cost $6,260 to install each ton of heating / cooling capacity. As seen in Figure B3.1 in Appendix B3, the small-scale case study would save $14,549 per year in heating but have a loss of $296,602 per year in cooling for a total loss of $282,053 per year. The second cost case study used the campus scale cost model. The geothermal system would save $7,967 per year in heating but would cost $278,474 per year for cooling, resulting in a net loss of $270,507 if the system were used for cooling as well as heating. Table B4.4 in Appendix 4 shows the geothermal heating and cooling system that could be installed with a $5M budget.

One of the main factors making cooling such a loss is the fact that the chillers that Calvin currently has installed are more efficient than geothermal systems for cooling. The performance of the chillers that Calvin currently uses can be seen in Table B4.2 in Appendix B4. One reason why the heating savings are so small is that natural gas is currently cheap and plentiful. Additionally, the boilers at Calvin are more efficient than many of the boilers being replaced in the other geothermal college case studies. The performance of the Calvin boilers is seen in Table B4.1 in Appendix B4. This means that for geothermal to become more cost effective, the price of natural gas would need to increase. While geothermal systems are more energy efficient than using the current boilers, the type of energy they use (electricity) costs much more than raw natural gas, keeping them from being economically viable. The price of natural gas would need to increase by nearly $0.15/100ft^3 from the current average of $0.53/100ft^3 for a payback period within the assumed system lifetime of 25 years. This can be seen in Appendix B3 through Figure B3.4.

Conclusion

It was determined that a geothermal system would not be feasible for Calvin College at a campus-wide scale as it would cost significantly more to run than the existing cooling system and slightly more than the existing heating system when using an averaged efficiency for all the boilers on campus. Given a smaller scale project, however, a geothermal system remains profitable. With a $5M investment, a 285 hp geothermal system could be installed to replace or supplement the aging boilers in the Commons power plant. Since the efficiency of these boilers is lower than the other boilers on campus, a geothermal system would stay profitable at this scale, saving around $14,500 annually under the current conditions. Additionally, around 3,000 tons of carbon emissions would be saved, equivalent to nearly $28,000 at the current price for carbon credits for a cumulative annual savings of $42,000 per year.

Further Considerations

A geothermal system is projected to last about 40 years. However, the heat pumps are only under warranty for 25 years. This means that the heat pumps would likely need to be replaced after the 25 years to avoid a breakdown, losing the opportunity to recoup some of the heat pump costs after a 25-year study period. The water loops, however, should outlast the heat pumps, providing some cost that can be recouped in a 25-year study. While heat pumps are not cheap, the bulk of the cost of a geothermal system comes from the installation costs of the water loop. This analysis does not account for any hidden costs such as unexpected maintenance or issues run into during the construction phase. It also assumes that the heat pumps and water loop last the whole 25 years without requiring any replacement. If there was a defect in the construction of the water loop, it would greatly reduce the viability of a geothermal system.

Geothermal systems, unlike solar, wind, or biomass systems, are an energy multiplier. They take energy and multiply the output. As a result, the savings from installing a geothermal system are completely dependent upon the price of electricity and the price of natural gas because the difference between the two determines the profit.

Due to the long life of geothermal, very few systems have approached the end of their usable life. As a result, little is known about the end of life of a geothermal system. One issue is what happens to the system after it is no longer in use. It is not known whether the geothermal system must be ripped up at the end of its life or if it would be abandoned in the ground.

Appendix B1: Technology of a Geothermal System

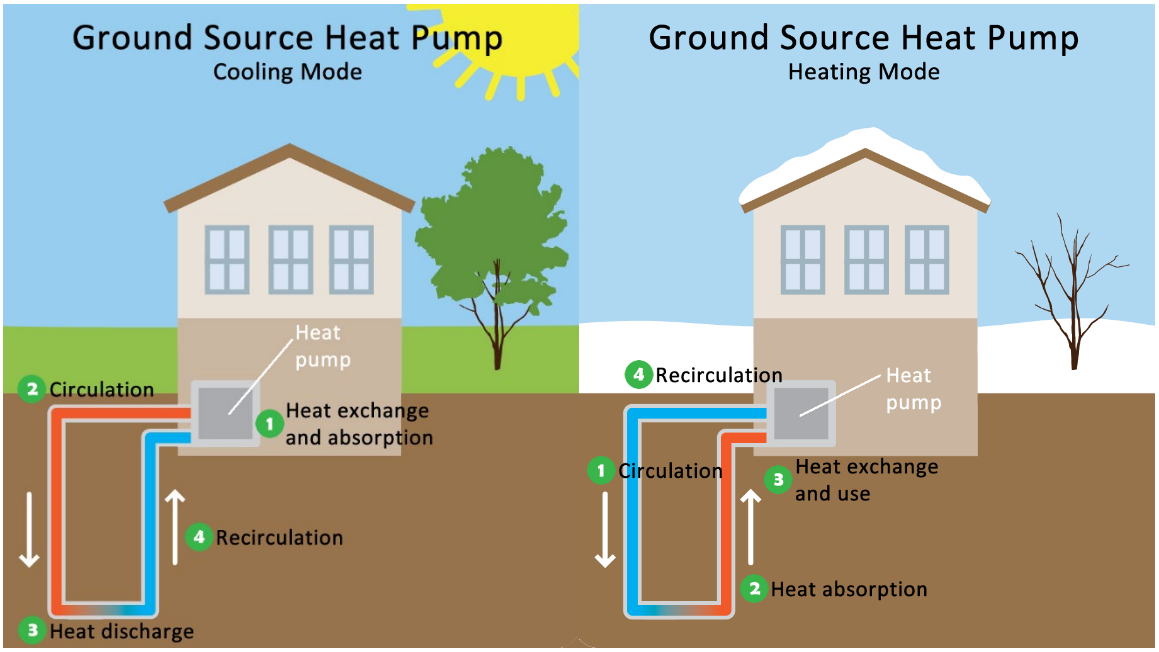

Figure B1.1: Heating and Cooling with a Ground Source Heat Pump

Appendix B2: College Case Studies

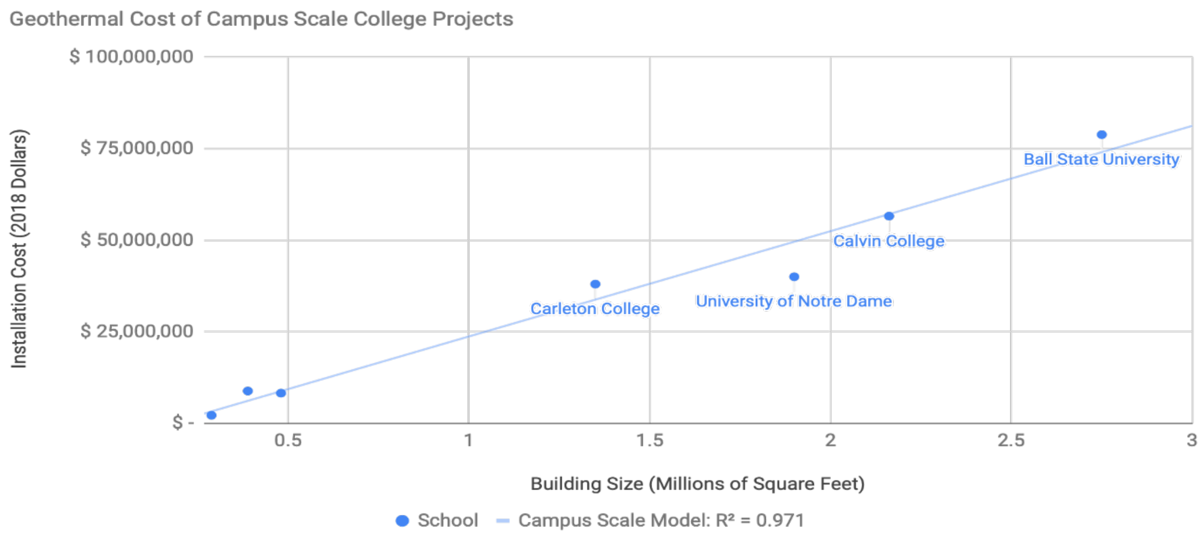

Figure B2.1: Large Scale College Case Study of Installation Cost vs. Building Size

Figure B2.2 shows the results for the small-scale case study. A project of $5 million would be consistent with the scale of other small-scale geothermal installations.

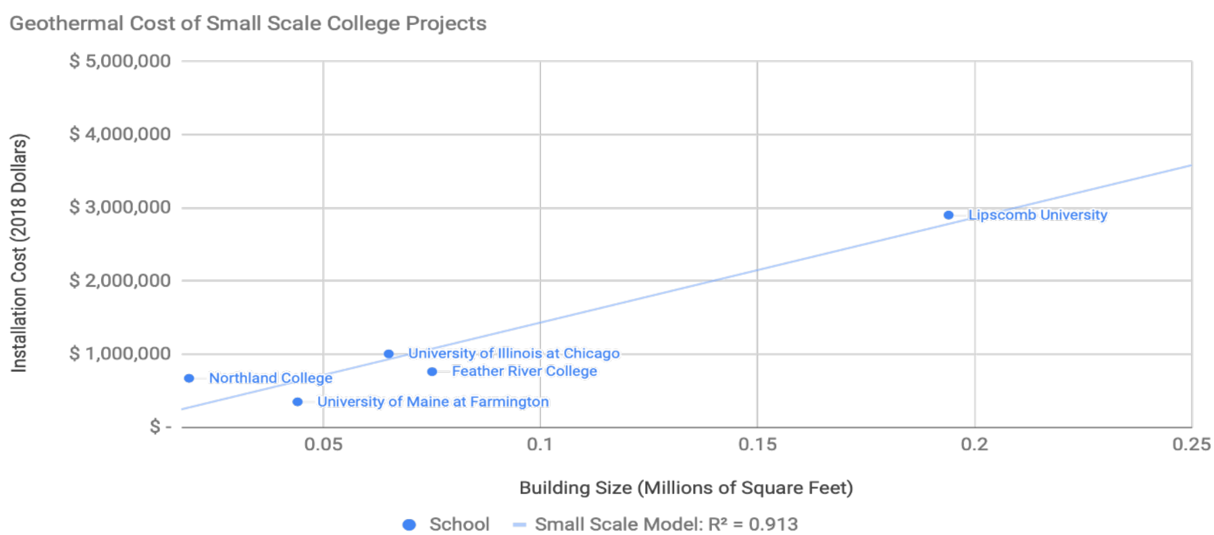

Figure B2.2: Small Scale College Case Study of Installation Cost vs. Building Size

Appendix B3: Calvin Cost Case Study

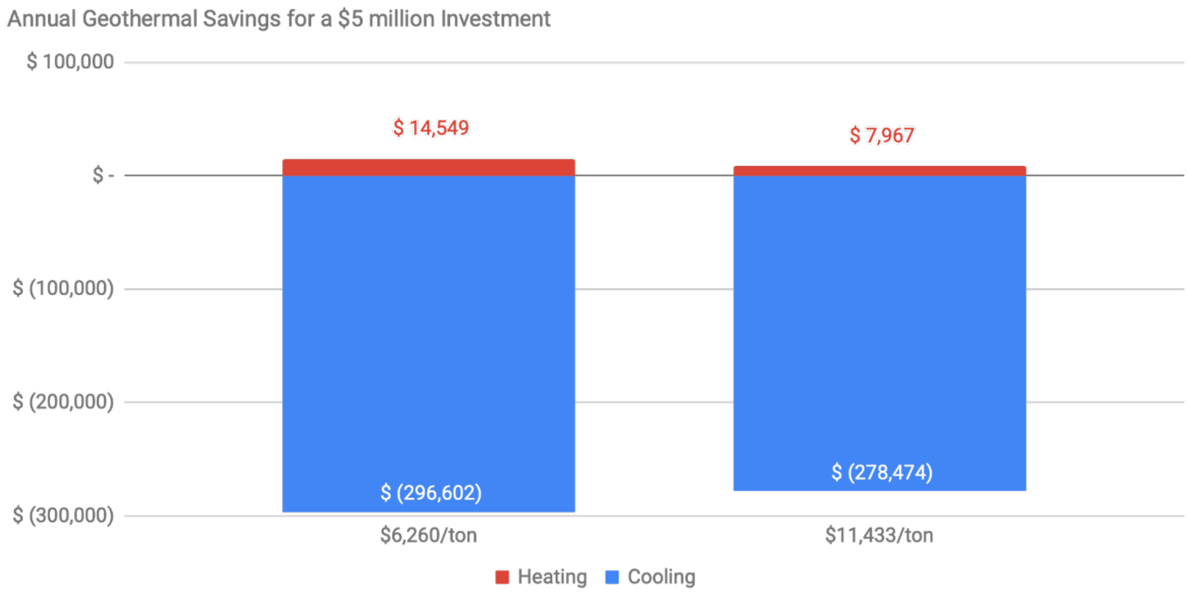

Figure B3.1: Calvin College Annual Savings for a $5M Investment

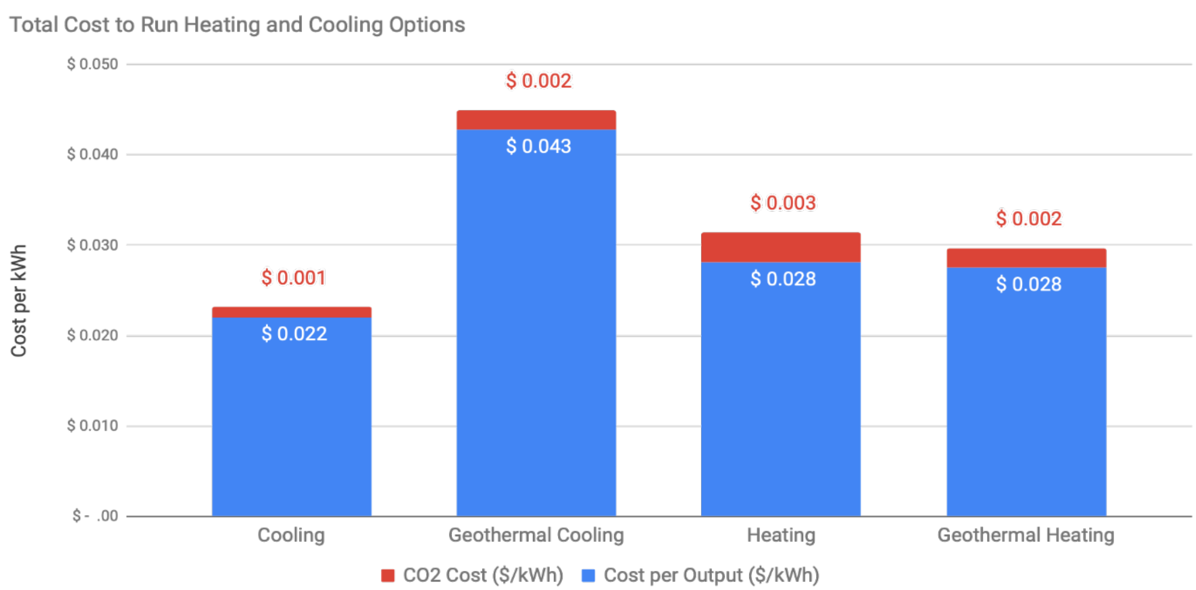

Figure B3.2: Total Cost of Heating and Cooling Options

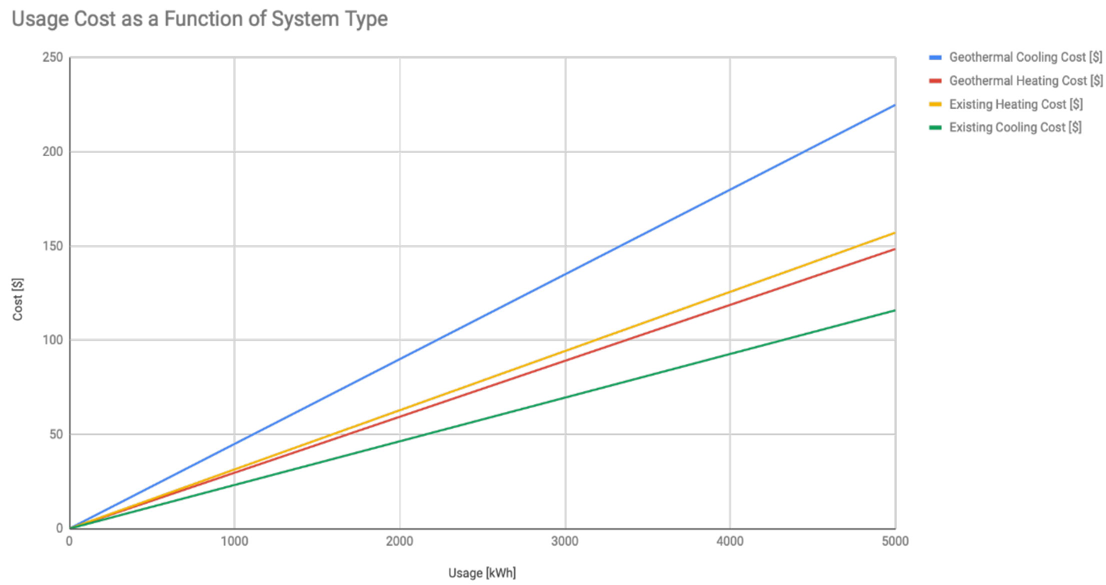

Figure B3.3: Usage Cost as a Function of System Type

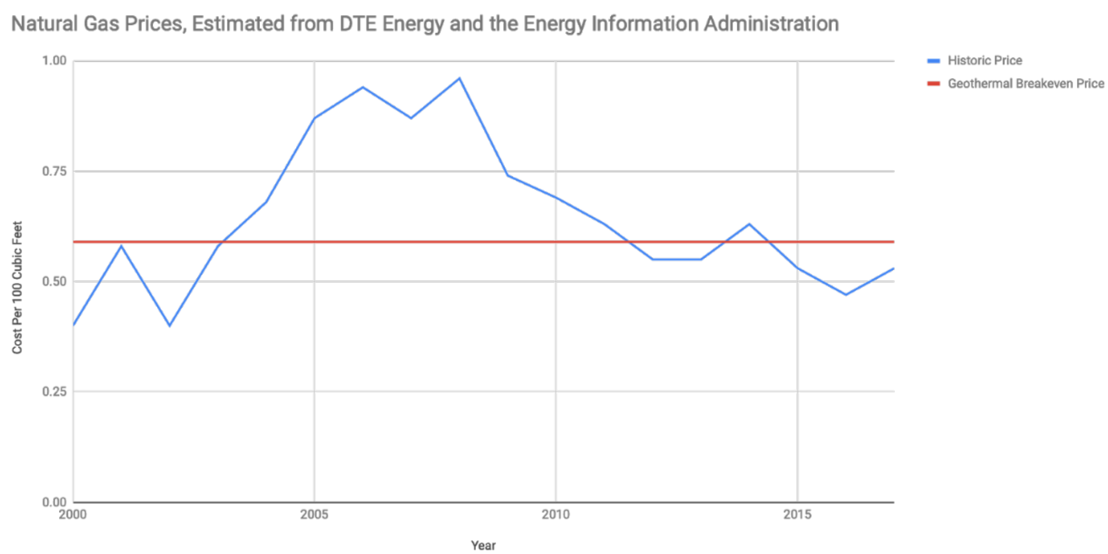

Figure B3.4: Natural Gas Prices (Estimated from DTE Energy and the Energy Information Admin.)

Appendix B4: System Analysis

Table B4.1: Calvin Boiler Performance

	Heating (hp)	Heating (BTU/hr)	Type	Efficiency	Weighted Efficiency
SB (Hurst)	800	26,866,000	Hurst	78.00%	35.15%
Commons (Kewanee)	666	22,714,000	Kewanee	65.00%	24.76%
Library (Hurst)	300	10,042,500	Hurst	78.00%	13.14%
Total	1766	59,622,500			73.05%

Table B4.2: Calvin Chiller Performance

	Cooling (ton)	Cooling (kW)	Power Rating (kW)	kW/ton	COP	Weighted COP
SB 1	850	2989	512	0.60	5.84	1.21
SB 2	1000	3517	524	0.52	6.71	1.64
Commons	1250	4396	708	0.57	6.21	1.89
Library	1000	3517	534	0.53	6.59	1.61
Total	4100					6.35

Table B4.3: Modeling Parameters

Model	Cost / hp	Cost / ton	Cost / sqrft
Small Scale	$ 17,536	$ 6,260.40	$ 14.33
Campus Scale	$ 32,024	$ 11,432.60	$ 26.16
Full	$ 31,971	$ 11,413.54	$ 26.12

Table B4.4: Model Calculations

	Heating		Cooling	
Load	0.0008	hp/ft^2	0.0019	ton/ft^2
Load (BTU)	27.3476	BTU/ft^2	22.6663	BTU/ft^2
Installation Cost	$ 17,536	$/hp	$ 6,260	$/ton
Capacity/million$	57	hp/million$	160	tons/million$
Installed Capacity	285	hp	799	tons

Table B4.5: Cost Calculations

	Annual Cost to Run	Efficiency or COP	Input (kW-hr/yr)	Output (kW-hr/yr)	Cost per Output ($/kWh)
Cooling	$ 315,235	6.35	2,251,677	14,290,770	$ 0.0221
Geothermal Cooling	$ 611,837	3.27	4,370,266	14,290,770	$ 0.0428
Heating	$ 906,300	65%	49,590,000	32,233,500	$ 0.0281
Geothermal Heating	$ 674,379	3.27	7,493,100	24,502,436	$ 0.0275

Table B4.6: Carbon Emissions Calculations

	Carbon per Output (kg/kWh)	CO2 Cost ($/kWh)	Total Cost ($/kWh)
Cooling	0.1194	$ 0.001	$ 0.0232
Geothermal Cooling	0.2318	$ 0.002	$ 0.0450
Heating	0.3538	$ 0.003	$ 0.0314
Geothermal Heating	0.2318	$ 0.002	$ 0.0297

Appendix B5: Geothermal Cost Modeling

Background

The following analysis is intended to help inform leadership at Calvin College decide how best to invest five million dollars in renewable energy projects. This analysis seeks to determine an initial cost estimate for converting different buildings on campus to geothermal heating and cooling.

Analysis

To determine estimates of how much it would cost to install geothermal systems at Calvin, a spreadsheet of other successful college geothermal projects has been compiled with data for the cost of the project and the number of square feet that it supplies, among other variables. Linear regression models are fitted to the data to form a prediction model. The square footage of buildings at Calvin are fed through this model and cost estimates are found for conversion to geothermal heating and cooling for each.

Read in the Data

```
geothermal <-read.csv("GeothermalSmall.csv")
 geothermal <-geothermal %>%
 subset(school!='Lake Land College') %>% #Remove Outliers and Projects with Insufficient Data
 subset(school!='Hamilton College') %>%
 subset(school!='Oberlin College') %>%
 subset(school!='Drury University') %>%
 subset(school!='Rice University') %>%
 subset(school!='Harvard University (Closed Loop)')%>%
 subset(cost_2018usd>1)

geothermal_campus <-geothermal %>%
 subset(scale=='Campus')
 geothermal_smallscale <-geothermal %>%
 subset(sqrft<200000) #Select Projects Intended for Less Than 20,000 ft^2

head(geothermal,3) #Return the first few rows of data.
##   school                      state  no_students  year  cost_milusd savings_yr
## 1 Ball State University        IN     22500        2012  70          2000000
## 2 University of Notre Dame     IN     12292        2018  40          NA
## 3 Carleton College             MN     2105         2018  38          2000000
##   savings_yr_2018usd savings_25yr_2018usd cost_2018usd cost_per_sqrft
## 1 2252325            56308121             78831369     28.66595
## 2 NA                 NA                   40000000     21.05907
## 3 2000000            50000000             38000000     28.16042
##   type                     no_bores depth_ft bore_per_sqrft  sqrft    scale
## 1 VerticalHorizontalClosed  1800     450      0.2945455      2750000 Campus
## 2 VerticalClosed            1303     300      0.2057998      1899419 Campus
## 3 VerticalHorizontalClosed  305      520      0.1175327      1349412 Campus

calvinsqrft <-read.csv("CalvinSquareFootage.csv") #Data From Physical Plant
```

```
head(calvinsqrft,3) #Return the first few rows of data.
##   constr_date    location          sqrft      function.
## 1 1910           Manor House    8,712      President's House
## 2 1954           Ravenswood     4,354     Guest House
## 3 1961           Beets/Veenstra 54,142   Residence Hall
##    notes
## 1 Remodeled in 1995 and 2012
## 2 Some remodeling  in 1995
## 3
```

```
calvinsqrft <-read.csv("CalvinSquareFootage.csv") #Re-imported for function reasons.
```

Create a scatterplot with a linear regression overlay.

The following three plots explore if there is a relation between cost and the scale of installation. The first plot contains all data while the other plots break this into small and campus scale projects. For example, some colleges have installed geothermal systems for only a few buildings (existing or new) while some have installed a geothermal system large enough for the entire campus.

```
gf_point(cost_2018usd ~sqrft,data =geothermal,
 title ="Cost as a function of Square Footage",
 xlab ="Square Footage",
 ylab ="Cost in 2018 US Dollars") %>%

 gf_lm()

gf_point(cost_2018usd ~sqrft,data =geothermal_campus,
 title ="Cost as a function of Square Footage for Campus Scale Projects",
 xlab ="Square Footage",
 ylab ="Cost in 2018 US Dollars") %>%

 gf_lm()

gf_point(cost_2018usd ~sqrft,data =geothermal_smallscale,
 title ="Cost as a function of Square Footage for Small-Scale Projects",
 xlab ="Square Footage",
 ylab ="Cost in 2018 US Dollars") %>%

 gf_lm()
```

Check possible predictors for collinearity.

When fitting linear models, it is important to check that there is no relationship between predictors and that they do not contain the same information. Collinearity increases the uncertainty in model coefficients and may make it hard to fit a model. This is done using a pairs plot, which gives correlation scatterplots and values, and using variance inflation factors (VIFs).

```
geopairs <-geothermal %>%select(sqrft,no_bores,depth_ft)
ggpairs(geopairs) #Check using a pairs plot.
geolmvif <-lm(cost_2018usd ~sqrft +no_bores +depth_ft, data =geothermal, na.action =na.fail)
```

```
vif(geolmvif) #Check using variance inflation factors. Numbers over 4 signify a problem.
##  sqrft       no_bores   depth_ft
## 12.899854 12.299938  1.412502
```

Create a model with independent predictors for information criteria testing.

The "Number of Bores" variable is removed due to high correlation with the number of square feet supplied by the system.

```
geolmtest <-lm(cost_2018usd ~sqrft +depth_ft, data =geothermal, na.action =na.fail)

vif(geolmtest) #VIF values signify no collinearity.
##  sqrft     depth_ft
## 1.050848 1.050848
```

Compare models using information criteria.

```
dredge(geolmtest, rank ="BIC")
## Global model call: lm(formula = cost_2018usd ~ sqrft + depth_ft, data = geothermal,
##     na.action = na.fail)
## ---
## Model selection table
##     (Int)      dpt_ft  sqr    df  logLik    BIC    delta  weight
## 3 -2296000            27.40  3   -182.631  372.5   0.00  0.689
## 4 -6714000   11900    27.13  4   -182.228  374.0   1.59  0.311
## 1 16520000                   2   -202.608  410.0  37.56  0.000
## 2 -10420000  69620           3   -202.225  411.6  39.19  0.000
## Models ranked by BIC(x)
```

The model with only square footage as a predictor is chosen due to the lowest BIC value, the simplicity of only one predictor, and the availability of data on square footage for when the model is used for cost predictions.

Model Assessment

Now that the model form has been chosen, models for the different datasets are created and model assessment is performed to determine if a linear regression model is acceptable for the data.

```
#Create Models with a Zero Intercept
geolm <-lm(cost_2018usd~0+sqrft, data =geothermal, na.action =na.fail)
geolm_small <-lm(cost_2018usd ~0+sqrft, data =geothermal_smallscale, na.action =na.fail)
geolm_campus <-lm(cost_2018usd ~0+sqrft, data =geothermal_campus, na.action =na.fail)

summary(geolm)
##
## Call:
## lm(formula = cost_2018usd ~ 0 + sqrft, data = geothermal, na.action = na.fail)
```

```
##
## Residuals:
##     Min   1Q Median      3Q Max
## -9610238 -3249863 -1198093  -259820 7005113
##
## Coefficients:
##          Estimate  Std. Error  t value  Pr(>|t|)
## sqrft  26.119      1.234        21.17    1.23e-09 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Residual standard error: 4533000 on 10 degrees of freedom
## Multiple R-squared:  0.9782, Adjusted R-squared:  0.976
## F-statistic: 448.3 on 1 and 10 DF,  p-value: 1.229e-09

summary(geolm_campus)
##
## Call:
## lm(formula = cost_2018usd ~ 0 + sqrft, data = geothermal_campus,
##    na.action = na.fail)
##
## Residuals:
##              2            3           5             6           11
## 6885128 -9693112  2696328 -1357396 -4354859 -5364637
## Coefficients:
##          Estimate  Std. Error  t value   Pr(>|t|)
## sqrft  26.162    1.716       15.24     2.2e-05 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
## Residual standard error: 6296000 on 5 degrees of freedom
## Multiple R-squared:  0.9789, Adjusted R-squared:  0.9747
## F-statistic: 232.3 on 1 and 5 DF,  p-value: 2.205e-05

summary(geolm_small)
##
## Call:
## lm(formula = cost_2018usd ~ 0 + sqrft, data = geothermal_smallscale,
##    na.action = na.fail)
##
## Residuals:
## 10          12       13          14         16
## 121915   72672 -313663  398248 -282210
##
## Coefficients:
##          Estimate    Std. Error   t value   Pr(>|t|)
## sqrft  14.326      1.339        10.7       0.000432 ***
## ---
```

```
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
## Residual standard error: 298700 on 4 degrees of freedom
## Multiple R-squared:  0.9663, Adjusted R-squared:  0.9578
## F-statistic: 114.6 on 1 and 4 DF,  p-value: 0.0004318
```

Check Constant Variance

For a linear-regression model, it is assumed that the residuals have constant variance (y-axis spread) over all fitted values (x-values).

There may be some concern when looking at this plot as the variance clustered around zero seems larger than that for greater fitted values. This is likely due to the minimal data for larger projects.

```
xyplot(resid(geolm) ~fitted(geolm), xlab ="Fitted Values", ylab ="Model Residuals")
xyplot(resid(geolm_small) ~fitted(geolm), xlab ="Fitted Values", ylab ="Model Residuals")
xyplot(resid(geolm_campus) ~fitted(geolm), xlab ="Fitted Values", ylab ="Model Residuals")
```

Check Residual Distribution

It is assumed that the residuals will roughly follow a normal distribution. This assumption holds for the full model and roughly for the small and campus scale models given the small number of datapoints.

```
histogram(resid(geolm), xlab ="Model Residuals",fit ="normal")
histogram(resid(geolm_small), xlab ="Model Residuals",fit ="normal")
histogram(resid(geolm_campus), xlab ="Model Residuals",fit ="normal")
```

Check Residual Independence

The assumption that the residuals are independent of each other should be checked. This is done using an ACF plot. This assumption seems to hold as the values are between the blue fence lines.

```
acf(resid(geolm)) #Sort by state / region / etc. first
acf(resid(geolm_small))
acf(resid(geolm_campus))
```

Predict Cost Using the Given Model

Given that the model asessment conditions have been satisfied, the model may be used to predict the installation costs for geothermal systems at Calvin. The data is written to a .csv file for download and analysis in Excel.

```
preds_full <-predict.lm(geolm, newdata =calvinsqrft,
  interval ="prediction",level =0.95, se.fit =FALSE)
preds_small <-predict.lm(geolm_small, newdata =calvinsqrft,
  interval ="prediction",level =0.95, se.fit =FALSE)
preds_campus <-predict.lm(geolm_campus, newdata =calvinsqrft,
  interval ="prediction",level =0.95, se.fit =FALSE)

costfit <-cbind(calvinsqrft, preds_small) %>%
```

```
 select(-lwr,-upr)

names(costfit)[names(costfit)=="fit"] <-"cost_estimate_small"

costfit <-cbind(costfit, preds_campus) %>%
 select(-lwr,-upr)

names(costfit)[names(costfit)=="fit"] <-"cost_estimate_campus"

costfit <-cbind(costfit, preds_full) %>%
 select(-lwr,-upr)

names(costfit)[names(costfit)=="fit"] <-"cost_estimate_full"

head(costfit)
##      constr_date  location         sqrft  function
## 1    1910         Manor House      8712   President's House
## 2    1954         Ravenswood       4354   Guest House
## 3    1961         Beets/Veenstra   54142 Residence Hall

##    notes                           cost_estimate_small
## 1  Remodeled in 1995 and 2012      124810.24
## 2  Some remodeling in 1995         62376.47
## 3  <NA>                            775651.50

##   cost_estimate_campus cost_estimate_full
## 1 227925.7             227545.6
## 2 113910.5             113720.6
## 3 1416477.6            1414115.3

write.table(costfit, "calvin_costfit.csv", sep=",",row.names =FALSE)
```

Appendix B6: Geothermal References

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Appendix C: Wind Renewable Energy Source

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Engineering 333B: Thermal Systems Design

Dr. Matthew Heun: Calvin College Engineering Department

December 18, 2018

Introduction

The overall goal was to determine the largest possible reduction in Calvin's annual energy costs from a $5M investment in wind energy. To do this, turbines were first analyzed based on size, power output, cut in speed, and cost. Next, wind data was collected from Gerald R. Ford Airport (GRR) and from Calvin's campus. This data was analyzed with the power curve from the selected wind turbine to determine how much energy savings it could produce in a year. In addition, there were heavy space restrictions on where the wind turbines could be located on Calvin's campus. Only 1 or 2 turbines would fit (one in Devos field and the other in the Gainey Sports Complex) which is not enough to generate a significant amount of energy.

Methods and Data Analysis

Wind data was gathered from both the Gerald R. Ford Airport (GRR) and the Bunker Center. The Bunker Center had wind readings approximately 30 ft above ground with trees close by. This data was put into a formula to approximate the wind speed at the height of the selected turbine (ADES 335), which was 118 ft tall. The new approximated wind speeds were then used to create a wind probability graph (see Figure C1.1 in Appendix C1). This graph gives the probability that the wind will be at a certain speed at any given time. The probability data was combined with the wind turbine's output (see Figure C3.1 in Appendix C3) at that given speed to give the real-world power output of the turbine. The data from GRR was already in the form of probability data (see Figure C1.2 in Appendix C1) which just needed to be extrapolated to the height of our turbine. The data showed that the ADES 335 would produce 30 MWh/yr using Calvin's wind data, which is shown in Table C3.1. When the turbine output was calculated with the GRR data, the power output was calculated to be 575 MWh/yr. These numbers are very different and present some risk when deciding if wind turbines are feasible on Calvin's campus.

Turbine Selection

The two types of turbines that were considered for installation on Calvin's campus were vertical and horizontal axis wind turbines. If a vertical axis wind turbine was to be used on campus, several of them would have to be placed on roof tops. Vertical axis turbines typically cannot produce large amounts of power due to their design. The applications of these turbines tend to require lower power output. The ideal spot for vertical axis turbines would be on top of existing buildings such as the Science Building and Hiemenga Hall. According to Professor De Rooy, the older buildings were not designed to have an extra load placed on their roofs. The added cost of reinforcing the roof and the turbulent air that buildings create made vertical axis turbines impractical.

Research into traditional turbines lead to the decision to use mid-sized turbines. The larger commercial turbines would be too large for an on-campus project due to lack of open space and height restrictions. The maximum height allowable by the city of Grand Rapids is 200 feet. Another consideration for choosing a wind turbine is the noise created during operation. The city of Grand Rapids allows a maximum of 60 decibels during operation but allows for a higher output during storms or utility outages. With these restrictions in mind, the ADES 335 wind turbine was chosen, seen in Figure C2.1 in Appendix C2. This turbine is unique in the sense that it has just one blade as opposed to having three, like on standard turbines. This turbine was selected based on its excellent power curve. It has a lower cut-in speed than most turbines considered, which is essential in a relatively low wind speed region. The ADES 335 has a maximum height of 180 ft, which abides by the city height ordinance. Using data provided from the manufacturer at a height of 65 feet, the data was extrapolated to approximate the sound experienced at ground level from this turbine at a hub height of 120 ft. Using wind speed data from the area, the maximum sound level during normal operations came out to be 57.7 decibels, which falls just under the maximum allowable noise level. Using information from the manufacturer and other online sources, the cost of the turbine and installation would be $650,000/turbine. This allows for multiple turbines to be purchased while still staying within the $5M budget that was given.

Financial Analysis

Using the power output numbers from Calvin and the GRR, the annual electricity savings can be converted to cost savings. The cost savings were done with the average price of electricity in Grand Rapids, which is $0.11/kWh. The ADES 335, using Calvin's wind data, would save $3,400 per turbine, per year in electricity costs. Unfortunately, the cost of maintaining the turbines would be $13,000 (Table C3.2 in Appendix C3), which is more than the money saved in electricity costs. This option would never "pay for itself," and would instead be a constant loss of money.

The data from GRR gives an annual cost savings of $26,500 per year after subtracting maintenance costs. Factoring in the $650,000 cost of buying and installing each turbine, the payback period of each turbine is 24.5 years. This is a longer payback period than desired because the lifespan of a wind turbine is generally expected to be 25 years. This means the financial benefits of placing turbines on campus will be negligible.

However, the government has introduced incentives to installing wind turbines. The incentives were introduced with The American Recovery and Reinvestment Act of 2009. This act includes the 1603 Program, which allows up to 30% of the upfront cost of the turbines to be reimbursed to the owner. If 30% of the turbine cost were given back to Calvin, this would lower the payback period to 17.2 years. With close to 8 years of life left in the turbines after their breakeven point, Calvin would net nearly $200,000 per turbine at their end of life.

The other benefit of these turbines that cannot be calculated is the good press Calvin would receive from having turbines on campus. The turbines would attract students interested in renewable energy. Along with this, an opportunity to integrate the turbines into the engineering curriculum would be presented. The financial benefits of slightly increased enrollment numbers are beyond the scope of this project but should not be overlooked.

Space Constraints and Restrictions

With wind turbines comes multiple space restrictions. The main restriction being distance away from any standing structure. Due to their large heights and potential for falling over, each turbine must be a minimum for 1.5 times its height (shown as a black circle in Figure C2.2 in Appendix C2) away from a standing structure. This restricts the placement of the large turbines to open fields (Devos Field) or inside forested areas (Gainey Fields). Based solely on being 1.5 times the height away from any standing structure, the turbine that has been selected can be place in the spots located on the map in Appendix C2, Figure C2.2.

Another restriction is based on the minimum recommended distance between turbines (shown as a red circle in Figure C2.2 in Appendix C2). This restriction is based on creating the most efficiency for each turbine by limiting the turbulence from each turbine. The exact distance shown in Figure C2.2 in Appendix C2 is five times the blades diameter, or 180 meters. This restricts the number of turbines that can placed in a given location to one in most cases. More turbines can be placed in a region if the Gainey Field is utilized. The main issue with using the Gainey Athletic fields is that it requires significant deforestation of the nature preserve. Both restrictions stated make the use of wind turbines on campus to be ineffective.

CO_2 Emissions for Wind Power Generation System

A study was done on the CO_2 emissions associated with the proposed wind power generation system. This study investigated the CO_2 emissions from the life cycle of a wind turbine, which includes the manufacturing, transport and installation emissions. The approximate amount of CO_2 emissions determined from a study by Smoucha at 420,730 lbs.

The “payback” period for the embodied CO_2 emissions of the wind power system was also calculated. The proposed wind power generation system had the capacity to produce approximately 384 MWh/year, which is equivalent to a savings of 707,544 lbs of CO_2 per year. The payback time for this value of CO_2 emissions rate is approximately 0.6 years.

Conclusion

In the end, implementation of wind turbines on Calvin’s Campus is not recommended. It is financially infeasible and extremely hard to effectively place on campus. While placing wind turbines would be visible symbol for Calvin’s passion and commitment to reducing their carbon footprint, wind turbines do not provide Calvin with an adequate return for such a large financial investment.

Appendix C1: Grand Rapids Wind Speed Data

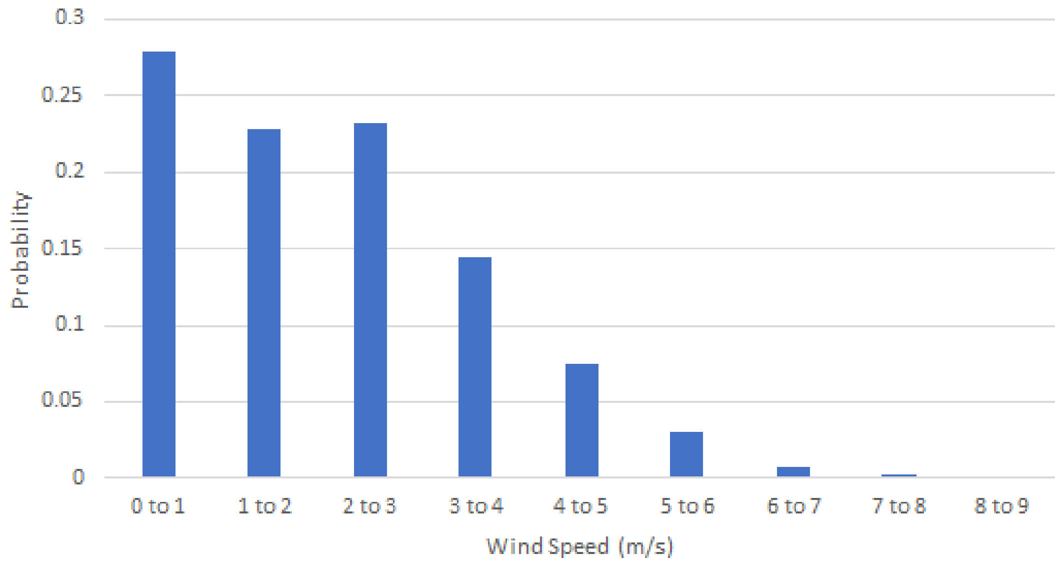

Figure C1.1: Calvin Wind Speed Probability

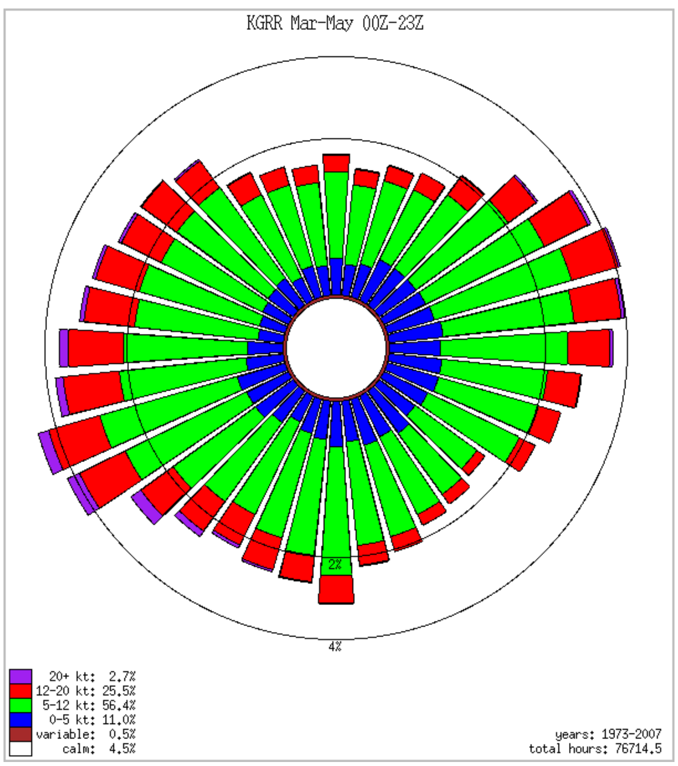

Figure C1.2: GRR Airport Wind Probability Data

Appendix C2: Wind Turbine Decision and Location

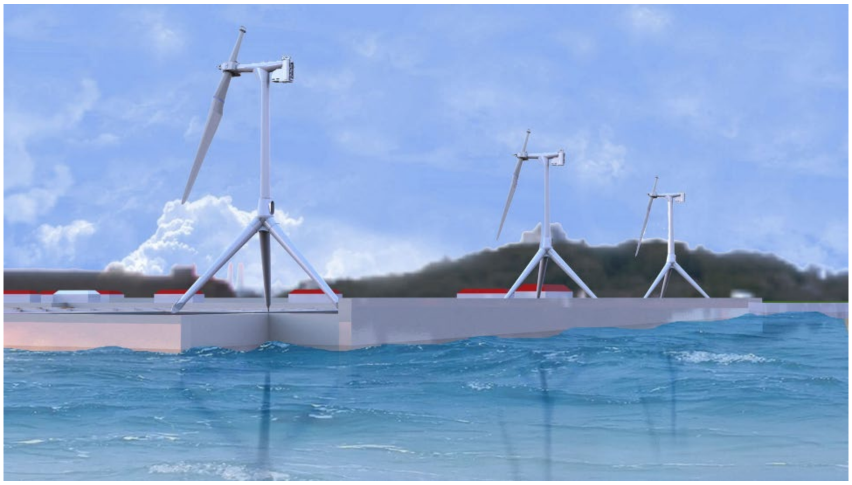

Figure C2.1: ADES 335 Wind Turbine

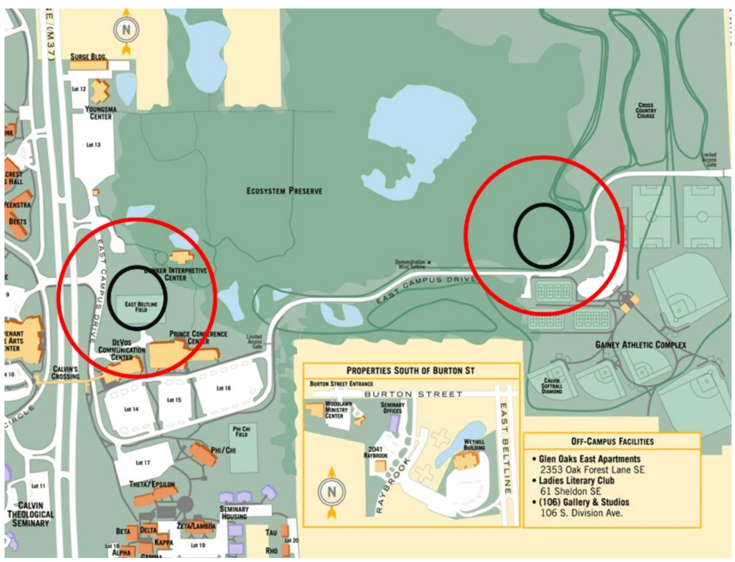

Figure C2.2: Potential Locations for the ADES 335 Turbine

Appendix C3: ADES 335 Turbine Specifications

Table C3.1: Turbine Output Calculations

Wind Speed (kn)	Wind Speed (m/s)	Yearly Probability	Power Output (kW)	Turbine Output (kW)
20	12.14	0.018	335	5.94
16	9.71	0.215	204	43.95
9	5.46	0.581	27	15.68
2.5	1.52	0.132	0	0.00
0	0.00	0.055	0	0.00

Table C3.2: Cost and Revenue Calculations

Cost installed	[$] 650,000
O.M.	[$/yr] 13,000
Power per year	[Kwh] 30,378
Power cost	[$/kWh] 0.11
Cost savings	[$/yr] 3,342
Net Profit	[$/yr] -9,658

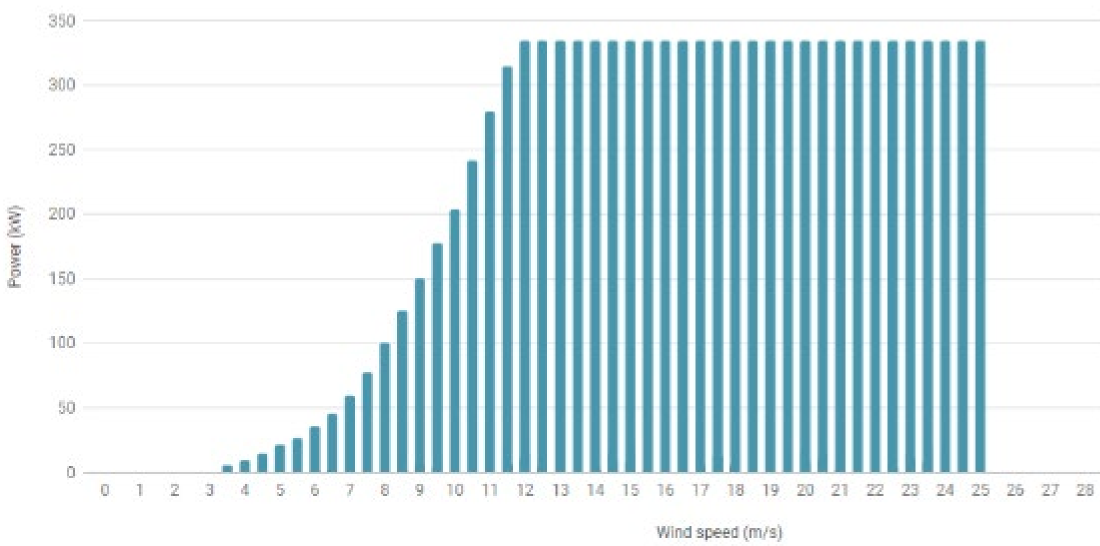

Figure C3.1: Power Curve for the ADES 335 Wind Turbine

Appendix C4: Wind References

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Appendix D: Biomass Renewable Energy Source

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Engineering 333B: Thermal Systems Design

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December 18, 2018

Introduction

Biomass renewable energy is energy produced from plant and animal waste matter. The waste can either be burned, and used to produce electricity, or allowed to decay, releasing methane which can then be burned for heat or electricity. Both methods of utilizing biomass release carbon dioxide but are considered carbon neutral because they utilize renewable resources (plants and animals) which are, ideally, growing and absorbing carbon dioxide at the same rate as they are burned. Woody biomass, such as trees and leaves, are used for burning, while food waste and manure are used for producing methane.

Method

For biomass energy production, there were two systems that were the focus of this team: a biomass incinerator and an anaerobic digester. Each system was analyzed, and the potential energy production of each system was calculated using data from previous biomass system examples, published scientific reports, as well as using data from Calvin's Physical Plant. The largest possible reduction in Calvin's annual energy costs from a $5,000,000 investment in biomass was investigated for both the incinerator and a biodigester. It was found that the savings was $220,000 and $11,755 per year for the best-case scenario for the Incinerator and the digester respectively.

Biomass Incinerator

The incinerator was compared to several other campuses that have biomass power, such as Northern Michigan University (NMU), University of Missouri, and Colby College in Maine. A more detailed comparison was done with Northern Michigan University's biomass power generation as it was a university in Michigan, and thus would have comparable results to Calvin College.

Northern Michigan University's unit costs $16.4 million and would save the college $1,500,000 per year. It would produce 18% of the university's electricity. This unit would use woody biomass waste as fuel. When scaling the biomass cogeneration plant of Northern Michigan to that of Calvin College for $5,000,000, it is evident that little electricity would be produced. It would provide around 10% of the electrical load that Calvin uses as seen in Figure D1.1 which would save Calvin around $220,000 per year if Calvin had enough fuel. It is also very optimistic to assume that it would be a linear scale as the more money you put up front, the better plant that one could build and thus be more efficient in the electricity or steam production.

The amount of fuel that Calvin would need to produce is around 415 tons per year as seen from a scaled comparison with NMU as seen in Figure D1.1. Calvin produces roughly zero tons of woody biomass per year, and therefore would have to purchase all the fuel. Thus, Calvin is essentially having to pay for this electricity and would not be saving the campus any money.

Calvin has also approved of a cogeneration system that would be implemented on Calvin's campus soon. Adding both a new cogeneration plant and a biomass incinerator at the same time does not make financial sense, especially considering that a biomass incinerator is not economically viable (see Figure D1.2 in Appendix D1).

An incinerator was not an economically wise decision for Calvin College. It would cost too much to install for the electricity that it would produce. Also, the fuel in the form of a woody waste would have to be purchased and would result in Calvin having to pay more money, in addition to adding significant logistical difficulty. This would cost more than just purchasing electricity from the grid. Therefore, it was recommended that Calvin does not pursue biomass in the form of a biomass incinerator.

Anaerobic Digester

Unlike the incinerator, the anaerobic digester would produce methane gas for the cogeneration power plant to run on. The produced methane would be used in conjunction with the natural gas Calvin College uses normally. This would cut down on Calvin's use of natural gas that it purchases from the city. Ideally, the yard waste produced from the daily upkeep of Calvin's lawns as well as the food waste produced from the dining halls each day would be used as fuel.

Methane is released from digestible material in the biodigester in the form of biogas. This biogas contains impurities such as CO_2 and water, so not all the biogas that is given off is methane. After researching they specific type of biomass that would produce the highest amount of biogas, the focus was shifted to using exclusively food waste in the biodigester. Food waste comparatively produces the greatest amount of biogas. Food waste gives off 14.9 ft^3 biogas per pound of food waste given the correct environment. The average percentage of methane contained in biogas is 60 to 65%. From Calvin's physical plant, the amount of food waste Calvin produces in a given academic year is approximately 600,000 pounds. Using data and values from previous scientific reports on biogas production per amount of food waste and the average percentage of methane in that biogas, the calculated amount of methane that could be produced solely from Calvin food waste per year is about 1.8 million cubic feet of methane.

This theoretical methane production, in comparison to the amount of natural gas that Calvin College needs each year, is not a significant source of fuel. The average amount of natural gas Calvin College uses is just shy of 180 million cubic feet of methane, which amounts to $880,000 per year. As can be seen from Figure D1.3, this is miniscule compared to the amount that Calvin produces. The amount of methane produced would save the college only $11,755 per year. The difficulty with using a biodigester to produce the fuel, unlike the other renewable energy sources, is that it cannot be scaled up to produce more methane for the college. The amount of methane produced is based on the fuel for the biodigester, which is finite, coming only from the waste of the dining halls. An idea was proposed to collect food waste from surrounding restaurants to increase the amount of fuel for the biodigester, but this idea was dropped due to logistical difficulties and an increase in costs to transport the fuel, a fuel that is otherwise free.

The final difficulty with a biodigester is that the machines that would be needed to clean the methane produced and separate it from biogas. This biogas contains CO2, water vapor, and other impurities that would harm the cogeneration system. This would require the filtration system to be higher quality, ensuring the methane is pure enough to not damage the cogeneration plant.

Therefore, there would be a significant maintenance cost, which would mitigate a portion of the $11,755 per year saved in energy costs.

Conclusion

A biodigester is not a viable source of methane, and therefore not a viable source of renewable energy. Due to Calvin College's small size, the amount of available food waste is too small to be converted into a viable source of methane. Therefore, both a biodigester and an incinerator are not good uses of the $5,000,000 renewable energy budget. It would be in Calvin College's best interest to focus money and resources on other renewable energy projects.

Appendix D1: Biomass Comparison Data

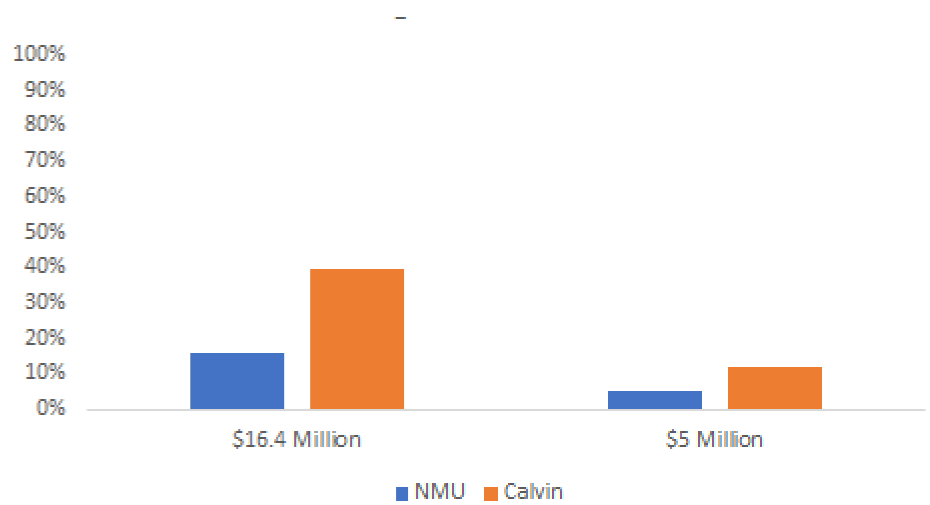

Figure D1.1: Percentage Scale of Electrical Load of NMU Power Plant Yearly Energy Production

Project	MW eq. Cap	MWh eq.	Wood tons	2013 status
CMU	17	134,028	227,848	Terminated
DTE	400	3,153,600	5,361,120	Terminated[15]
Escanaba	25	197,100	335,070	Under development
Gwinn	20	157,680	268,056	Pending
LBW&L	300	2,365,200	4,020,840	Terminated
Mancelona	36	283,824	482,501	Terminated
Dow Corning	40	315,360	536,112	Terminated
Newberry	24	189,216	321,667	Terminated
NMU	10	78,840	134,028	Completed
TCL&P	20	157,680	268,056	Terminated
Verso	25	197,100	335,070	Complete
White Pine	50	394,200	670,140	Pending
Wolverine	120	946,080	1,608,336	Terminated
Totals	**1,087**	**8,569,908**	**14,568,844**	

Figure D1.2: Biomass Power Projects

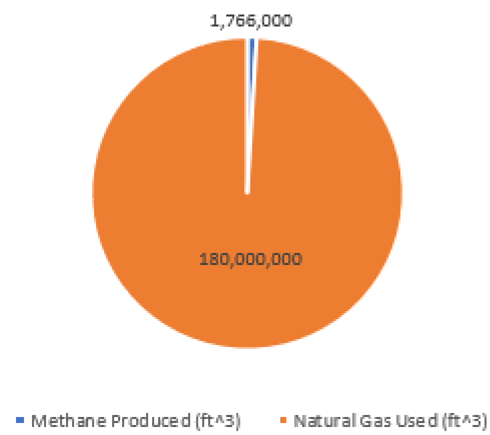

Figure D1.3: Methane Production for Ideal Biodigester Compared to Calvin's Consumption

Appendix D2: Biomass References

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Appendix E: Alternative Option A - Geothermal System

Engineering 333B: Thermal Systems Design

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December 18, 2018

Proposal

The proposal for Alternative A includes installing 75 bores in a geothermal bore field in Commons Lawn at an average depth of 400 feet per bore. This bore field would be connected to a geothermal system to aid the two aging 333 hp Kewanee boilers in the Commons power plant. Using the remaining $1.32M, a 75 hp geothermal system could be installed, replacing 11.3% of the current capacity. This system would be able to serve 92,000 square feet, roughly the size of the Bolt-Heyns-Timmer (BHT) dormitory. It would save nearly $4,000 and 790 tonnes of carbon dioxide emissions per year at the current utility rates.

Method

The above recommendation was formed using the geothermal cost analysis model and spreadsheet. The key parameters are summarized in Table E1.1. At the small-scale model price of $17,536/hp, a system size of 75 hp was determined. The small-scale model was used because the project was under the approximate threshold of $5 million. The lower boiler efficiency of 65% was used because the proposed geothermal system was small enough to count toward replacing the older Kewanee boilers without replacing some of the newer Hurst boilers.

Table E1.1: Key Model Parameters

Parameter	Value	Units
Geothermal Budget	1.32	Million USD
Model	Small Scale	
Price of Natural Gas	$ 0.53	$/100ft^3
Boiler Efficiency	65%	

From the college case studies, the average bore depth was 367 feet; a depth of 400 feet is recommended to reduce the number of bores, though geologic studies were not explored to confirm if this depth is feasible for Calvin's location. The number of bores needed for the 75 hp system was calculated using the average bore length needed per square foot, calculated from the other college case studies, and the 400 foot bore depth.

Feasibility

The above proposal is deemed feasible based on information from the other college case studies. Most notably, the feasibility of placing a 75 bore system in the area of Commons Lawn was confirmed by comparing with the 77 bore "Mini Bald Spot" bore field installed at Carleton College. Assuming the system at Carleton was properly designed and spaced, a suggested array of 75 bores can easily be fit in the main area of Commons Lawn using similar spacing as shown in Figures E1 and E2. Note that the figures are equal in scale.

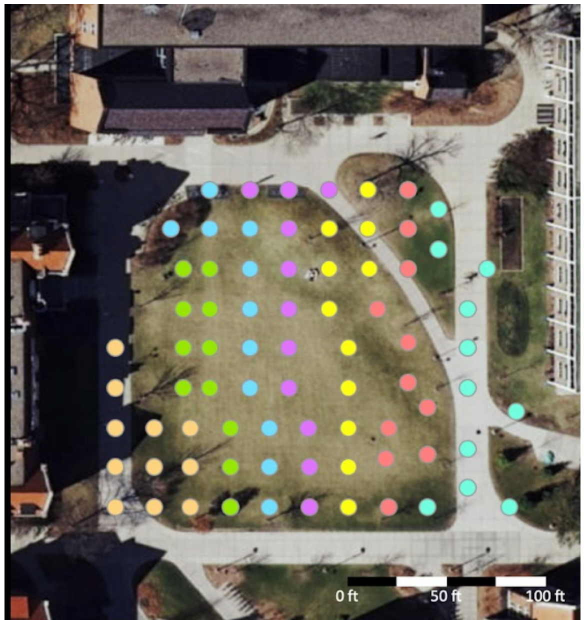

Figure E1: "Mini Bald Spot" Geothermal Field at Carleton College

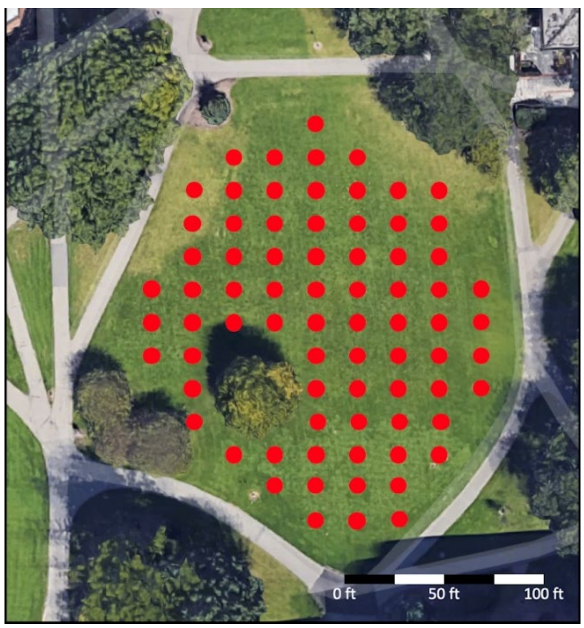

Figure E2: Proposed Geothermal Field on Calvin's Commons Lawn

Appendix F: Alternative Option B - Small Wind Turbines

Engineering 333B: Thermal Systems Design

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December 18, 2018

Proposal

The last option for spending the remaining money after maxing out solar panels at Calvin is to invest in smaller scale wind turbines. These turbines could be placed strategically around campus to be a power source for smaller electrical components like the street and walkway lights. Using smaller scale wind turbines with the remaining money would have less of space constraint due to the smaller overall size. This allows them to be placed almost anywhere on campus without requiring the cutting down of trees to make enough space or to allow for proper wind flow to the turbines. The zoning laws would also not be as big of an issue due to the wind turbines not being tall enough to even come close to the maximum allowable height limit.

Method

Using the wind speed data collected from the Bunker Center, it was determined that a small wind turbine could power the street lights and walkway lights throughout Calvin's campus. The small wind 1.5 kW wind turbines would have to be placed on top of each lamp post, as one turbine would not have the capability of producing the power for all street lights and walkway lights. Each individual light post would have to have its own wind turbine attached to it. These small turbines cost $1,500 each and would pay themselves back in nearly 19 years.

Feasibility

This alternative is somewhat infeasible since the street lights and walkway lights would need to be reinforced. This reinforcement is required because the wind turbines added additional bending loads to the posts. These small wind turbines could be added to roofs around campus. However, considering this system is an alternative option to be implemented in addition to the solar system as stated in Appendix A above, most of the roof top space capable of supporting such many small wind turbines, would be used already. Therefore, addition of even small wind turbines will not prove to be a worthwhile investment.

Appendix G: Alternative Option C – Carbon Credits

Engineering 333B: Thermal Systems Design

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December 18, 2018

Proposal

Finally, Alternative C is to spend the remaining budget on carbon credits. The money spent on carbon credits is used for projects that would reduce the emissions in other areas of the world. Some of the example projects would be constructing a geothermal power plant in Turkey or starting a wind farm in India. Carbon credits cost roughly $10 USD to offset one ton of carbon emissions. With the remaining budget, Calvin would be able to offset their annual emissions for roughly five years if the price remains $10 per ton. As long as the United States doesn't have a carbon tax, this option sees no financial return, unlike solar panels, which have a financial return and also help reduce carbon emissions.

Appendix G1: Carbon Credit References

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