Natural Gas CO_2 Emissions Reduction Project

Fall 2022

ENGR 333B

Calvin University

Professor Heun

Abstract

Sustainability is a multi-faceted grand challenge. One of today's largest challenges is related to sustainability: CO_2 emissions from energy consumption. Calvin University purchases natural gas for the energy services it provides; however, it is a major contributor to the amount of CO_2 emitted into the atmosphere. The ENGR 333 section B class was tasked with the question: *What would it take to eliminate Calvin's natural gas-related net CO_2 emissions?* After many hours of research and calculations, the ENGR 333 section B class answered this question with recommendations such as implementing ground source heat pumps, console heat pumps, air source heat pumps, efficiency measures, and a biodigester in concordance with Consumers Energy's pledge of carbon neutral electricity by 2040.

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Introduction

President Boer and Professor Heun tasked the mechanical engineering class of 2023 with answering the following question: *What would it take to eliminate Calvin's natural gas-related CO_2 emissions?* A strong note to this question was that it asked: *What would it take?* and not *What is the cheapest option?* To answer this question, heating solutions that utilized energy sources other than natural gas were needed.

Methods

The ENGR 333 section B class was split into five main teams to find necessary information and study relevant solutions towards achieving carbon neutrality.

A. The Ground-Source and Console Heat Pumps Team researched these heat pumps and how they pair with electricity.
B. The Air Source Heat Pumps Team researched these heat pumps and how they pair with electricity.
C. The Renewable Natural Gas Team researched implementations of both purchasing and producing RNG for Calvin's consumption.
D. The Energy Markets Team researched future changes that could affect the timing and strategy for solution implementation.
E. The Energy Efficiency Team researched different building improvements to reduce Calvin's demand for heating.

Throughout the project, two supplementary teams were created to find additional information to encapsulate the full scope of the project.

F. The Building and Heating Loads Team researched and calculated the maximum and yearly heating loads for Calvin's buildings.
G. The New Building Additions Team researched the imbedded carbon costs of Calvin's future building projects.

Results

The proposed solution for Calvin's heating related carbon neutrality can be found below in Figure 1.

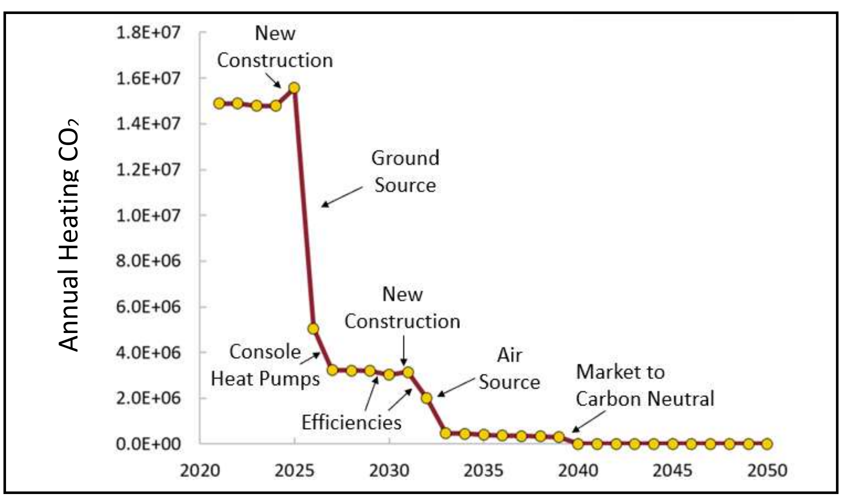

Figure 1. Annual Heating CO_2 Emissions Showing Carbon Neutrality by 2040.

While minimizing cost was not the driving goal of this project, total costs—including both operating costs and capital costs—were calculated to determine the economic investment necessary for the completion of the goal. The graph below (Figure 2) displays the cost of the proposed solution with new heating systems as well as Calvin's current trend based on projected natural gas prices. Assuming the middle *Business as Usual* projection (yellow line), the proposed solution will breakeven in 2067.

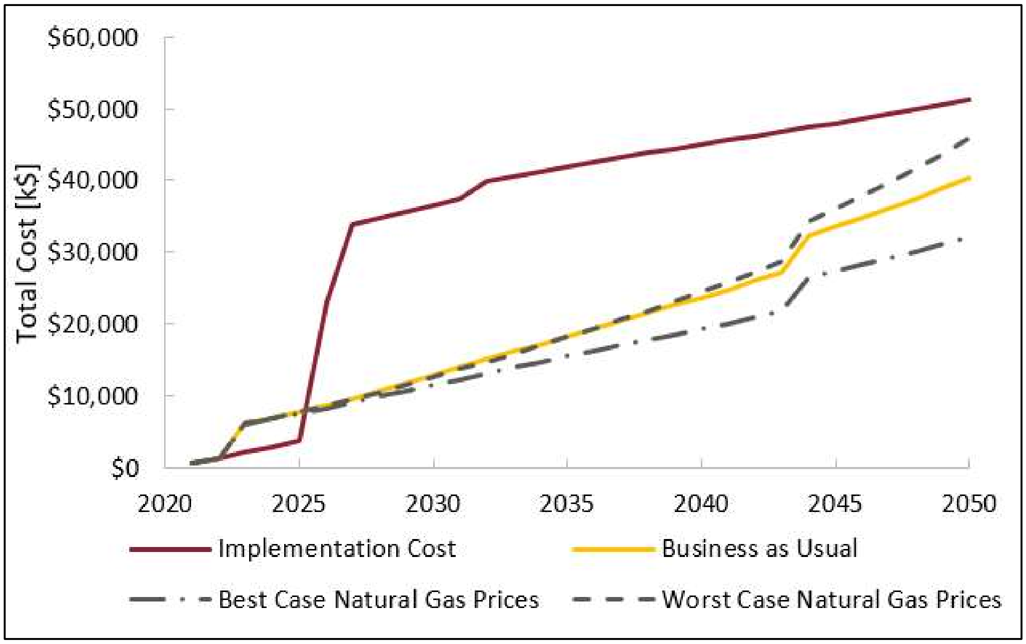

Figure 2. Total Costs Comparing the Proposed Solution with Business as Usual.

Refer to Appendix H for further graphs displaying the overall recommendation plan for Calvin to achieve heating-related carbon neutrality.

Conclusion

Through full analysis across all teams from the ENGR 333 section B class, Calvin can become carbon neutral by converting its heating systems to ground source heat pumps (GSHP), console heat pumps (CHP), and air source heat pumps (ASHP). Because of this, by purchasing carbon free electricity from Consumers Energy, Calvin's heating will be carbon neutral by 2040. A biodigester will be incorporated with the future Commons Union plan to generate renewable natural gas (RNG) from the dining hall's bio-waste. In addition to these heat pumps and biodigester, different building efficiency measures will be implemented to reduce the necessary heating load, further lowering cost and carbon emissions.

Appendices

Appendix A – Ground Source & Console Heat Pumps

Introduction

The purpose of the Ground Source Heat Pump team was to determine what ground source heat pumps (GSHP) were, how they could be implemented into Calvin's campus and the impact they would have on Calvin's finances and carbon emissions. As the project developed the Ground Source team began to explore console heat pumps (CHP) to be implemented as a similar system to GSHP in the dorms. This team consisted of Nicholas Paternoster, Nick Grossman, Jared Ruba, Zac Runhaar, and Caleb Styf.

Methods

A ground source heat pump is a type of heating and cooling system that exchanges energy with the earth, using loops of pipes that pump a working fluid underground to be heated or cooled by the constant underground temperature. This working fluid, usually water, is then pumped to a central heat pump above ground and used to heat or cool the buildings. A similar system of working fluid loops can also be used to power console heat pumps, in which the working fluid is pumped directly to smaller local heat pumps to heat areas.

The working fluid loops can be oriented vertically or horizontally, shown in Appendix A1, Figures A1.1 and A1.2, respectively. Horizontal loops are generally cheaper, as they do not require expensive boring, but they also require more disruption of the surface soil. If a ground water or deep-water source is available, that can also be tapped directly as the working fluid in an "open loop" where the working fluid is not recirculated, instead it is taken from and then reinjected into the ground.

As proof of concept, research was done on similar systems implemented at educational institutions across the country. Ball State University, in Indiana, installed a $83 million system that handles 100% of the heating a cooling for their 7 million square feet and approximately 15,000 undergraduate students. This system saves Ball State $2.3 million a year. John Stockton University in New Jersey installed a $5.1 million system that handles about 0.5 million square feet and paid itself off in 6 years.

Calvin currently has two primary heating loops on campus, the main heating loop which includes most academic buildings and accounts for approximately 76% of Calvin's heating load, as well as the upper heating loop which is made up of dormitories. The main distinction between these two loops is that the main loop utilizes liquid water to distribute energy, while the upper loop uses steam to distribute energy.

Since the main heating loop is comprised of water heat, it is proposed that the boilers be replaced at their respective locations feeding the main loop and replaced with GSHP systems. These pumps will be located at the Commons Union Building and the Engineering Building. They will be fed from bore fields underneath parking lots 9 and 10, and parking lots 1 through 5, respectively. A map of this is shown in Appendix A1, Figure A1.3.

Since the upper loop is currently a steam loop, to avoid reconfiguring the loop for hot water, it is proposed that a console heat pump system be implemented in the upper loop, which is comprised of the dormitories. This will allow for more localized heating of the dorms without the added cost of looping them together. This will be fed by a bore field located under parking lot 8, and a field located under the former Knollcrest Dining Hall. CHP locations and bore fields are shown in Appendix A1, Figure A1.4.

The fields were sized using the same method for both GSHP and CHP. First the energy demands of the loop or area being served were determined by the building loads teams. That information was then used in conjunction with information from GMB Architecture about energy typically available per borehole, the typical depths of the boreholes, and the spacing of the boreholes to determine the number of boreholes needed, and the area they would occupy.

Results

Ground source heat pumps should be used to cover the main heating loop, which is approximately 76% of Calvin's heating load. Console heat pumps should be used to cover the remaining dorms, approximately 16% of Calvin's heating load. These two implementations alone would reduce Calvin's CO_2 emissions by 13.9 million kg of CO_2 per year. The cost and space required to implement these systems can be seen below in Table A1, and full calculations can be found in Appendix A2.

Table A1. Cost and Space Required to Implement Systems.

Variable	Ground Source Heat Pumps	Console Heat Pumps
Cost of System [$]	18,500,000	9,000,000
Space Required [ft^2]	225,000	35,000
Number of Boreholes	1100	175

The total cost shown in Table A1 includes the cost of the bore fields, installation, the heat pumps, and the parking lots. These are the initial capital costs required to implement this system, and due to the low maintenance nature of the system. There is not much maintenance that needs to be performed regularly, other than a complete system inspection every five years. This results in a projected maintenance cost of $50,000 every five years provided that the heat pumps last for their typical lifespan. Since these systems are electrically powered, all the carbon produced by this system is through the construction process and any carbon being produced due to electrical power production. The construction of each system, as the boring machines are very carbon intensive, will be 5,600,000 kg of CO_2 for the GSHP—per year of construction—while the carbon emitted from the CHP will be 2,400,000 kg of CO_2 per year of construction due to the smaller scale of the project. These are to be implemented by 2027 to coincide with the building of the Commons Union and the destruction of Knollcrest Dining Hall. This was done for GSHP to save on repair costs and for CHP to allow the Knollcrest steam (upper) loop to be removed at the same time as the Knollcrest Dining Hall building.

Conclusion

Through the research performed this semester, it was found that a vertical loop ground source heat pump would be capable of supplying all the heating and cooling needs for the main campus loop. Utilizing a separate vertical bore field system, console heat pumps would be able to be implemented for the dorms. This result was found through a cross analysis of existing ground source heat pumps systems implemented at other universities, information from meetings with GMB, and a heating load analysis of Calvin. Through this work and analysis, the final result of the 13.9 million kg of CO_2 per year carbon emission reduction was able to be calculated.

Appendix A1 – Ground Source Heat Pump Figures

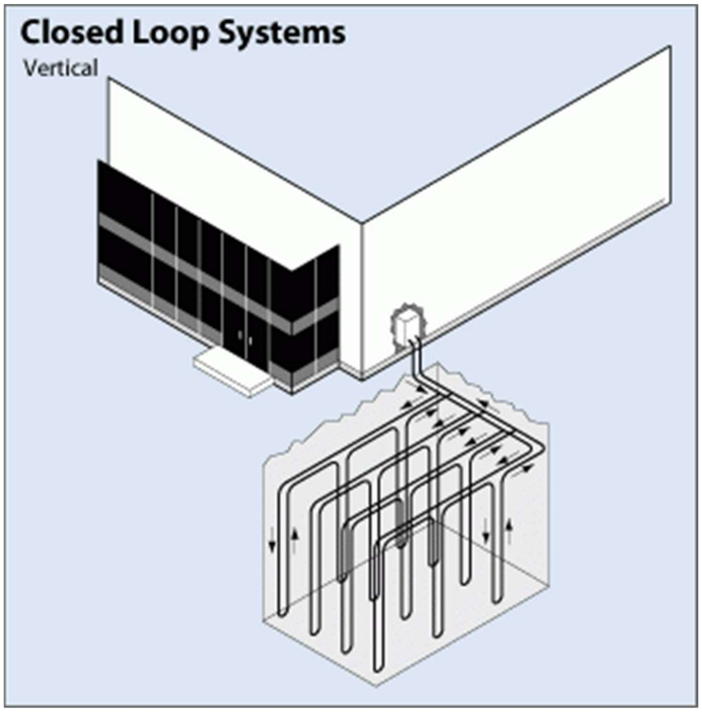

Figure A1.1. Vertical Loop System.

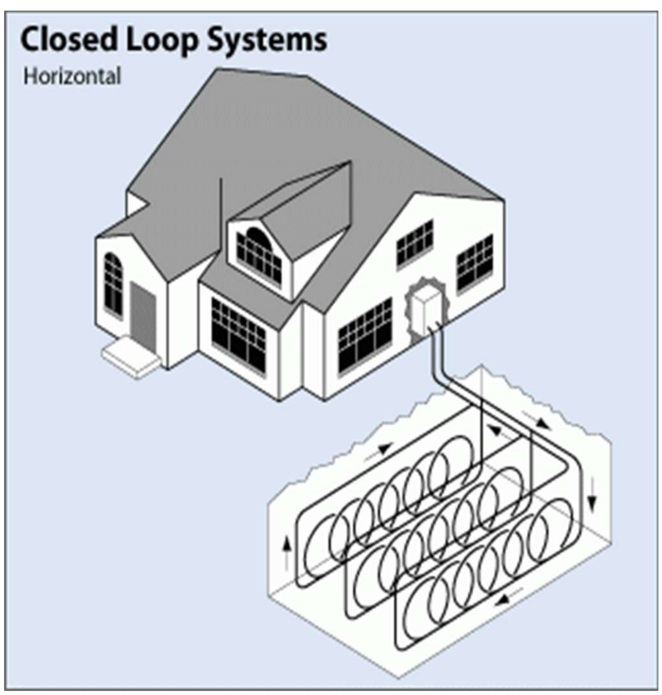

Figure A1.2. Horizontal Loop System.

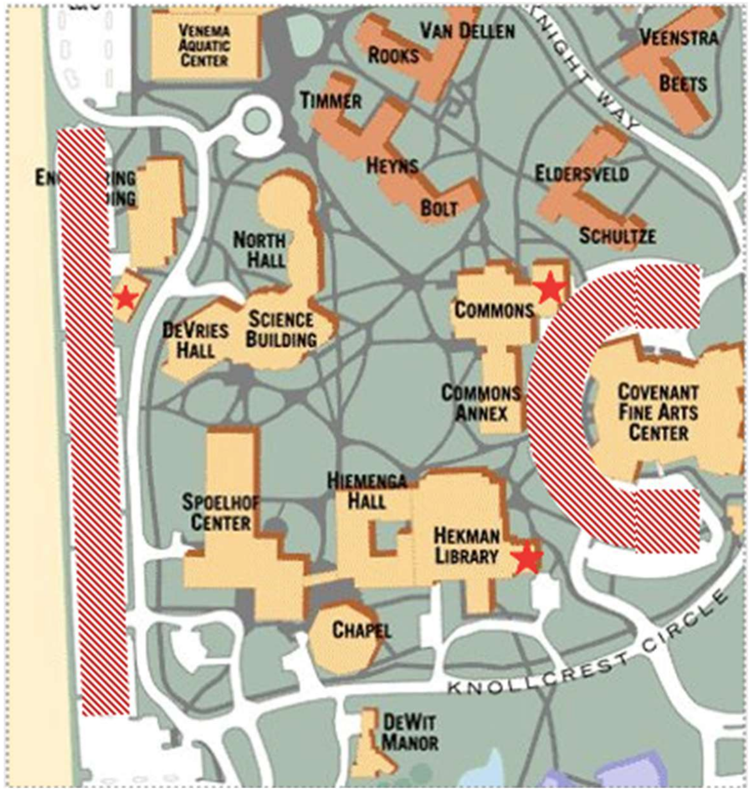

Figure A1.3. Map of Proposed GSHP Locations (Stars) and Bore Fields (Stripes).

The star on Hekman Library in the figure above denotes a pumping station, not a GSHP.

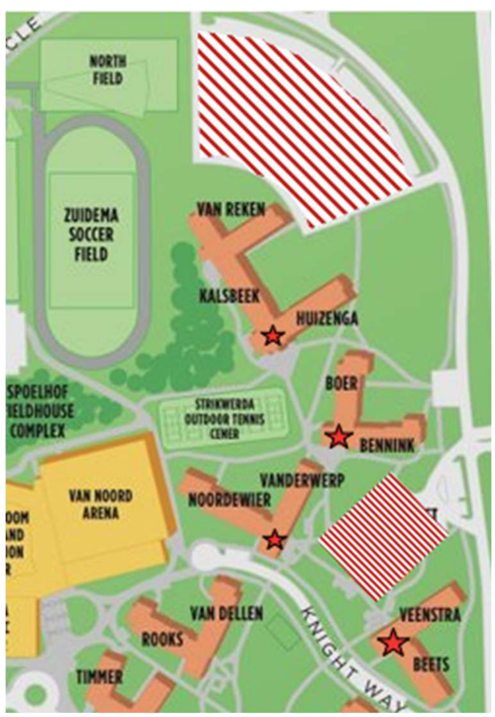

Figure A1.4. Map of Proposed CHP Locations (Stars) and Bore Fields (Stripes).

Appendix A2 – Ground Source Heat Pump Tables

Table A2.1. GSHP Middle Case Cost Calculations.

Middle Case Parameters	Values
Heating Load	30329752.19 Btu
Heating Load	2527 tons
Cost per Foot	$25
Bore Depth	400 feet
Tons per Hole	2.3 tons
Holes Needed	1106 holes
Safety Factor	1.2
Area Needed	221,113 ft^2
Cost	$11,055,625
Cost Safety Factor	$13,266,750
Parking Lot Costs	$1,700,000
Heat Pump Cost	$2,500,000
Total Cost	$18,306,750

Table A2.1 shows the middle case cost calculation for the GSHP. The middle case involved a 400 foot bore hole depth and 175 feet of boring per ton of heat required. This was sized for the maximum heating load required in a day. The final GSHP cost, incorporating bore costs, parking lot destruction and construction, and the cost of the actual heat pumps resulted in a total cost of $18.3 million.

Table A2.2. GSHP Middle Case Cost Calculations.

Middle Case	Values
Piping Footage	22911.25 ft
Heating Load	4,790,000 Btu
Heating Load	399 tons
Cost/ft	$25
Bore Depth	400 ft
Tons per Hole	2.3
Holes Needed	175 holes
Safety Factor	1.2
Area Needed	34,927 ft^2
Cost	$1,746,354
Cost Safety Factor	$2,095,625
KHVR Dorm Building	140 dorms
BB Dorm Building	120 dorms
BV Dorm Building	120 dorms
NVW Dorm Building	120 dorms
Total dorms	500 dorms
Cost of a Console Unit	$1,500
Cost of the Consoles	$750,000
Total Cost of the System	**$2,845,625**
Building Retrofit Cost per Square Foot	$50
Square Feet per Room	200 ft^2
Space Multiplication Factor	1.2
Square Feet per Room + Factor	240
Total Heating Area	120,000 ft^2
Total Cost of Square Footage Heating	**$6,000,000**
Complete Total Cost	**$8,845,625**

Table A2.2 shows the middle case cost calculation for the CHP. The middle case involved a 400 foot bore hole depth and 175 feet of boring per ton of heat required. This was sized for the maximum heating load required in a day. The final CHP cost, incorporating bore costs, parking lot destruction and construction, dorm renovation, and the cost of the actual consoles resulted in a total cost of $8.8 million.

Appendix B – Air-Source Heat Pumps

Introduction

The purpose of this appendix is to explain the air source heat pump (ASHP) implementation proposal. These systems pump energy in the form of heat from the outside air into buildings, as is depicted in Figure B1.1. This team was tasked with proposing a heating solution that would eliminate carbon emissions due to heating in the Knollcrest East apartments, the Mail and Print building, and other facility and residential buildings outside of the main and upper heating loops on campus. The team aimed to solve this issue by implementing ASHPs in these areas (proposed locations are shown for some buildings in Figures 1.2-1.4 in Appendix B1), and the following report details the team's proposal for ASHP use at Calvin University. This team consisted of Anne Ghata, Micah Lee, and Thomas Noble.

Methods

Heat pump selection was an initial area of focus for the Air Source Heat Pump team. Various brands such as American Standard, Trane, LG, and Goodman were explored for their ASHPs during the research phase for the project. After investigating these companies, the group decided to source their ASHPs from Goodman due to the quality of the units provided by the company and the highly intricate data available in their catalogs for heat supply, power consumption, and overall heat pump efficiency depending on outdoor ambient temperature. These catalogs can be accessed through the link in Appendix B3, and the compared efficiencies can be seen in Table B2.1 in Appendix B2. Specific ASHP models from the Goodman catalog were chosen based on their overall efficiency, with a few exceptions that were chosen based on their maximum heat supply to reduce quantity of heat pumps.

Heat supply and power consumption were also analyzed. After choosing the most feasible heat pump models, the annual heat supply and power consumption were calculated using the catalog information. Heat pump selection per building depended on the assumption of an annual worst-case temperature scenario of 5°F. The number of indoor and outdoor units per building can be seen in Table B2.2, and the full calculations can be accessed through the link in Appendix B2.

Financial costs for the air source heat pumps were investigated. The purchase costs for each component of the setup (indoor unit, outdoor unit, thermostat) were found based on estimates provided by a few of the dealers that were suggested on the Goodman website. Most dealers had the same prices or prices within a close range. The highest, most frequent price was used per model and unit for a safety factor. A table of the estimated costs of each ASHP model and its associated components is shown in Table B2.3 in Appendix B2. These costs were then multiplied by the number of units needed for each of them to find the total component costs.

This proposal includes duct installation for buildings without ducts, so an estimate for this cost was made based on average costs for duct installations in an already existing 2000 ft^2 house. Assuming an average duct installation cost of $15,000 per house, the total ducting cost per building was multiplied by the size ratio of the building to the 2000 ft^2 house. The total installation cost was then calculated by adding the component costs to these ducting costs with labor being about 20% of these costs.

The annual operating costs were calculated by multiplying the annual ASHP power consumption by the cost of carbon-free electricity. This could be compared with the annual operating costs of keeping Calvin's current heating system, which is approximately 13% of the total ($997,990) that goes to the supply areas of

ASHPs. Since ASHPs do not need much maintenance, the maintenance assumed was filter changes done once a year at a maximum cost of $90 per filter and with labor being 20% of the filter cost.

There are carbon emissions associated with air source heat pumps. CO_2 would exist in the ASHP installation process as either emissions or embedded carbon. The emissions would come from transportation and concrete mixing, and the embedded CO_2 would be in the concrete for mounting the ASHPs and in the ASHPs themselves. Transportation emissions were calculated as a product of an average freight truck emission of 0.16 kg per ton-mile, a maximum HVAC dealer distance of 20 miles from Calvin, and a total ASHP weight of 13.38 US tons. The emissions from mixing concrete with a concrete mixer on campus were calculated as a product of the emission rate of 23.91 kg per 18 m^3 of concrete mixed and poured, where each ASHP outdoor unit would occupy a 1 m × 1 m × 0.25 m slab of concrete on the ground. The embedded CO_2 in concrete was calculated by multiplying the mass of the volume of concrete to be used with the embedded factor of 0.13 kg of CO_2 per kg concrete. The same was done for the ASHPs, but with an assumed ASHP composition of 5% plastic, 10% aluminum, and 85% steel.

Results

The annual power consumption with the Goodman heat pumps added up to 1292 MWh with an annual heat supply of 11.95 million Btu. The total cost of the ASHP components was calculated to be $965,100, and the total cost for adding ductwork to the buildings that need it was calculated to be $861,465. The estimated installation labor cost would be $371,313, adding up to a $2,227,878 upfront ASHP installation cost. Heat pump replacement costs every 15 years would then exclude the ducting cost. Annual operation costs were found to be $258,421 as compared to $129,740 if Calvin keeps its current system. This is because more sustainable power options cost more. The annual maintenance cost for replacing the filters (with labor) was found to be $9,612. If Calvin decided to buy back up boilers for each outdoor ASHP unit, it would cost about $445,000 upfront.

The direct CO_2 emissions from installing ASHPs were calculated to be 43.31 kg CO_2 from transportation of the heat pumps to Calvin and 29.55 kg CO_2 from concrete mixing. This is very minimal in comparison to the tons of carbon emissions from Calvin's current system. Even the embodied carbon in the ASHPs and the concrete (65,978 kg CO_2 and 6942 kg CO_2, respectively), are less than 2.5% of the 2.85 million kg of CO_2 that ASHPs decrease Calvin's heating emissions by.

Conclusion

Although the implementation of this proposal would not be cheap, this report has demonstrated that carbon emissions on campus would see a significant decrease, and this would be a major step towards net zero carbon emissions due to heating at Calvin University. The goal was not to find the cheapest method of eliminating carbon emissions due to heating but simply what it would take to do so. This proposal in tandem with the GSHP proposal and the electricity supplier pledge for electricity generation to become renewable energy-based accomplishes this goal. As seen in the hero graph in Appendix H, the ASHP proposal is the final step to bringing Calvin's carbon emissions down to zero after GSHPs and CHPs and before Consumers Energy completely converts to renewable energy sources. The ASHP proposal is a vital component in the answer to what it would take to bring Calvin's carbon emissions due to heating down to zero.

Appendix B1 – Air Source Heat Pump Figures

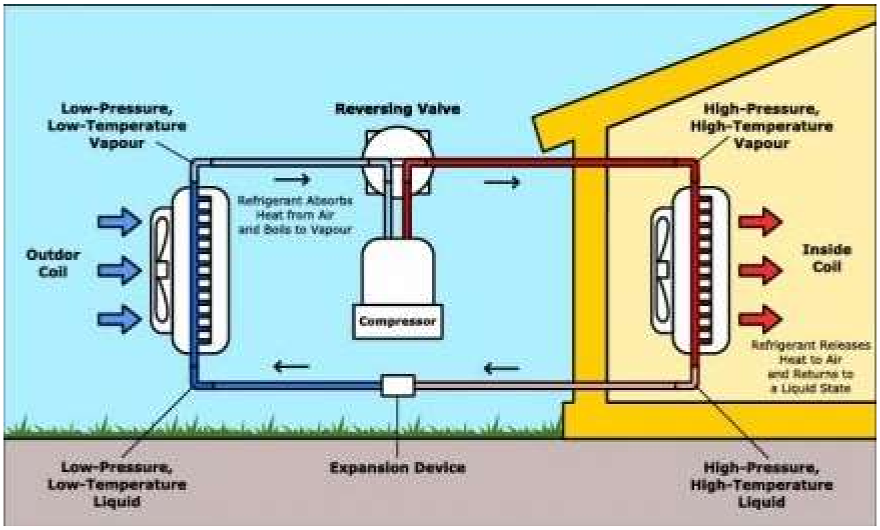

Figure B1.1. How an ASHP Works.

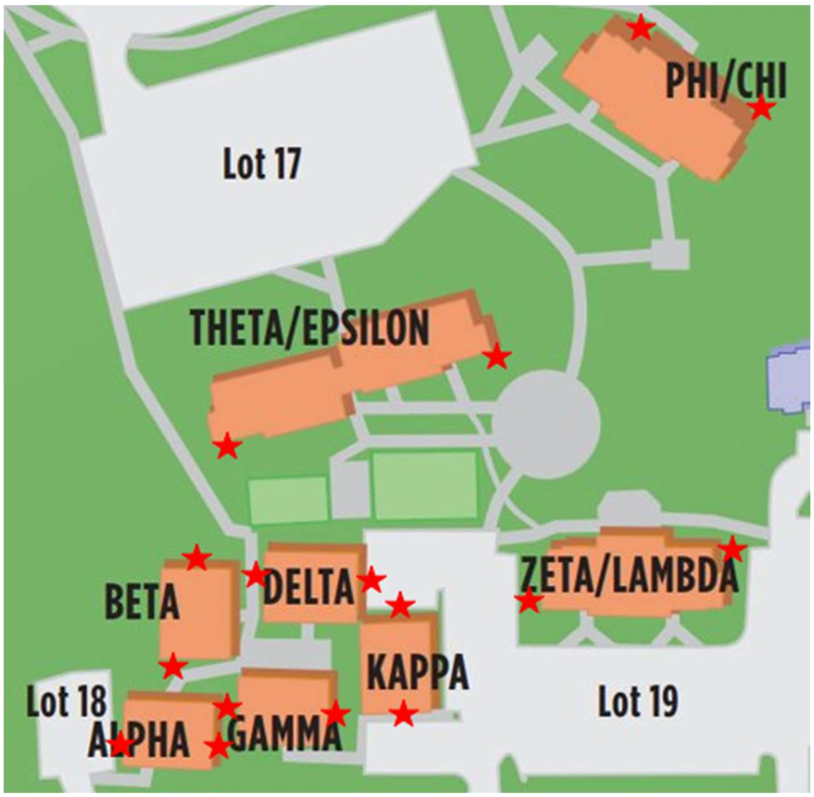

Figure B1.2. Proposed ASHP Locations for Knollcrest East Apartments.

Figure B1.3. Proposed ASHP Locations for DeWit Manor.

Figure B1.4. Proposed ASHP Locations for the Bunker Interpretive Center.

Appendix B2 – Air Source Heat Pump Excel Calculations and Tables

Table B2.1. Goodman ASHP Model Decision Matrix.

Pump Models	Stages	Power Consumption [kW]	Heat Supply [Btuh]	# Of Heat Pumps	Total Power Consumed [MW]	Total Heat Supply [Btu]	Efficiency [Btu/ MWh]
KE Courtyard Apartments [at 5 F] [Only Looking at High Stage if 2 Stage] [Max Heat Required is 32,900 Btuh]							
GSZC16							
GSZC160241C	2	1.47	10,230.00	3	0.00441	30,690.00	6,959,183.67
GSZC160361C	2	2.18	16,640.00	2	0.00436	33,280.00	7,633,027.52
GSZC160481C	2	3.78	21,520.00	2	0.00756	43,040.00	5,693,121.69
GSZC160601C	2	4.28	24,640.00	2	0.00856	49,280.00	5,757,009.35
GSCZ18							
GSZC180241C	2	1.76	11,520.00	3	0.00528	34,560.00	6,545,454.55
GSZC180361C	2	2.33	17,640.00	2	0.00466	35,280.00	7,570,815.45
GSZC180481C	2	2.57	15,720.00	2	0.00514	31,440.00	6,116,731.52
GSZC180601C	2	4.23	24,640.00	2	0.00846	49,280.00	5,825,059.10
GVZC20							
GVZC200241A	1	1.6	11,400.00	3	0.0048	34,200.00	7,125,000.00
GVZC200361A	1	3.48	22,100.00	2	0.00696	44,200.00	6,350,574.71
GVZC200481A	1	3.99	26,000.00	2	0.00798	52,000.00	6,516,290.73
GVZC200601A	1	4.29	28,300.00	2	0.00858	56,600.00	6,596,736.60

Table B2.2. Goodman ASHP Model and Component Quantity per Building.

Buildings	Heat Pump Model	Air Handler Model	Heat Pump Quantity	Air Handler Quantity
KE Apartments				
Courtyard	**GSZC160361C**	CA*F3743*6D* + MBVC1600	10	55
Phi-Chi	**GVZC200601A**	CA*F4961*6D* + MBVC2000	6	24
Theta-Epsilon	**GVZC200601A**	CA*F4961*6D* + MBVC2000	9	32
Zeta-Lambda	**GVZC200601A**	CA*F4961*6D* + MBVC2000	6	20
On-Campus Houses				
DeWit Manor	**GVZC200601A**	CA*F4961*6D* + MBVC2000	6	8
JM Perkins Leadership House	**GVZC200601A**	CA*F4961*6D* + MBVC2000	1	6
Rho-Tau	**GVZC200601A**	CA*F4961*6D* + MBVC2000	4	8
Off-Campus Houses				
Flat Iron Lake House	**GSZC160481C**	CA*F4961*6D* + MBVC2000	2	2
Koinonia House	**GSZC160361C**	CA*F3743*6D* + MBVC1600	1	2
Travis House	**GSZC160361C**	CA*F3743*6D* + MBVC1600	2	2
Garden House	**GSZC160361C**	CA*F3743*6D* + MBVC1600	4	4
Cooper House	**GSZC160481C**	CA*F4961*6D* + MBVC2000	2	2
Bunker House	**GSZC160361C**	CA*F3743*6D* + MBVC1600	3	3
Tongue House	**GSZC160361C**	CA*F3743*6D* + MBVC1600	3	3
Service Buildings				
Ecosystem Preserve Greenhouse	**GSZC180361C**	CA*F3743*6D* + MBVC1600	2	2
Ecosystem Preserve Interpretive Center	**GSZC160481C**	CA*F4961*6D* + MBVC2000	2	2
Ecosystem Preserve Study Center	**GVZC200601A**	CA*F4961*6D* + MBVC2000	3	3
Mail and Print Services	**GVZC200601A**	CA*F4961*6D* + MBVC2000	5	5
Service Buildings	**GVZC200601A**	CA*F4961*6D* + MBVC2000	9	9
Recycling Building	**GVZC200601A**	CA*F4961*6D* + MBVC2000	2	2
Surge Building	**GSZC180361C**	CA*F3743*6D* + MBVC1600	6	6

Table B2.3. Costs of Each Goodman ASHP Component.

Model	Outdoor Unit	Indoor Unit	Thermostat
GSZC160361C	$3,300	$1,500	$200
GSZC160481C	$3,900	$1,800	$200
GSZC180361C	$3,800	$1,500	$200
GVZC200601A	$9,000	$1,900	$200

Appendix B3 – Air Source Heat Pump Sources

"2022 Ductwork Cost: Cost to Install or Replace Air Ducts." *Fixr.com*, 17 Jan. 2022, https://www.fixr.com/costs/ductwork.

"Air-Source Heat Pumps." *Energy.gov*, https://www.energy.gov/energysaver/air-source-heat-pumps.

Embodied Energy and Carbon Coefficients (Selected Materials). https://www.researchgate.net/figure/Embodied-Energy-And-Carbon-Coefficients-Selected-Materials_tbl1_310022790.

"Green Freight Math: How to Calculate Emissions for a Truck Move." *EDF+Business*, 6 Apr. 2021, https://business.edf.org/insights/green-freight-math-how-to-calculate-emissions-for-a-truck-move/.

"Home." *Civil Engineering*, https://civiltoday.com/civil-engineering-materials/concrete/361-density-of-concrete.

Literature Library | Product Specification | Goodman. https://www.goodmanmfg.com/support/literature-library.

Sullivan, Aaron. "What Percentage of Construction Costs Is Labor? Pricing Your Bids Correctly." *Botkeeper*, Botkeeper, 23 Aug. 2021, https://www.botkeeper.com/blog/construction-labor-cost-percent.

ZhiDong (Tony) Li California State University, et al. "Carbon Dioxide Emission Evaluation in Construction Operations Using DES: Proceedings of the 2017 Winter Simulation Conference." *ACM Conferences*, 1 Dec. 2017, https://dl.acm.org/doi/pdf/10.5555/3242181.3242383.

Appendix C – Renewable Natural Gas

Introduction

The goal of the renewable natural gas team (RNG) was to investigate the feasibility of replacing natural gas used for heating with RNG. Unfortunately, that was not a feasible solution and Calvin does not produce enough waste to accommodate the heating load with just RNG. It is important to note that after some extensive research and partnering with a local wastewater plant, it was determined that burning RNG releases less CO_2 than natural gas, but it still results in CO_2 emissions. Therefore, burning RNG would not be a feasible solution as it would contribute to Calvin's net CO_2 rather than eliminating it.

These efforts would not be turned down yet because as more professionals were consulted and more research was done, a HomeBioGas Commercial System seemed to be the solution for the waste produced by the dining halls. This RNG team consisted of Liam Austin, Kai Barboza, and Mark Bekhet.

Methods

The first step taken was to find out the global warming impact of burning RNG. The major factor in RNG consumption is that the methane emitted from RNG sources escapes into the atmosphere if not converted to biogas and burned, converting it to CO_2. The EPA has created a statistic called *100 Year Global Warming Potential* per kilogram (100 GWP), which assigns a numerical value to a greenhouse gas reflecting its global warming effect and lifetime in the atmosphere. CO_2 was assigned a baseline value of one. Methane has been given a score of 27 to 30 by the EPA—so a value of 28 was used for calculations. This meant that methane was 28 times more harmful to the atmosphere than CO_2. Knowing this, converting methane to CO_2 would diminish the effect on the climate. For every 16 kilograms of methane burned, 44 kilograms of CO_2 would form. This is a factor of 2.75, meaning burning methane and thus converting it to CO_2 is 2.75 times better for the environment than allowing the methane to naturally escape into the atmosphere. Applying this to the 100 GWP, methane's 100 GWP drops from 28 to 10.18. This displays that using RNG is an effective means of reducing carbon emissions when considering that the methane from RNG sources would escape to the atmosphere naturally.

By partnering with the markets team, it was determined that if RNG was purchased, the estimated price would be about 40% more than purchasing conventional natural gas. Importing enough RNG to meet Calvin's heating needs would cost roughly $5.85 million over five years from 2023 to 2037. Using RNG for all of Calvin's heating needs proved not to be the best option present, thus the option was not explored further.

Using wastewater to power an anaerobic digester was initially investigated, but it was found to be ineffective. Using a study produced by Washington's Department of Health, averages for the flow rate of sewage were calculated for the number of people using that facility each day. This can be found in Appendix C1 in Table C1.1. From these values, the EPA estimates on the amount of RNG that could be produced, and an assumption that the growth of RNG of facilities was linear, an estimate on the amount of heating that could be provided by wastewater per month was found. This value was 9.5 DTh. This number was inconsistent with even the least heating required in the month of July, which was 5,867 DTh. Therefore, investigations into other solutions were pursued.

Results

Another idea explored in the dining halls was to convert the kitchen to operate on electricity 100% rather than any natural gas. That was not a feasible solution for Calvin's size and commercial kitchen due to the demand for dining services provided by the number of students. Rather than eliminating natural gas, a better solution would be to substitute it with RNG and lower the volume of overall natural gas supplied to the kitchens. In addition, Calvin's food waste was a problem that needed to be accounted for in the proposed solution.

It was important to understand Calvin's food waste production. Based on a waste study audit done by the dining services on April 20th, 2022, it was estimated that annually, Calvin would have 300 kilo-lbs of food waste per 745 students. This did not factor in actual kitchen food waste such as bad meals or internal food waste; it was only food waste produced by students. In addition, dining services believed that the regular number should be closer to 1200 students which will yield 483 kilo-lbs of food waste per year. The information was collected with the assistance of Todd Kurtz, executive chef at Calvin University. In Appendix C2, Tables C2.1 and C2.2 provide a detailed breakdown of both cases.

The goal shifted from being able to heat most buildings with RNG to providing an alternative to current natural gas supplying to the kitchens for stoves and ovens, while still reducing the amount of CO_2 produced from throwing away compostable food waste. Therefore, an anaerobic digester was investigated. The investigations led to a company known as HomeBioGas, an Israeli-based company that expanded into the American and commercial markets. The system setup is described in detail under Appendix C4.

The focus was on their commercial system shown in Figure C3.1, which can be found in Appendix C3. This commercial system can produce up to 576 kWh of energy and receive up to 1,000 kg or 2,200 lbs of food waste input per day. The system would be odorless, approximately the size of two parking spots, and would be able to seamlessly be integrated into both current and future designs of Commons Dining Hall with minimal extensive construction. This is due to the existing garbage disposal and centralized gas piping in both the current and future designs of the dining hall. From this, the findings from Calvin's food waste audit could be applied to the biodigester. Based on the data provided, a study of both the economic life and embodied CO_2 of the system was investigated.

The cost of the system would be approximately $1.2 million. The money saved from using the biodigester over its lifetime of 24 years would be $2.1 million, and the payback period would be 11 years. This is shown in Figure C3.2 in Appendix C3, which provides a cost accounting of the system from start to end of life.

With the embodied cost determined, the embodied CO_2 was calculated. By using manufacturing CO_2 averages for the specific parts and components of the biodigester, carbon emission from transportation, and carbon output from installation, the implementation carbon cost of the system is found to be 845 kg of CO_2. The amount of CO_2 that would be emitted by the system would be the same amount of CO_2 emitted by the electrical grid to provide electricity to power the motors. The grid is set to shift to 50% renewable by 2030 and 100% carbon neutral by 2040. The amount of CO_2 that was removed by the system was found by calculating the difference in the amount of CO_2 from the methane of unutilized food waste to the total CO_2 emissions every year. It would save 2.8 million kg of CO_2 over the system's lifetime while being carbon neutral from year one. This is shown graphically in Figure C3.3 in Appendix C3.

Conclusion

The RNG solution for all of Calvin's heating loads was not feasible compared to other solutions proposed. However, biogas can still be used for Calvin's dining services and Commons use within a commercial kitchen. The proposed solution through HomeBioGas provides an alternative use to Calvin's current food waste. In addition, the system would be net positive in terms of CO_2 emissions in the first year of implementation. The biodigester pays for itself over the course of 11 years, and the system would have a savings of $2.1 million over the course of its lifetime of 24 years. This system would reduce both Calvin's carbon emissions and food waste, while also being a sensible economic solution.

Appendix C1 – Heat Produced by Wastewater

Table C1.1. Amount of Heat Produced by Wastewater.

	[Gallons per Person]	[People per Day]	[Gallons per Day]
Dining Hall (B)	7	400	2,800
Dining Hall (L)	7	1,500	10,500
Dining Hall (S)	7	900	6,300
Dorm	50	1,750	87,500
Hotel	45	20	900
Office	13	400	5,200
Apartment	60	300	18,000

Table C1.2. Total Amounts of Heat Produced.

Total [Gallons per Day]	131,200
Total [MMBtu per Day]	0.32
Total [MMBtu per Month]	9.45

Appendix C2 – Food Waste Audit Results

Table C2.1. Waste Audit for 745 Students.

745 Headcount	Waste [lbs/day]	Waste [lbs/year]
School (36 Weeks)	1,073	270,270
Summer (16 Weeks)	268	30,030
Total	1,341	300,300

Table C2.2. Waste Audit for 1,200 Students.

1200 Headcount	Waste [lbs/day]	Waste [lbs/year]
School (36 Weeks)	1,727	434,700
Summer (16 Weeks)	432	48,348
Total	2,158	483,048

Appendix C3 – HomeBioGas Commercial System

Figure C3.1. HomeBioGas Commercial System.

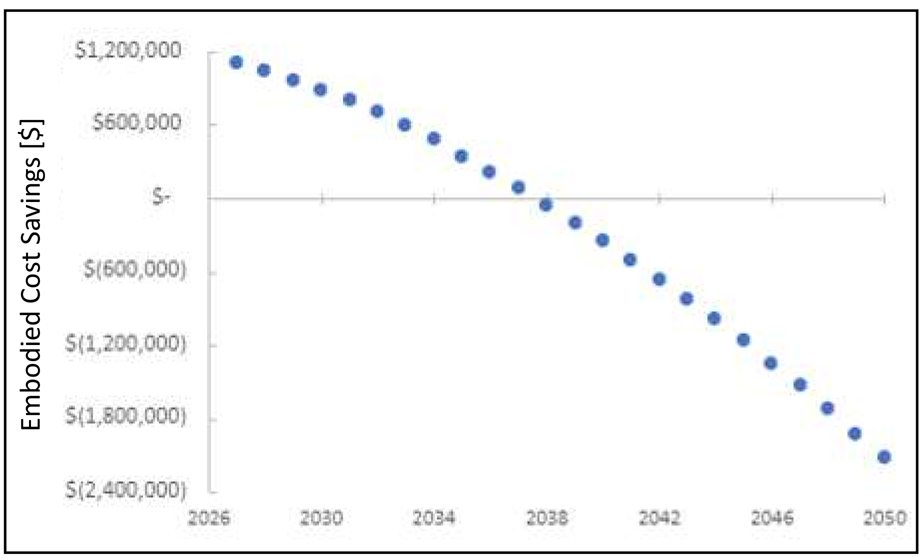

Figure C3.2. Embodied Cost Over Time For HomeBioGas System.

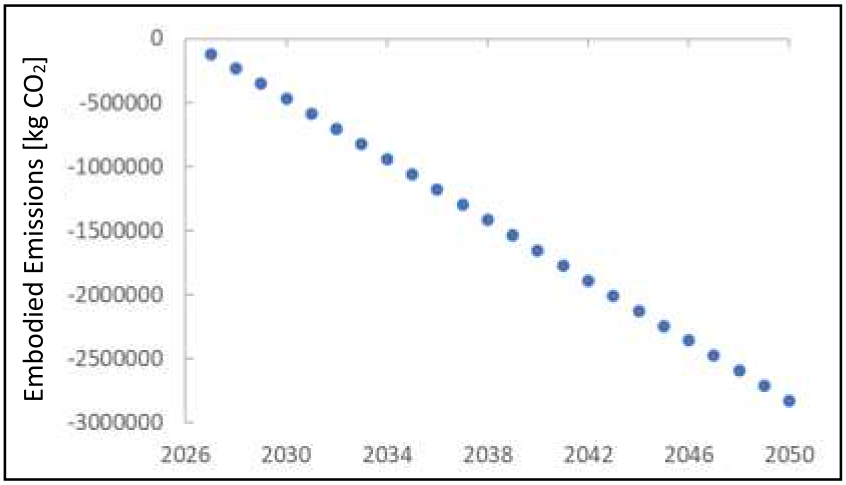

Figure C3.3. Embodied kg of CO_2 Over Time For HomeBioGas System.

Appendix C4 – HomeBioGas System Implementation

Regarding the HomeBioGas Commercial system, the plan would be to implement it with the existing plans for the Commons Union project in 2027. Figure C4.1 represents the location we found to be most suitable for the system. Placed outside commons near parking lot 9.

Figure C4.1. HomeBioGas Proposed Location.

The system's key components are a boiler, a gas filter, a gas outlet, a feeding tank, and an anaerobic biodigester, and the addition included in the system is a natural gas rectifier to supply the stoves. A breakdown is provided in Figure C4.2.

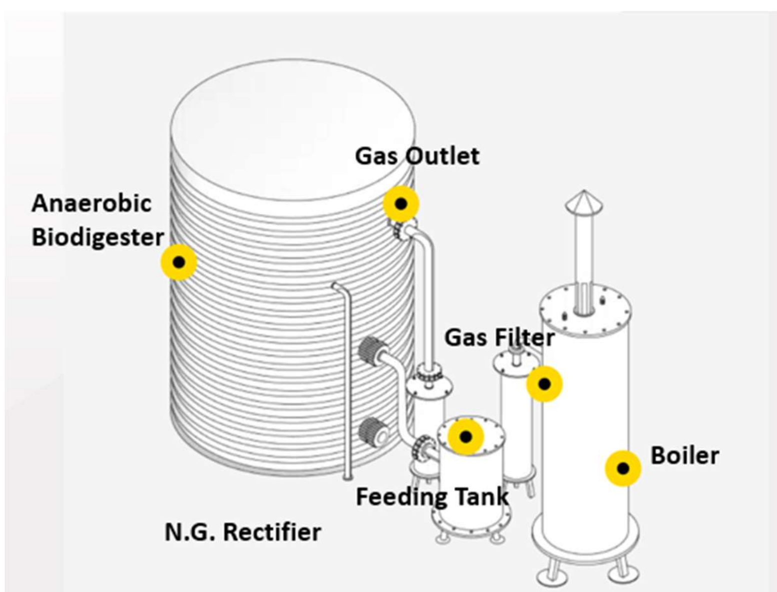

Figure C4.2. System Breakdown of Each Component.

In terms of operation as shown in Figure C4.3, the kitchen waste is fed into a grinding unit or garbage disposal that pumps directly into an anaerobic digestor. The waste is broken down into gas via an anaerobic process. The generated gas is then converted into hot water which is redirected to the kitchen for daily use or supplied directly to the stoves as gas for daily use. The main usage is to have it supplied directly to the stoves instead of hot water. Figure C4.4 provides a simple illustration of how the system will look installed.

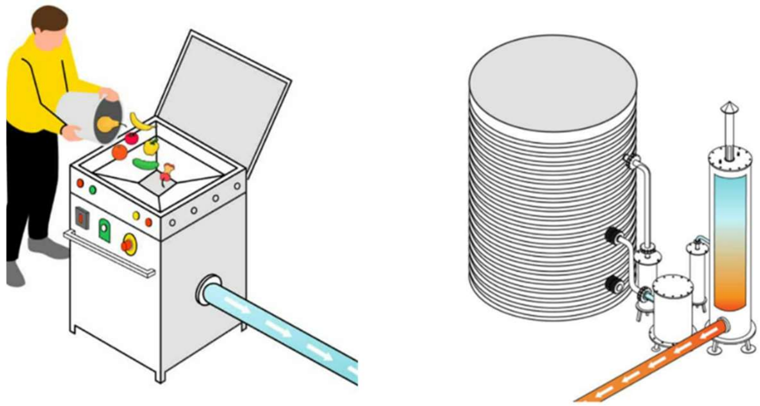

Figure C4.3. System Waste Illustration.

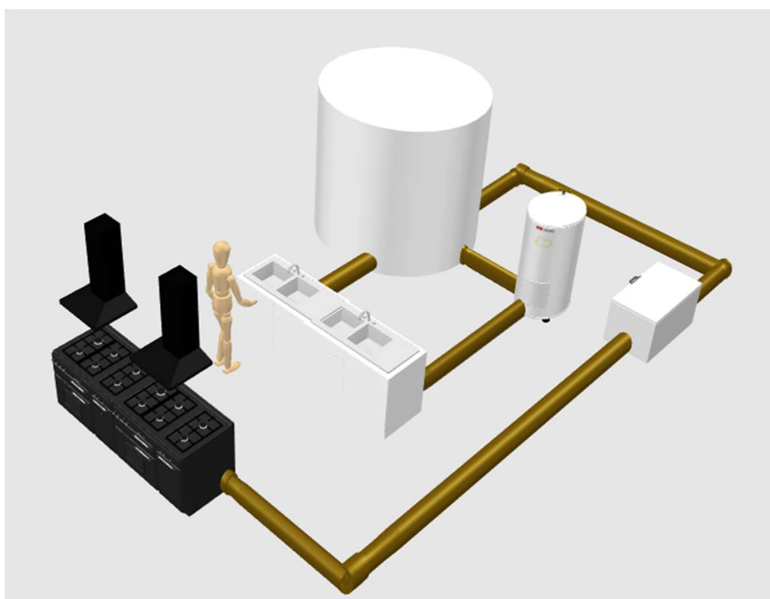

Figure C4.4. System Illustration in a Commercial Kitchen.

Appendix C5 – Renewable Natural Gas References

Authorship, Janis SkaldisClose, et al. "7 Things to Know about Renewable Natural Gas." *Greenbiz*, https://www.greenbiz.com/article/7-things-know-about-renewable-natural-gas.

Booth, DeJanay. "DTE Proposes Renewable Energy Investment, Emission Reductions." *CBS News*, CBS Interactive, 4 Nov. 2022, https://www.cbsnews.com/detroit/news/dte-proposes-michigan-made-renewable-energy-investment-emission-reductions/.

EPA, Environmental Protection Agency, https://www.epa.gov/ghgemissions/understanding-global-warming-potentials#:~:text=Methane%20(CH4)%20is%20estimated,less%20time%20than%20CO2.

"Household Biogas Digester System." *HomeBiogas*, 1 Dec. 2022, https://www.homebiogas.com/.

U.S. Environmental Protection Agency | US EPA. https://www.epa.gov/sites/default/files/2015-07/documents/opportunities_for_combined_heat_and_power_at_wastewater_treatment_facilities_market_analysis_and_lessons_from_the_field.pdf.

Washington State Department of Health Wastewater Management Program ... https://doh.wa.gov/sites/default/files/legacy/Documents/Pubs//337-103.pdf.

Appendix D – Energy Markets

Introduction

To accomplish the goal of eliminating Calvin's natural gas-related net CO_2 emissions, projected CO_2 emissions of natural gas and electricity—as well as the projected cost of natural gas and electricity—needed to be found. The goal of the Energy Markets team was to identify any effect that future markets would have on implementation and strategy for a zero-carbon heat system at Calvin. This team consisted of Jordan Tuter, Jacob Tanis, and Sara VanSolkema.

Methods

The first step to finding projected CO_2 emissions and future costs of both natural gas and electricity included extensive research on these energy sources. Several different sources were utilized and compared to ensure the best projections were created. Cites such as the Energy Information Administration (EIA) and Henry Hub proved to have good projections, and therefore served as the main sources for price projections. These sources are cited in Appendix D1.

Along with finding the projected costs and CO_2 emissions of natural gas and electricity, research was done on other clean energy sources that Calvin could implement. Different research was done on both solar panels and wind turbines. Calvin's new partnership with Sun FundED was looked into, and the effect it had on Calvin's carbon emissions was included in getting Calvin to net zero emissions for heating. Wind energy was also researched, and even though one wind turbine could produce Calvin with 4,000 MWh of electricity, implementation on Calvin's campus would not be easy. There are too many spatial rules and regulations that keep Calvin from implementing these anywhere on campus.

Results

For natural gas, the Henry Hub projections reflected the price of natural gas, but did not accurately portray the price that the customer pays. The cost that Calvin currently pays for natural gas was scaled according to the Henry Hub projections, and a more accurate natural gas cost projection was created. For electricity, the EIA and Consumers Energy gave cost projections up until 2050 as well. For further specifics on costs, reference Appendix D2. The amount of Btu of energy for every dollar spent was found for both natural gas and electricity, and this can be found in Figure D1 below.

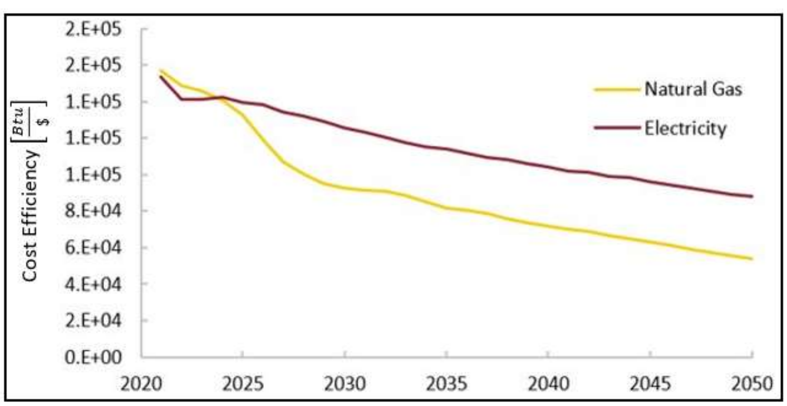

Figure D1. Projected Cost Efficiency of Natural Gas & Electricity.

As can be seen in Figure D1, for every dollar spent, more Btu come from electricity than from natural gas starting near 2025. This further indicates why switching from natural gas sourced heating techniques to electricity sourced heating techniques needs to be a part of Calvin's future.

Natural gas emits 14.8 $\frac{kg\ CO_2}{ccf}$, and this is a constant emissions rate. Electricity, however, is projected to be carbon neutral by 2040. This projection is a pledge by Consumers Energy, and it played a large role in solving Calvin's heating related CO_2 emissions. Refer to Appendix D3 for more information on this pledge.

The projected costs can be seen in the overall estimated cost of the project. This cost projection graph can be found in Figure D2 below.

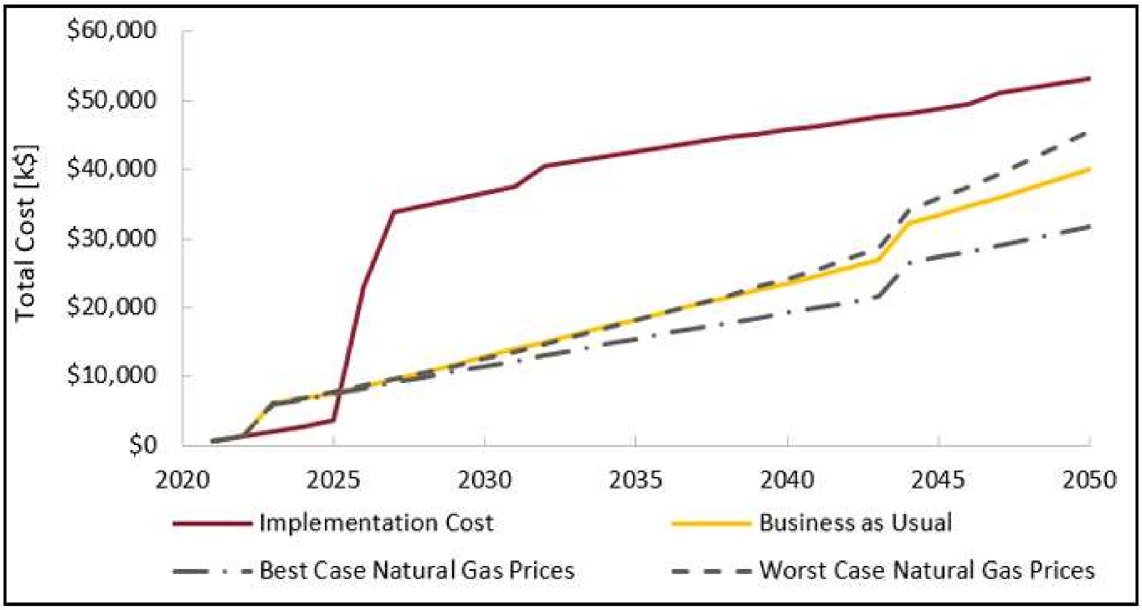

Figure D2. Projected Costs of Proposed Implementation Plan.

The yellow line on the graph portrays the expected cost of natural gas, and the dashed lines portray the possible best-case and worst-case scenarios for the cost of natural gas. If prices continue on the yellow business as usual line, the point where the current system will cross over with the recommended implementation plan for the new heating systems that run off electricity will be around 2060. The graph above proves that switching over to ground source heat pumps and air source heat pumps that run off electricity will not only reduce Calvin's heating related CO_2 emissions, but it will also make more financial sense because in the future, the cost of heating systems that run on natural gas will be more expensive.

Conclusion

In order for Calvin's heating-related CO_2 emissions to be zero, a switch from natural gas-based heating to electricity-based heating needs to occur. Through different cost projections, CO_2 emissions projections, and Consumers Energy's pledge to be completely carbon neutral by 2040, this is a feasible goal once ground source heat pumps, console heat pumps, and air source heat pumps are implemented on Calvin's campus.

Appendix D1 – References for Cost and CO_2 Emissions Projections

Clean Energy Plan. https://www.consumersenergy.com/-/media/CE/Documents/sustainability/integrated-resource-plan-summary.ashx?la=en&hash=9F602E19FE385367FA25C66B6779532142CBD374.

Going Net Zero - Consumers Energy. https://www.consumersenergy.com/-/media/CE/Documents/renewables/net-zero-faq.ashx?la=en&hash=DF9241FCF6ED6E7D874393533FF59800.

Henry Hub Natural Gas Spot Price (Dollars per Million Btu), https://www.eia.gov/dnav/ng/hist/rngwhhdm.htm.

"News Release." *News Release | Consumers Energy*, https://www.consumersenergy.com/news-releases/news-release-details/2020/02/24/16/03/consumers-energy-commits-to-net-zero-carbon-emissions-takes-stand-for-the-planet.

Retail Rate Projections for Long-Term Electricity System Models - NREL. https://www.nrel.gov/docs/fy22osti/78224.pdf.

"U.S. Energy Information Administration - EIA - Independent Statistics and Analysis." *Short-Term Energy Outlook - U.S. Energy Information Administration (EIA)*, https://www.eia.gov/outlooks/steo/report/electricity.php#:~:text=We%20forecast%20the%20U.S.%20residential,by%20higher%20natural%20gas%20prices.

Appendix D2 – Cost Projections for Natural Gas & Electricity

Figure D2.1 shows the estimated projected costs of natural gas, assuming Calvin does not make any changes to its current heating system. These cost projections were done in current dollars, and if the worst-case price scenario were to occur for natural gas, the price of could be closer to 2.90 $\frac{\$}{ccf}$.

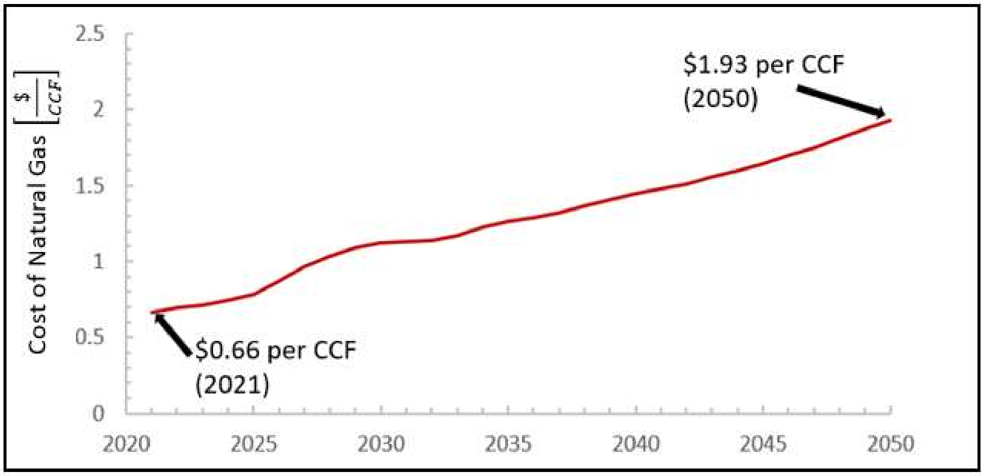

Figure D2.1. Projected Costs of Natural Gas up to 2050.

Figure D2.2 shows the estimated projected costs of electricity, which is important because electricity is the source for ground source, console, and air source heat pumps. This is the price that Consumers is estimated to charge for its electricity.

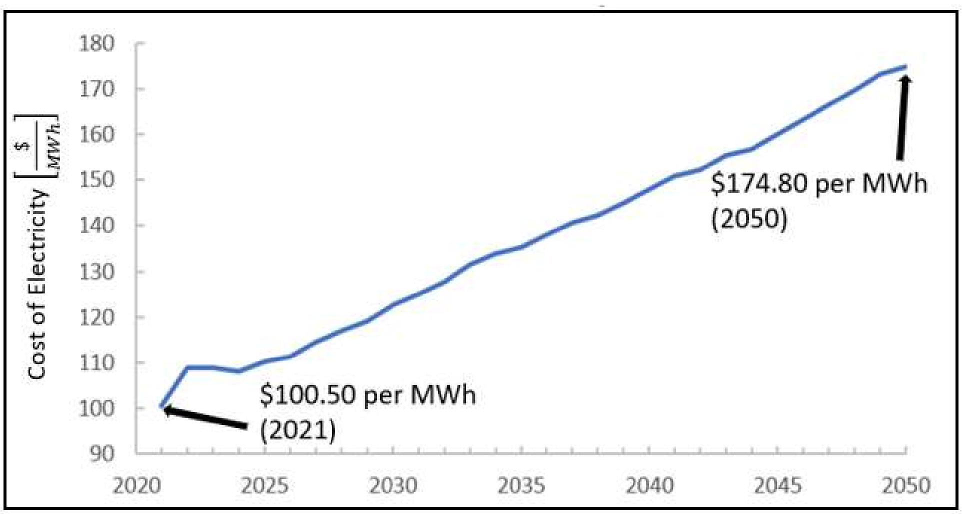

Figure D2.2. Projected Costs of Electricity up to 2050.

Appendix D3 – Consumers Pledge for Carbon Neutral Electricity

Figure D3.1 below shows Consumers pledge to be carbon neutral by 2040. In 2025, 35% of its electricity will be renewable, and it will no longer have coal or oil sourced electricity. In 2030 and 2035, around 50% of its electricity will be completely renewable. In 2040, 63% of its electricity will be completely renewable. The 10% natural gas aspect of Consumers electricity in 2040 will be renewable natural gas, therefore making the electricity completely carbon neutral.

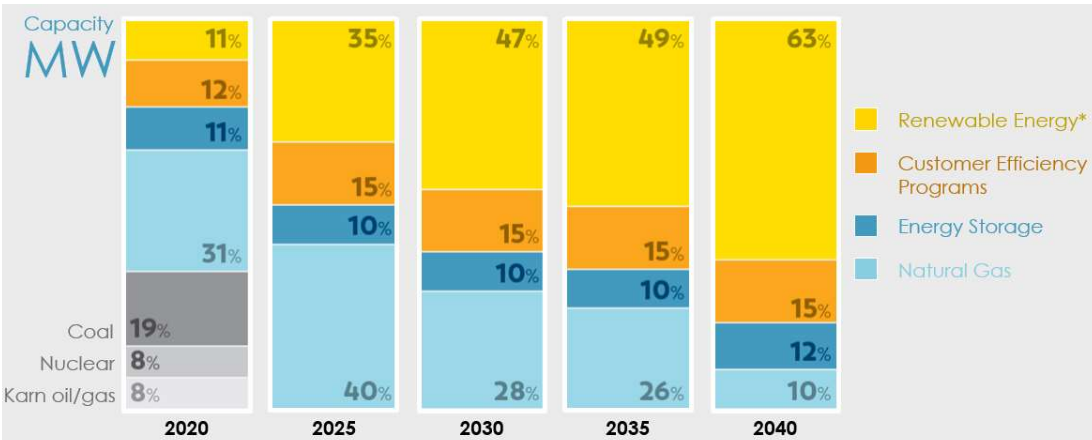

Figure D3.1. Consumers Energy Plan to be Carbon Neutral by 2040.

If Consumers Energy does not fulfill their pledge to be carbon neutral by 2040, there is an option to buy completely carbon neutral electricity starting in 2025. This option is about 58% more expensive than Consumers' regular electricity, but it is an option for Calvin to achieve carbon neutrality. Another figure that displays Consumers Energy's plan for CO_2 emissions can be seen in Figure D3.2 below.

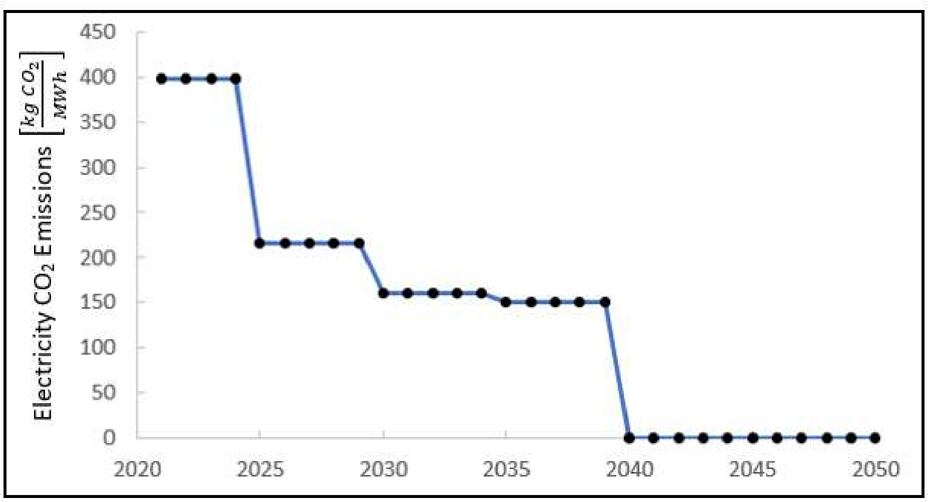

Figure D3.2. Projected CO_2 Emissions for Electricity.

This figure shows the drops in CO_2 emissions of electricity until Consumers' pledge to become carbon neutral will come to fruition in 2040.

Appendix E – Energy Efficiency

Introduction

The objective of the efficiency team was to determine potential improvements to the current heating solutions on campus and discover viable alternatives to decrease the heating loads on campus. This team consisted of Aidan Bakker, Ben Casey, Sarah MacCarthy, Elise Miera, and Christine VanOyen.

Methods

To assess potential areas where heating loads could be reduced on campus, the university was divided into categories. The campus was broken down into the following classifications: dorms/apartments, dining halls, athletic buildings, academic buildings, and large gathering areas. In doing so, each team member was assigned a category to research and develop initial solutions to reduce heating loads in these areas. After gathering preliminary findings, the group consolidated ideas and decided to move forward with the most viable solutions. These solutions included replacing the current dorm single pane windows with double pane windows (see Appendix E1), installing energy recovery ventilators in academic buildings (see Appendix E2), and adding a thermal cover to the swimming pool (see Appendix E3).

It is important to note that many other potential solutions were examined but proved to not have much benefit, and therefore plans to implement these solutions were not pursued. See Appendix E4 for these other findings such as window film and solar shades, which were not included in the final proposal for reducing heating loads on campus. Furthermore, efforts were made by the energy efficiency teams in both ENGR 333-A and ENGR 333-B to limit overlap of solutions. This decision was made due to the large scale of the project, time constraints, and each team striving to produce quality solutions over a variety of approaches. Ideas from both energy efficiency teams were then combined and included in the final seminar presentation.

Results

Implementing these ideas would have a positive impact in reducing total CO_2 emissions related to heating on Calvin University's campus. See Table E1 for these results.

Table E1. Total CO_2 Emission Decreases due to Efficiency Improvements on Campus.

Efficiency Improvement	CO_2 Emission Decrease (%)	Annual CO_2 Emission Decrease (kg CO_2)
Double Pane Windows	2.7%	554,537
Energy Recovery Ventilators	17%	4,100,155
Pool Cover	0.1%	23,000

Conclusion

Implementing double pane windows in the dorms, energy recovery ventilators in the academic buildings, and a cover for a portion of the swimming pool would significantly decrease the heating loads on campus. These additions would reduce the annual total heating load by 19.8%, which would reduce CO_2 emissions by 4,680,000 kg of CO_2 annually.

Appendix E1 – Double Pane Windows

Introduction

Most dormitory windows are currently single pane, resulting in unnecessary heat loss. Double pane or triple pane windows provide energy savings that would decrease the overall heating loads of the dorms. The feasibility of replacing all dorm windows needed to be analyzed to provide a basis for implementing this suggestion into the overall project plan. This included determining the CO_2 emissions saved from the new windows by reducing the heating loads in the dorms. Determining the costs of replacing the windows was also needed.

Methods

The building load calculations were used to determine the current heating loads for each of the dorms on Calvin University's campus. In an Excel model, the thermal resistance networks of the dorm walls were adjusted to account for the scenarios of double or triple pane windows. These calculations were contrasted against the current dorm heating loads to calculate the energy savings from the new windows. To gather cost estimates, Pella Windows of Grand Rapids was contacted. Estimates were collected for the cost of replacing all current dorm windows with sliding vinyl 6' x 4' double pane and triple pane windows. Refer to Appendix E1.1 for these calculations.

Results

Calculated using the methods described above, the heating load reductions can be found in Table E1.1.

Table E1.1. Total Dorm Heating Load Reductions.

Window Type	Heating Load Reduction
Double Pane	18.2%
Triple Pane	23.6%

The cost breakdown for replacing these windows can be found in Table E1.2. These costs reflect the price to purchase, install, and seal the new windows, as well as the labor costs for removing current windows.

Table E1.2. Cost to Replace Current Single Pane Windows with Double Pane or Triple Pane Windows.

Window Type	Total Cost
Double Pane	$1,315,000
Triple Pane	$1,592,000

It is important to note that the KHVR dorm was excluded from this study, as this dorm already has double pane windows in place.

Conclusion

Double pane windows should be implemented in all dormitory buildings that currently have single pane windows. While double pane windows provide less heat savings compared to triple pane windows, they are cheaper to purchase, making this option more feasible. Overall, this would cost around $1.3 million and would decrease the dorms' current heating loads by roughly 18%. Most importantly, CO_2 emissions would be reduced by 554,000 kg of CO_2 per year.

Appendix E1.1 – Pella Windows Cost Estimates

The estimates below were provided by Pella Windows of Grand Rapids by Chris Nance. These estimates reflect the cost of replacing 1,500 windows. In addition to the 'Amount Due' values, the price of labor to remove the old windows, install the new windows, and seal the new windows would be $704,000.

Table E1.1.1. Material Cost of Vinyl Dual Pane Window from Pella Windows.

Order Totals	
Taxable Subtotal	$782,490.00
Sales Tax @ 6%	$46,949.40
Non-taxable Subtotal	$0.00
Total	$829,439.40
Deposit Received	$0.00
Amount Due	**$829,439.40**

Table E1.1.2. Material Cost of Vinyl Triple Pane Window from Pella Windows.

Order Totals	
Taxable Subtotal	$1,087,230.00
Sales Tax @ 6%	$65,233.80
Non-taxable Subtotal	$0.00
Total	$1,152,463.80
Deposit Received	$0.00
Amount Due	**$1,152,463.80**

Appendix E2 – Energy Recovery Ventilators

Introduction

In a book named "Humidification and Ventilation Management in the Textile Industry," B. Purushothama defines an energy recovery ventilator (ERV) as "a type of mechanical equipment that features a heat exchanger combined with a ventilation system for providing controlled ventilation into a building". ERVs use exhaust air in an HVAC system to precondition (pre-heat/pre-cool and moisturize) incoming fresh air. Implementing ERV systems would reduce the amount of energy HVAC systems need to use when cooling or heating a building.

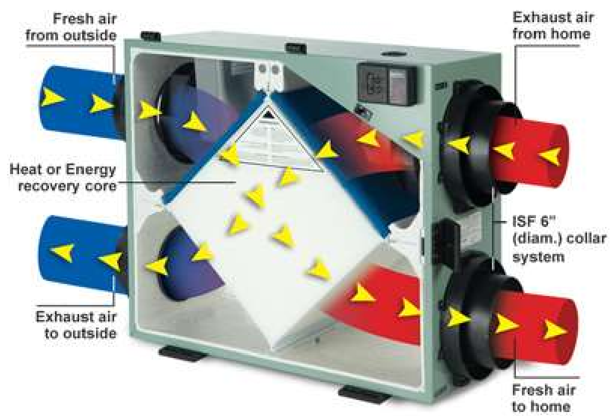

Figure E2.1. How Energy Recovery Ventilators Work.

Methods

The idea of using ERVs to improve the efficiency of buildings that get their heating supply from the main loop was derived from a previous ENGR 333 design project. Once it was discovered that ERVs can increase the efficiency of heating the buildings and cut back on the amount of energy needed for heating, research was performed to see how much waste heat the systems could recover from exhaust air.

The efficiency of the most common ERVS was found to be around 60%, meaning that they recover 60% of heat from exhaust streams. Then, using the value of heat in air that leaves the main loop buildings calculated by the building loads team, the amount of heat recovered was found, and these figures were used to find the potential energy and cost savings of implementing ERVs at Calvin.

Results

The results of the analysis can be found in Table E2.1 below. It shows the total costs of purchasing the ERV unit and installing and fitting them to Calvin's current HVAC systems, as well as the energy savings in Btu and the cost savings in dollars. The plan for implementation would be two or three buildings fitted with ERVs a year over a period of 10 years.

Table E2.1. Energy Savings and Total Cost of ERV Implementation in the Main Loop Buildings.

Total Installation Cost	$966,000.00
Annual Cost Savings	$212,000.00
Annual Energy Savings	17,188,221,445 Btu

Conclusion

Energy recovery ventilators have one of the biggest impacts of the efficiency of Calvin's buildings at maintaining a specified temperature over time. They would reduce the demand for natural gas at Calvin, whilst Calvin still uses natural gas to provide heating, and would also reduce how much heat ground source and air source heat pumps would need to provide once they are implemented. One of the problems that would arise with ERVs is the increase in the demand for electricity, as they are electrically powered devices, and would increase operating costs for Calvin.

Appendix E3 – Pool Cover

Introduction

Evaporation can be a large source of energy loss, with 1048 Btu lost for every pound of water that evaporates, with about 70% of the energy loss coming from evaporation. Covering the surface of the water with a pool cover drastically reduces the rate of evaporation and is the single most effective means of reducing pool heating costs. Savings of 50% to 70% are possible with the implementation of a pool cover. Beyond energy savings, pool covers also allow for savings in the amount of chemicals needed as well as the amount of water needed to make up for the water lost to ventilation.

Methods

To calculate the energy savings, thermal analysis was used to calculate the energy lost from the evaporation of water into the air. Initial research and estimates provided the air and water temperature, humidity of the air, and indoor air velocity. These estimates are shown in Table E3.1 below. It was also presumed that the area of the pool to be covered would be a 25m by 10m section of the pool beneath the diving boards.

Table E3.1. Variables Used in Pool Cover Calculations.

Variable	Value Used
Water Temperature	78°F
Air Temperature	80°F
Air Humidity	50%
Air Velocity	$0.1 \frac{m}{s}$

Results

After calculations, the total evaporated water savings would be 67.6 kg of water per hour covered. Accounting for the enthalpy of evaporation for water, the energy savings would be 46.08 kW per hour. Assuming the pool would be covered only from Saturday evening through Monday morning—or around 37 hours per week—this would save 88,658 kWh worth of heating over the course of the year. Accounting for efficiencies in the heating system and using the amount of CO_2 released by the burning of natural gas, the calculation was that a pool cover could save 23,000 kg of CO_2 per year. The amount of natural gas burned for this amount of heating currently also costs about $5,000 per year.

Conclusions

The impact of pool covers is significant in terms of both CO_2 and cost savings. Implementation has the potential to offer significant savings to Calvin, especially as the pool cover itself costs approximately $7,000 and lasts about 10 years. The main caveat in recommending the implementation of a pool cover is the logistical issues of storing the pool cover and having someone available to cover the pool late in the evening when the open pool hours end and someone coming early to uncover the pool before the swim team needs it.

Appendix E4 – Other Findings (Window Films and Solar Shades)

Introduction

Two other findings that were not deemed beneficial enough to implement on campus are window films in the dorms and solar shades on large windows. Double pane windows provide energy savings that would decrease the overall heating loads of the dorms; however, the installation cost and CO_2 emitted during the construction process would be high. Window films could be an easy solution to implement to the dorm windows until the single panes are replaced with double panes. The feasibility of adding window films to all dorm windows needed to be analyzed to provide a basis for implementing this suggestion into the overall project plan. This included determining the CO_2 emissions saved due to this addition to the windows by reducing the heating loads in the dorms, as well as determining the costs of the window films.

Large windows, especially those that face east or west, allow large amounts of light and therefore large amounts of heat into the buildings where they are located. This heat causes increased cooling demand in the summer, which increases energy usage and costs. This could be decreased with the addition of solar shades for large east and west facing windows.

Methods

The building load calculations were used to determine the current heating loads for each of the dorms on Calvin University's campus. In an Excel model, the thermal resistance networks of the dorm walls were adjusted to account for the addition of film to the windows. These calculations were contrasted against the current dorm heating loads to calculate the energy savings due to the addition of film.

Bare windows were estimated with a solar heat gain coefficient (SHGC) of 0.5 to 0.76, while solar shades were found to reduce this to 0.3 to 0.4. The 2015 ENGR 333 analysis of the CFAC used an SHGC of 0.766, which was used for the final analysis since the Covenant Fine Arts Center (CFAC) main lobby serves as a prime candidate for solar shades. An online calculator was used to determine the solar heat entering the building per square meter of windows at SHGCs of 0.35 and 0.766. The heat added was compared for the months of June, July, and August, because the average climate in Grand Rapids primarily requires cooling in those three months.

Results

With the implementation of window film on the single pane dorm windows, the heading load reduction when compared to single pane windows is 10.3%. The cost for purchasing film to add to these windows would be approximately $369,200, making the payback period about 21 years. This would save about 313,300 kg of CO_2 per year.

Solar shades on the CFAC east lobby would save approximately 88 kWh per square meter throughout the summer. This would equate to savings of approximately $1.232 per square meter and 12 kg of CO_2 per square meter annually. However, the cost of solar shades was $4 to $5 per square foot—or approximately $50 per square meter. This means that payback would be at least 40 years, assuming 100% utilization which would not be the case. Additionally, as the impact would be primarily on the cooling loads, it falls outside of the main scope of the project.

Conclusion

Window films would be useful to implement any time before the dorm windows would be replaced with double pane windows, but they fall short to double pane windows regarding reducing energy and CO_2 emissions. Solar shades are useful when it comes to limiting direct sunlight into rooms for the purposes of comfort and aesthetics, but they fall short when it comes to energy reduction and CO_2 emissions reductions. Additionally, cooling loads fall outside the main scope of the project. Therefore, neither window films nor solar shades were implemented in the final solution to reduce heating loads on Calvin University's campus.

Appendix F – Building Heating Loads

Introduction

As the project progressed, the need for accurate building heating load information became more and more prevalent, so a separate team was created to calculate the amount of heat required for Calvin's campus. This data provided total annual usage (in Btu) information for cost analysis as well as peak load (in Btu per hour) information for system sizing. Additional applications for this work included the impact of the implementation of the efficiency team solutions. This team consisted of Ben Casey and Caleb Styf.

Methods

The basic formula for calculating a building's heat loss at a specific temperature is shown below in Equation F1. This value changes with variation in temperature as shown below in Equations F2 and F3.

$$\dot{Q}_{heatloss}\left[\frac{Btu}{hr}\right] = \dot{Q}_{walls} + \dot{Q}_{roofs} + \dot{Q}_{windows} + \dot{Q}_{Outsideair} \qquad \textit{Equation F1}$$

The heat loss from outside air intake ($\dot{Q}_{OA}$) required for air quality and HVAC systems was calculated by using an average specific heat of air (Cp_{avg}), an average density (ρ_{air}), and a temperature difference between interior and exterior air (ΔT) as shown in Equation F2. The estimated specific heat and density of air used in calculating the heating loads are shown below in Table F1.

Table F1. Values of Constants Used to Calculate Heating Loads for Calvin University.

Variable	Value
Specific Heat (Cp_{avg})	0.2403 $\left[\frac{Btu}{lbm\ F}\right]$
Density (ρ_{air})	0.0778 $\left[\frac{lbm}{ft^3}\right]$

$$\dot{Q}_{OA}\left[\frac{Btu}{hr}\right] = OA_{intake}[CFM] \cdot \rho_{air}\left[\frac{lb}{ft^3}\right] \cdot Cp_{avg}\left[\frac{Btu}{lb}\right] \cdot \Delta T[°F] \cdot \frac{60\ [min]}{1\ [h]} \qquad \textit{Equation F2}$$

To find the amount of heat lost from the building, a thermal resistance network calculation was used to find the heat loss of each building, with a different U-value found for the windows, walls, and roofs, shown in Table A1. The basic structure for a thermal network element (TNE) is shown in Equation F3 which uses surface area ($Area_{TNE}$), temperature difference (ΔT), and the U-values of the section (U_{TNE}) to calculate heat loss ($\dot{Q}_{TNE}$). An example of a single building set of data is shown in Appendix F1.

$$\dot{Q}_{TNE}\left[\frac{Btu}{hr}\right] = \Delta T[°F] \cdot U_{TNE}\left[\frac{Btu}{hr \cdot ft^2 \cdot °F}\right] \cdot Area_{TNE}\,[ft^2] \qquad \textit{Equation F3}$$

Table F2. U-values For Each Resistance Network Section and Building Type.

Type of Building	Wall $\left[\frac{Btu}{hr \cdot ft^2 \cdot °F}\right]$	Window $\left[\frac{Btu}{hr \cdot ft^2 \cdot °F}\right]$	Roof $\left[\frac{Btu}{hr \cdot ft^2 \cdot °F}\right]$
Academic Building	0.106	0.490	0.055
Dorm	0.346	1.099	0.055
House	0.209	0.490	0.090

Once the equations for heat loss were set up for each building, the same system of equations was used to find the rate of heat loss across various temperatures (i) within an average range for the state of Michigan in increments of 5°F. These values were then multiplied by the estimated hours spent at each temperature per year to find the total Btu spent annually, per building, per temperature. A summation of each building's annual Btu load per year yielded the annual heating load for Calvin University. This process is shown in Equation F4.

$$Heat\ Load_{total}\ [Btu] = \sum\nolimits_{Buildings} \left(Time_i \left[\frac{h}{year}\right] \cdot \dot{Q}_{heatloss_i} \right) \qquad \textit{Equation F4}$$

Results

From the data discussed above, Calvin's annual heating load was calculated to be 104.4 billion Btu per year. However, when designing the systems for this load, the desired system size only needed to be able to cover the peak heating load, which was calculated to be 32.8 million Btu per year for the entire campus. A table of useful datapoints from this analysis is shown below in Table F3. Also, a breakdown of the total heating allocation on Calvin's campus can be seen below in Figure F1.

Table F3. Results of the Building Loads Calculations.

Location	**Calculated Annual Load** [Billion Btu]	**Peak Load** Calculated at 2.5°F [Million Btu per hour]
Main Loop (Ground Source)	76.79	25.41
Upper Loop (Console Heat Pumps)	15.65	4.79
Miscellaneous (Air Source)	11.95	2.64
Total System	104.39	32.84

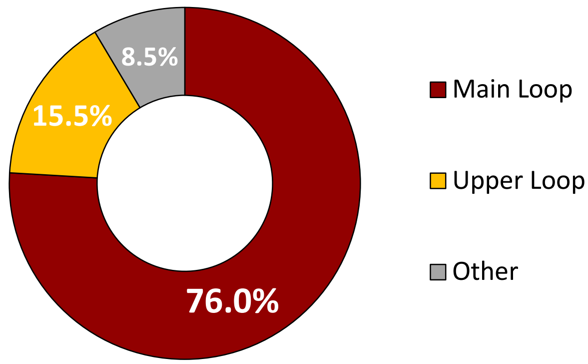

Figure F1. Total Heating Allocation for Calvin University.

Conclusion

Using a thermal resistance network for the various types and geometries of buildings on Calvin University's campus, the temperature-dependent values of peak heat loss (as a rate) as well as the annual loads for every building and for Calvin University were determined using the assumptions outlined above. This was important for the CO_2 reduction project because it provided the necessary information for the other groups to size their systems from and provided the total annual usage values to calculate financial and carbon savings per year.

Appendix F1 – Example Set of Building Load Data

Table F1.1. Heating Load Data Set of Knollcrest Dining Hall.

Upper Heating Loop										
				Knollcrest Dining Hall						
	Outside DB Temp (F)	Delta Temp (F)	Hours/Year at Temp (h)	Delta T * H	Roof Loss (Btu)	Windows (Btu)	Walls (Btu)	OA (Btu)	Total (Btu)
Per Temperature Calculations	92.5	-24.5	0	0	0	0	0	0	0
	87.5	-19.5	3	-58.5	-85009.83925	-35546.16287	-38612.4453	-754637.3991	-913805.8465
	82.5	-14.5	34	-493	-716407.7051	-299559.9708	-325400.607	-6359593.808	-7700962.091
	77.5	-9.5	301	-2859.5	-4155310.006	-1737508.594	-1887389.53	-36886934.06	-44667142.19
	72.5	-4.5	557	-2506.5	-3642344.651	-1523016.363	-1654394.77	-32333310.1	-39153065.88
	67.5	0.5	751	375.5	545661.4468	228163.8317	247845.6958	4843869.117	5865540.092
	62.5	5.5	720	3960	5754512.195	2406201.794	2613765.527	51083147.02	61857626.53
	57.5	10.5	495	5197.5	7552797.256	3158139.855	3430567.254	67046630.46	81188134.82
	52.5	15.5	721	11175.5	16239785.62	6790532.361	7376297.134	144161542.8	174568157.9
	47.5	20.5	621	12730.5	18499448.86	7735391.904	8402662.132	164220707.9	198858210.8
	42.5	25.5	699	17824.5	25901844.1	10830642.39	11764915.06	229932210.6	278429612.2
	37.5	30.5	347	10583.5	15379515.11	6430817.345	6985552.388	136524870.3	165320755.2
	32.5	35.5	728	25844	37555457.87	15703504.84	17058120.27	333382033.2	403699116.2
	27.5	40.5	1383	56011.5	81393651.47	34034083.79	36969931.27	722536285.1	874933951.6
	22.5	45.5	708	32214	46812084.81	19574087.02	21262586.54	415553661.1	503202419.5
	17.5	50.5	324	16362	23776598.12	9941988.322	10799603.93	211066275.6	255584466
	12.5	55.5	140	7770	11291050.44	4721259.581	5128524.784	100231326.3	121372161.2
	7.5	60.5	144	8712	12659926.83	5293643.947	5750284.16	112382923.4	136086778.4
	2.5	65.5	42	2751	3997642.184	1671581.095	1815774.991	35487307.43	42972305.7
	-2.5	70.5	18	1269	1844059.59	771078.3022	837593.0439	16369826.66	19822557.59
	-7.5	75.5	16	1208	1755416.851	734013.0725	797330.4941	15582939.8	18869700.21
	-12.5	80.5	0	0	0	0	0	0	0
	-17.5	85.5	0	0	0	0	0	0	0
	-22.5	90.5	0	0	0	0	0	0	0

Each building owned by Calvin University had a set of data identical in format to this example allowing for accurate heat load calculations and system sizing.

Appendix G – New Building Additions

Introduction

One factor that needed to be analyzed throughout the Natural Gas CO_2 Emissions Reduction Project was Calvin's plans for future construction projects. These construction projects and new building additions needed to be analyzed because not only will they add additional heating loads to Calvin's total usage, but they will also add carbon emissions due to their construction. The goal of the New Building Additions analysis was to calculate the new heating loads and the embodied carbon emissions of planned future construction projects on Calvin University's campus. This team consisted of Jacob Tanis, Jordan Tutor, and Sara VanSolkema.

Methods

The first step to finding Calvin's planned construction projects was researching different announcements made through Calvin's website. Through this research, plans were found for dorm renovations, the new Commons Union building, and the new football and soccer stadiums. Although this research helped with finding the future construction projects, there was not much information on the sizing and timing of these implementations. After a meeting with Tim Fennema was held to discuss Calvin's future construction projects, a better timeline and an estimate of new square footage was created. Refer to Figure G1 for information on Calvin's plans for implementation.

Figure G1. Timeline of Calvin's Planned Construction Projects.

In 2025, the School of Health will be constructed and completed. It will be implemented into North Hall—an academic building on Calvin's campus that already exists—and there will be a new entrance constructed coming off from Knollcrest Circle SE Rd. Also in 2025, the new sports complex construction will be completed. This new construction will include two turf fields at the existing soccer field on Calvin's campus, as well as two new stadiums: one for football and one for soccer. There will also be a new amphitheater with a stage constructed by the Noordewier-VanderWerp dorm.

In 2027, the construction of the Commons Union Building will be completed. This plan includes the destruction of the current Commons Dining Hall, the Commons Annex, and the Knollcrest Dining Hall. The new Commons Union building will be attached to Hekman Library.

In 2031, construction will be completed for renovations on all the dorms and all the apartments on campus. In addition to these renovations, by 2031 a new pod-style apartment building will be constructed and completed.

Results

Through information found in the documents cited in Appendix G1, it was estimated that for every square foot of demolition or of new construction, 11.7 kg of CO_2 were emitted into the atmosphere. These emissions are caused by the vehicles and equipment used to perform construction. For demolition and new construction only, Table G1 below displays the kg of CO_2 emitted. For specific building CO_2 emissions and square footage estimates, refer to Appendix G2.

Table G1. Demolition and Construction Carbon Emissions.

Year	Total CO_2 Emissions [kg CO_2]
2025	2,574,000
2027	1,170,000
2031	468,000

Because the School of Health will be implemented into the current North Hall building, there will be no new square footage and therefore no new heating load. For the sports complexes, there will be an estimated new 100,000 square footage, which will require an estimated heating load of 6 billion Btu. The new Commons Union building will be approximately 50,000 square feet, but the buildings it is replacing are also in sum approximately 50,000 square feet, resulting in net zero new square footage and no additional heating load. Because the dorm and apartment renovations will not involve any additions to the buildings, there will be no new heating load. The new pod-style apartments, however, will be a completely new addition to Calvin's campus. With the construction of these new apartments, there will be an estimated new 40,000 square footage, which will require an estimated heating load of about 1 billion Btu.

See Figure G2 below for a graph which demonstrates the new carbon emissions from these construction projects. Refer to Appendix G2 for further calculations on how these heating loads and embodied carbon amounts were calculated.

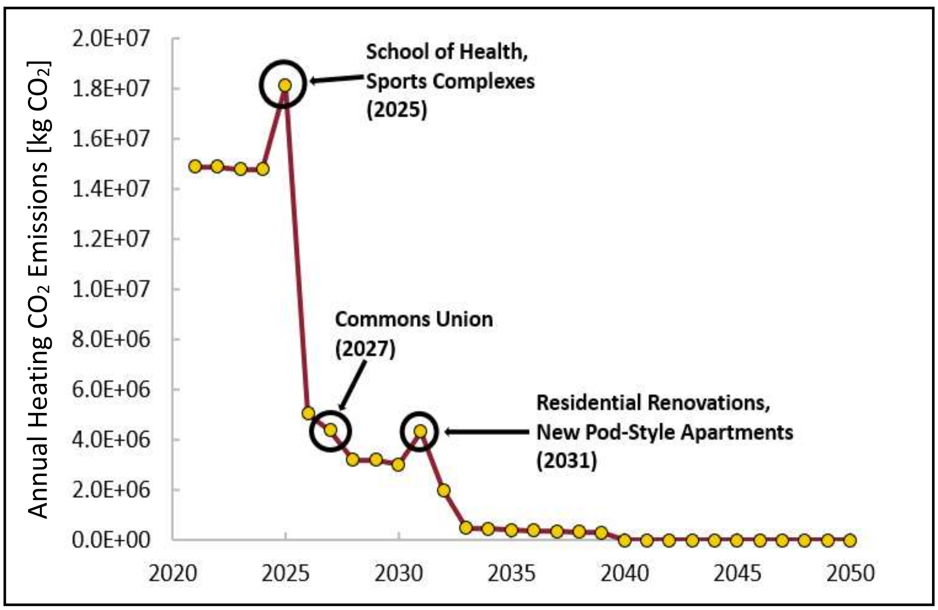

Figure G2. Carbon Emissions Spikes due to New Construction Projects.

Conclusion

Planning for how Calvin's construction projects would impact its carbon emissions was an important step in this project. These new projects caused spikes in Calvin's projected carbon emissions due to construction and additional heating loads, and understanding their influence was necessary in order to eliminate Calvin's natural-gas related net CO_2 emissions.

Appendix G1 – References for Embodied Carbon Emissions Estimations

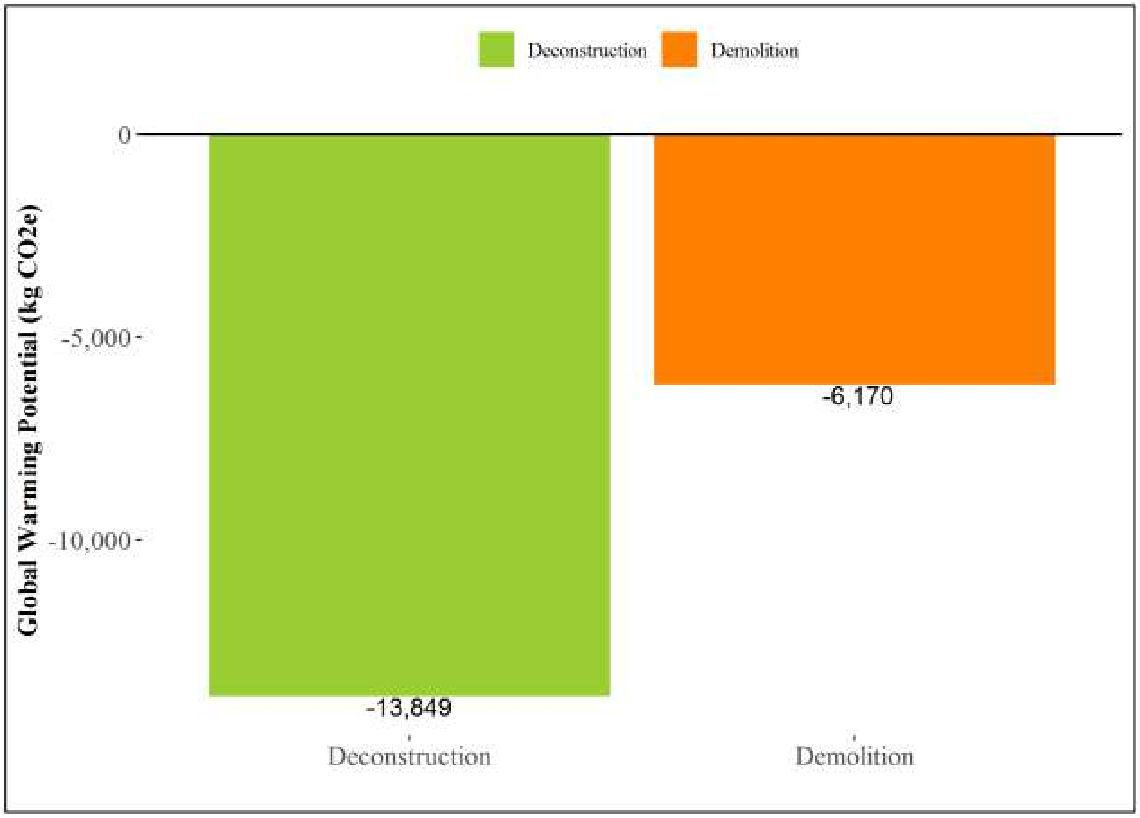

Figure G1.1. Kilograms of Carbon Emitted during the Construction of a House.

As an estimate, the 13,849 kg of CO_2 for deconstruction over the average house size of 1,177 square feet determined that for every square foot of construction or demolition, 11.7 kg of CO_2 are emitted. Further support for this estimate can be found in the articles and reports cited below.

Oregon.gov: State of Oregon. (n.d.). Retrieved December 1, 2022, from https://www.oregon.gov/deq/FilterDocs/DeconstructionReport.pdf

Sizirici B, Fseha Y, Cho CS, Yildiz I, Byon YJ. A Review of Carbon Footprint Reduction in Construction Industry, from Design to Operation. Materials (Basel). 2021 Oct 15;14(20):6094. doi:10.3390/ma14206094. PMID: 34683687; PMCID: PMC8540435.

Appendix G2 – Calculations for New Building Heating Loads & Emissions

Table G2.1. CO_2 Emissions & New Heating Loads for Planned Construction Projects.

Year of Final Implementation	Building	Square Feet	Demolition CO_2 Emissions [kg CO_2]	Construction CO_2 Emissions [kg CO_2]	New Heating Load [Btu]
2025	School of Health	10,000	117,000	117,000	0
2025	Sports Complexes	100,000	1,170,000	1,170,000	6,000,000,000
2027	Commons Union	50,000	585,000	585,000	0
2031	Dorms/KE Renos	50,000	585,000	585,000	0
2031	Pod Style Apartment	40,000	0	468,000	1,000,000,000

The calculations performed in Table G2.1 above were done with estimations and assumptions of the sizing of the new buildings. For the School of Health, Commons Union, and the dorm and KE apartment renovations, it was estimated that there would be no new heating load because the net new square footage would be zero. The new heating loads for the sports complexes and the pod style apartments were estimated based on the known heating loads of other buildings with similar square footage. For the CO_2 emissions for demolition and construction, the factor of 11.7 kg of CO_2 per square foot was used. The CO_2 emissions for these new building construction projects were factored into the calculations done to get Calvin to net zero CO_2 emissions from natural gas.

Appendix H – Hero Graphs

Introduction

With the scope of the project and the range of results it produced, effective and concise means of presenting this data was required. Graphs which include a major portion of the results from this project were given the name "hero graphs." These were used not only to visualize ENGR 333 section B's plan for carbon neutrality for heating, but also as a roadmap in the final presentation. The hero graphs were put together by the executive team of this project consisting of Sara VanSolkema, Aidan Bakker, Nicholas Paternoster, Micah Lee, Mark Bekhet, and Ben Casey.

Methods

The final presentation of data for this project consists of three main hero graphs. The first hero graph plots the carbon emissions due to heating for Calvin University as a function of time (Figure H1). The drops, rises, and eventual approach to zero on this graph show the implementation and timeline of the recommended solutions. The emissions (E_{CO2}) per year (i) for this graph were calculated using the following equation.

$$E_{CO_2,i} = E_{CO_2,i,electricity} + E_{CO_2,i,natural\ gas} \qquad \textit{Equation H1}$$

The emissions values depended on two major factors: the required heating area of Calvin University (see Appendix G for New Building Loads) and the power source of the heating systems being either electricity or natural gas. Any increase in square footage of projected new buildings would increase the necessary load on campus and the emissions. This can be seen in Figure H1.

As ground source, air source, and console heat pumps were implemented, the required energy from electricity increased, and the required energy from natural gas decreased. Therefore, emissions due to natural gas decreased. This formed the basis for the second hero graph (Figure H2) which directly compared Calvin's heating-related emissions.

Finally, a graph composed of the costs of operation and maintenance as well as installment cost for the proposed solutions (Figure H3) was generated. This graph shows the cost comparison to theoretical cost scenarios over time for Calvin University, should no additional steps be taken for carbon neutrality.

Results

The results of the work for the hero graphs are shown below in this section in the form of annotated hero graphs. For additional versions of the hero graphs—versions without annotation or including embedded carbon—see Appendix H1.

The first graph as mentioned in the methods section is shown below in Figure H1. This graph was used as the roadmap for the final presentation as it provided a convenient way to introduce each system with respect to the impact it made on Calvin's CO_2 emissions. Annotations of the implementation which caused the changes in the graph were included for readability.

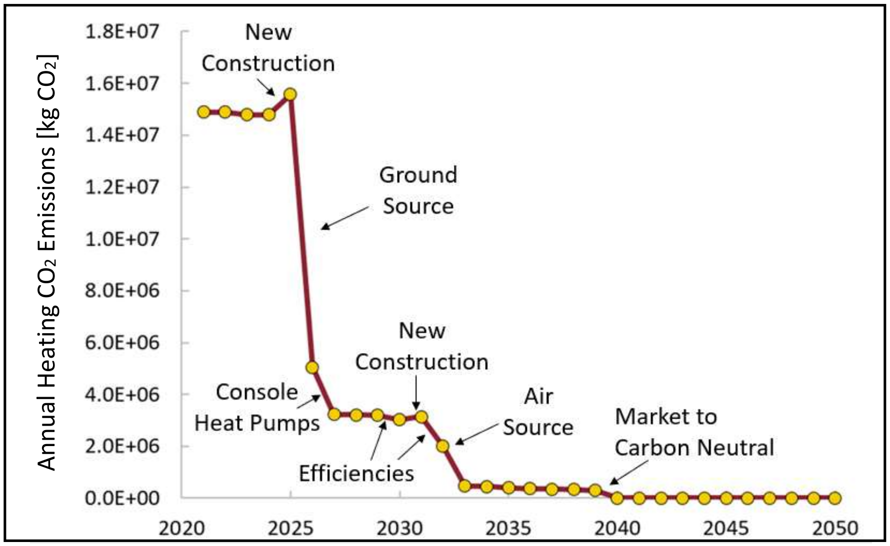

Figure H1. Hero Graph Displaying Calvin's Annual Net Heating Emissions.

The next graph shows the general strategy of the project to move all heating sources to electricity-based means. This was an important step because the grid and the electricity it provides can and has pledged to move to carbon neutrality by 2040 as shown in Figure H2. If purchased electricity couldn't be made carbon neutral, the solution of this project would not be effective, and Calvin would still produce emissions. Each year from 2021 to 2050 was represented by the yellow dots along the emissions line. The two gray lines shown in the graph represent lines of constant CO_2 emissions.

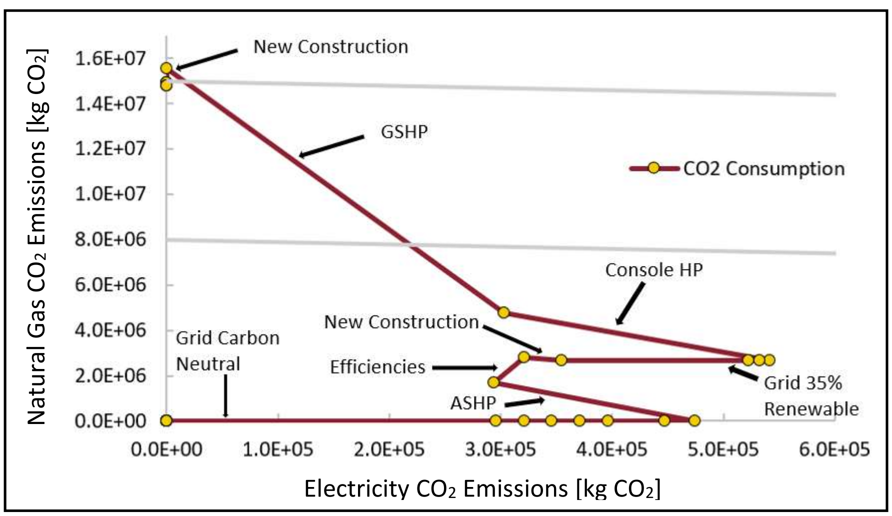

Figure H2. Hero Graph Displaying Emissions from Heating Sources Over Time.

It was important to compare the different cost scenarios related to future natural gas prices. The cost comparison hero graph in Figure H3 below displays the estimated installment, operation, and maintenance cost of the proposed solution compared to a scenario where Calvin continues to operate as is. The three scenarios for Calvin, not including the proposed solution, are different due to possible changes in market cost for natural gas.

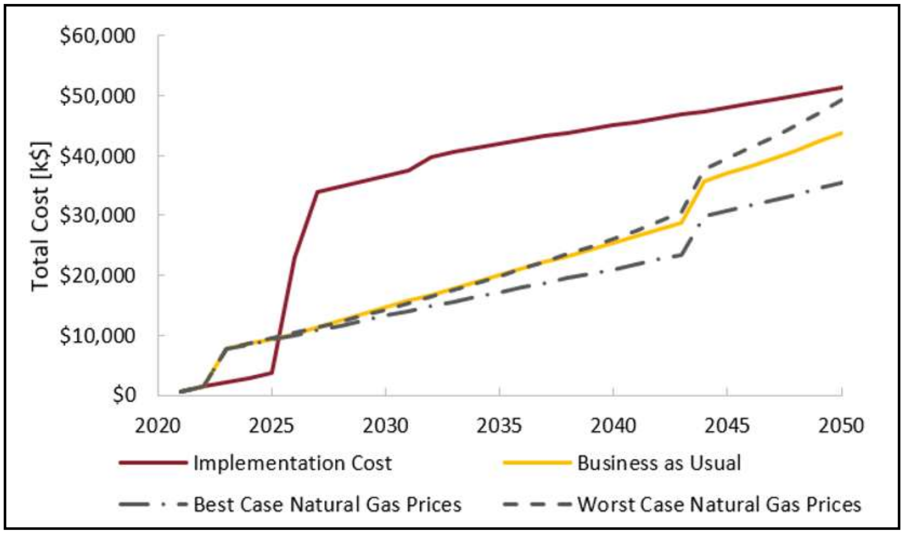

Figure H3. Cumulative Costs of Recommended Solution vs. Business as Usual Natural Gas Heating.

Conclusion

Hero graphs were a very important visual tool for this project, and they were used to show the conglomerate results of the work of various groups in a single image. The first hero graph in Figure H1 shows the emissions of Calvin over time, resulting in the 2040 carbon neutral goal at zero emissions. The second graph in Figure H2 shows the emissions from heating with natural gas versus electricity. Due to Consumers Energy's pledge to be carbon neutral by 2040, there will be no CO_2 emissions associated with purchasing its electricity. Therefore, by transitioning all heating on Calvin University's campus from natural gas sources to electricity, heating-related CO_2 emissions will reach carbon neutrality.

Appendix H1 – Other Hero Graph Formats

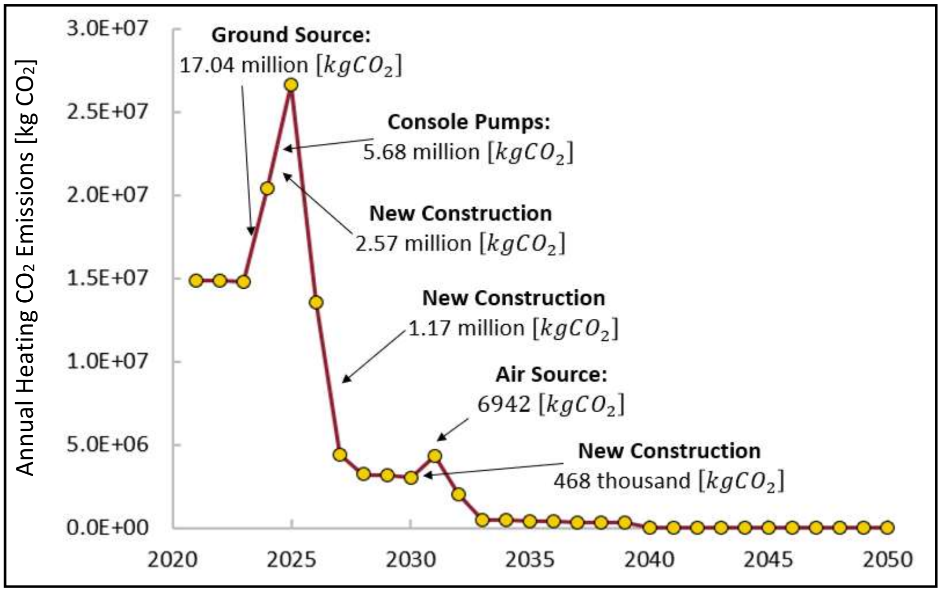

Figure H1.1 Hero Graph Displaying Embodied Carbon Costs.

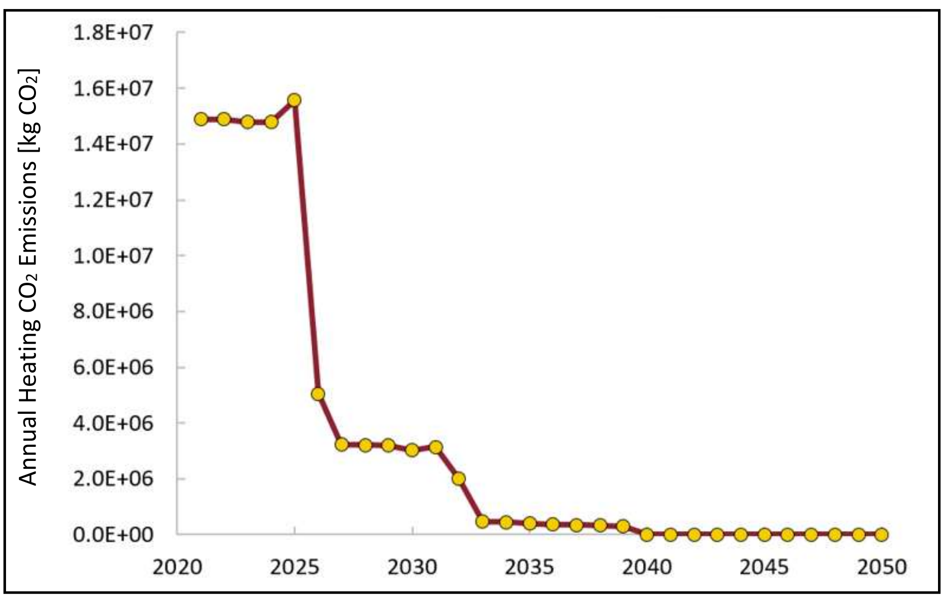

Figure H1.2. Hero Graph of Annual Emissions without Annotation.

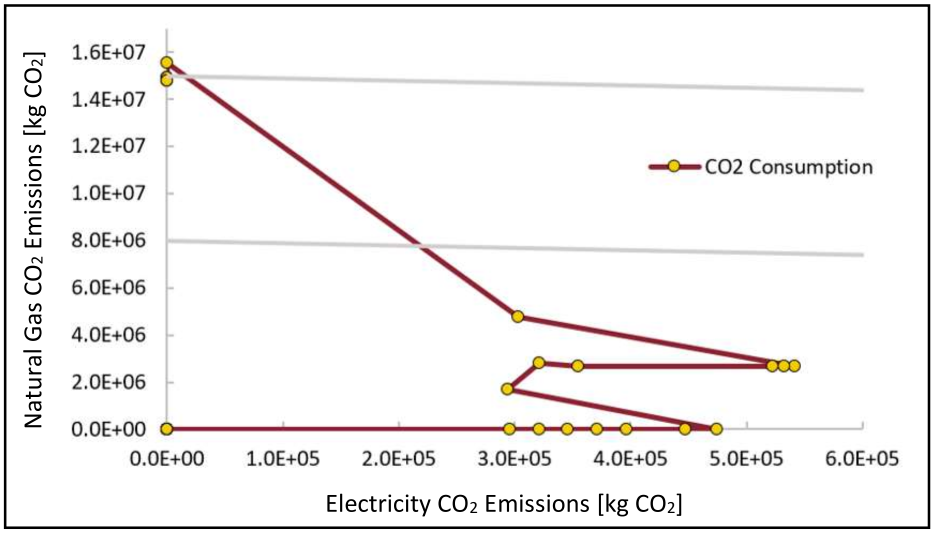

Figure H1.3 Hero Graph of Annual Emissions by Source without Annotation.