

St. Gertrude's Monastery Heating System Cost-Benefit Analysis

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Executive Summary

The main purpose of this cost-benefit analysis was to examine varying systems and determine which option would be the cheapest to run which would preferably be more environmentally friendly than the current coal-fired boiler system. The current system runs hot water through radiators to heat the building. The analysis was only based off heating loads, and any cooling system would remain the same for any of the proposed heating systems.

The geothermal heat pump was the most environmentally friendly and economically sound option among the proposed heating systems. Replacing the current coal-fired boiler system with a geothermal heat pump would save the monastery of St. Gertrude a minimum of \$533,780 over a period of 20 years.

There is also the potential for adding systems to power the heat pump using sustainable methods such as solar panels and wind turbines. These methods could be used to reduce the operational costs associated with the proposed systems.

Section 1: Introduction

The monastery of St. Gertrude currently utilizes a coal-fired boiler for its heating; however, the sisters want to move to a more a reliable, economical, and environmentally friendly heat source. For the first phase of the project, the sisters request a cost-benefit analysis on alternative systems, so that they may make an informed decision on how to proceed.

Background

General

The St. Gertrude's property includes two buildings: The monastery and the Spirit Center. The Spirit Center was recently retrofitted to allow for heating by use of a geothermal heat pump. The main building and its annex, however, still run off of coal-fired boiler system. In the past, geothermal and hydroelectric studies have been conducted, but were much too expensive and thus have not been implemented. In order to reduce energy costs and be environmentally friendly, the sisters have asked that our senior design team provide a cost-benefit analysis on alternative heating methods for the main building and its annex. The possible heating alternatives requested for the cost-benefit analysis include: a geothermal heat pump system, biomass boiler, electric boiler, propane boiler, and #2 fuel oil boiler.

Technical

The current operating cost of the current coal-fired boiler is \$75,000/year using up to 1 ton of coal/day during the coldest days of the year. The type of coal used was found to be "oiled slate". This is assumed to be a type of bituminous coal which has a wide range of heating values. The building consists of three sections: the main building, annex, and chapel as shown in figure 1. The main building and its annex use hot water radiators for the delivery system, while the chapel uses steam radiators. The temperature of water delivered to these radiators must be at least 100⁰ F, but optimally around 140⁰ F. The water delivered is heated through a heat exchanger between the steam from the boiler and the building's hot water loop. The chapel portion requires a higher temperature input than the rest of the building and thus draws steam directly from the boiler.

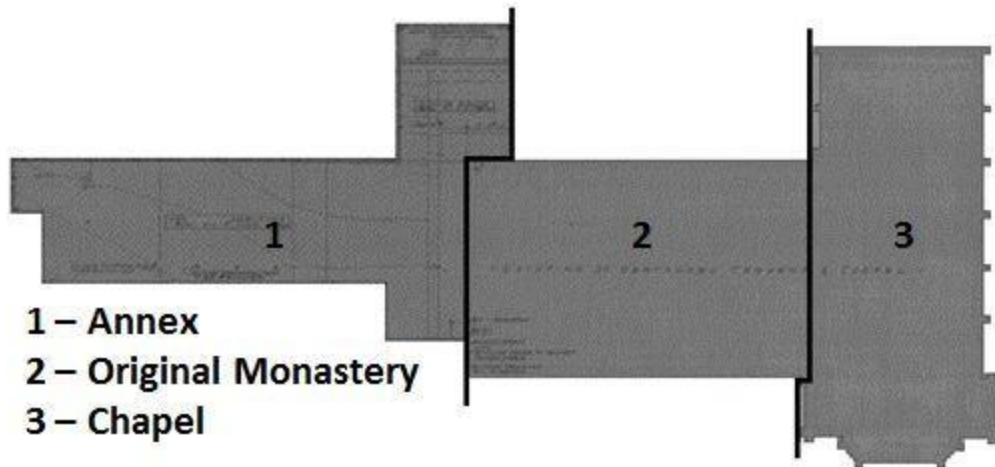


Figure 1. St. Gertrude's Monastery building schematic.

Objective

The objective of this project is to conduct a cost-benefit analysis on the alternative heating systems. After analysis, a system will be chosen to best suit the economic and environmental needs of the monastery of St. Gertrude.

Section 2: Heating Load Calculation

Calculations

At the coldest times of the year, up to 1 ton of coal is used per day to heat the original monastery, chapel, and its annex. Using this information, a maximum heating load estimate was developed, which was used as a base number to validate any additional calculations.

Hand calculations were developed using heat transfer and thermodynamic relationships and equations. This involves accounting for the total surface area of the building, number of windows, and the materials used. This allows the calculation of heat loss for an extreme outdoor temperature. This secondary calculation was compared to the maximum heating load estimate to ensure accuracy.

Results

- Total heating load calculation for main building and annex from coal usage:

$$\begin{aligned} \text{Mass of coal} &= 2,000 \text{ lbs/day} = 80 \text{ lbs/hr} \\ \text{Heating value} &= 9,150 \text{ Btu/lb} \\ \text{Efficiency} &= 75\% \end{aligned}$$

$$\text{Max heating load}_{\text{coal use}} = \left(80 \frac{\text{lbs}}{\text{hr}}\right) \left(9,150 \frac{\text{Btu}}{\text{lb}}\right) (0.75) = 549 \frac{\text{kBtu}}{\text{hr}} \quad (1)$$

- Total heating load calculation from hand calculations:

Table 1
Weather data from close proximity locations

City	99.6%		99%	
	°F	°C	°F	°C
Boise	2	-16.8	9	-12.6
Spokane	1	-17.4	7	-13.8
Idaho Falls	-11.9	-24.4	-5.6	-20.9
Lewiston	6.4	-14.2	14.5	-9.7
Mountain Home AFB	0	-17.9	5	-14.8
Pocatello	-6.9	-21.6	0.14	-17.7

Weather data was taken from Table 1 above. The table provides values of design conditions for Idaho cities from the ASHRAE Handbook of Fundamentals. The closest city to Cottonwood in terms of climate is Spokane, so calculations are performed using Spokane numbers.

$$\begin{aligned} \Delta T &= 69 \text{ °F} \\ \text{Wall area} &= 35,018 \text{ ft}^2 \\ \text{Roof area} &= 18,880 \text{ ft}^2 \\ \text{Window area} &= 4,700 \text{ ft}^2 \end{aligned}$$

To find the heat loss the following equation was used for each unique portion of the building.

$$\text{Heat loss} = U \cdot A \cdot \Delta T \quad (2)$$

where U is the overall heat transfer coefficient, A is the surface area, and ΔT is the difference in temperature between indoors and outdoors. U is the inverse of thermal resistance. It is one of the key variables in determining heating load. More or less, it is how well the building is insulated from the outside. Values for U were computed using tables in the ASHRAE Handbook of Fundamentals (1997) and the architectural drawings provided by St. Gertrude's.

$$\text{Max heating load}_{\text{hand calc}} = 594 \frac{\text{kBtu}}{\text{hr}}$$

$$\text{Annual heating load}_{\text{hand calc}} = 1,435 \text{ MBtu}$$

Section 3: Cost-Benefit Analysis

Multiple systems were analyzed for their cost and environmental impact. Maintenance costs were estimated by using the number of man-hours per year at \$100.00 per hour. Operational costs were estimated using Pellet Heat’s fuel cost calculator and an annual heating load of 1,435 MBtu. The geothermal cost estimate was based off of the electricity costs and coefficient of performance for heating of a Carrier Water-to-Water Geothermal Heat Pump for heating only. Coal operation costs were calculated using the current system rather than estimates and includes the cost of shipping coal. Boiler initial costs were calculated using RS Means Mechanical Cost Data (M. Mossman (Ed.), 2011). Additions were made to the initial cost data to include demolition costs, radiator and electrical work. The cost data for each heating system are shown below in Table 2. Table 3 shows the environmental impacts, emissions, and renewability for each system.

Table 2
Cost Data of Proposed Systems

	Coal	Geothermal	Biomass	Electric	Propane	#2 Fuel Oil
Fuel Cost (\$/MBTU)	13.52	8.37	18.67	35.17	34.81	37.72
Operation Cost (per year)	\$50,499	\$12,011	\$26,360	\$50,468	\$49,952	\$54,128
Maintenance Cost (per year)	\$24,501	\$1,000	\$24,500	\$0.00	\$2,000	\$2,000
Initial Cost (Including material and install costs)	\$0	\$277,000-\$700,000	\$53,375	\$36,600	\$52,975	\$64,350
Total Cost Over System Life Cycle (20 years)	\$1,500,000	\$537,220-\$960,220	\$1,070,575	\$1,045,960	\$1,092,015	\$1,186,910
Expected Life of Boiler/heat pump	n/a	20 years	20 years	20 years	25 years	22 years

1. Initial Cost Breakdown: Appendix A

Table 3
Environmental effects of proposed heating systems

	Coal	Geothermal	Biomass	Electric	Propane	#2 Fuel Oil
Environmental Impact	Non-renewable	Renewable	Renewable	Semi-renewable	Non-renewable	Renewable
Emissions (lbs/MWh)	CO ₂ = 2,249 SO ₂ = 13 NO = 6 Particulates	Only through electric costs	Carbon neutral Particulates	Low emission 50% hydro-electric 25% natural gas 25% other	Clean burning CO - Low	Low emissions CO NO Particulates Hydrocarbons

System Summaries

Coal Boiler

The coal boiler is the current system, and as such, requires no initial investment. Among the fuel alternatives, it is also among the cheapest options alongside biomass. Because of this, most other systems will be difficult to pay off with any savings that they may contribute. However, coal is one of the dirtier forms of energy and has the highest emissions among the systems analyzed. Another disadvantage comes with the fact that the boiler is old and difficult to maintain. The coal is shipped from Montana. This disadvantage is quantified in the operation cost.

Geothermal

Geothermal has the most advantages of all the other systems. The only emissions it has are related to the electricity used to run the system. It is the most sustainable system. A single system can be used for both heating and cooling and even heating hot water. The operating cost is 65-70% lower than traditional systems. Also, because it runs off of electricity, other systems can be added in the future to run it such as solar panels and hydroelectric turbines. The biggest disadvantage of this system is the initial cost. Compared to the other systems, it is the only system that runs at a lower combined operation and maintenance costs than the coal system.

The team developed the initial calculations by analyzing the Spirit Center heating system, which has a similar heating load. That particular system was budgeted at around \$200,000 dollars. The situation is similar for the larger heating load. The estimate provided of \$277,000 is the low range for costs of a geothermal system based on scaling the Spirit Center heating load and costs. \$700,000 was the maximum budget allowed for a geothermal system provided by the client.

Biomass

One of the advantages of the biomass system is that it can be retrofitted from the current system. The feed system would have to be updated, but since the boiler is balanced draft, it seems that the rest of the system can be retrofitted since both coal and biomass are solid fuels. An alternative to installing either a new boiler or retrofitting is using a co-firing option where both coal and biomass are mixed and burned together.

All methods of using biomass will yield better emissions than pure coal. Running off of pure biomass is considered carbon neutral since it emits carbon that was only recently converted to solid fuel rather than carbon that was emitted and stored long ago. Among its disadvantages are that it still has emissions especially sulfur dioxide and nitrogen oxides. Another disadvantage is that the lumber industry's future is uncertain. Currently, it is in decline. However, if the housing industry picks up again, the lumber industry will almost certainly follow.

Propane

Propane is a gaseous, clean-burning fossil fuel. Most of the system would have to be replaced. However, since propane is liquid-fueled, there is no ash like there is with solid-fueled systems. The emissions of propane are also lower than coal and the system is much smaller. The disadvantage is that the operating costs are high and the most expensive of the alternatives looked at. Because of this, it will be more difficult to make a return investment on installation. The return investment would be nearly impossible.

Electric

The advantages of electric are that it is low-maintenance and easy to access. The energy is also produced off-site with the capability of adding renewable systems on site. Among the disadvantages, electricity off the grid is not completely green. Electric power is more expensive than the current coal power system and subject to blackouts. Being a more expensive option to run, electricity will also be nearly impossible to make a return on investment on installation.

#2 Fuel Oil

Number 2 fuel oil is a distillate home heating oil. Trucks and some cars use similar diesel fuel with a cetane number limit describing the ignition quality of the fuel. Both are typically obtained from the light gas oil cut. With some adaptations, it can be run in boilers that burn diesel fuel. However, this requires installation of a diesel boiler which itself can be expensive.

Decision Matrix

Rank of sustainability is determined by the renewability of the fuel used to run the system. Rank of emissions is determined primarily by the amount of emissions provided by the system. Rank of cost is determined by a combination of payback period and initial cost. Accessibility is determined by distance from installers and fuel suppliers. Ease of maintenance and operation is determined by the type of fuel used and how it is used.

Using all this information we created a decision matrix to rank the systems, as shown in Table 4.

Table 4

Decision matrix for system ranking

Criteria	Weight	Coal	Geothermal	Biomass	Electric	Propane	#2 Fuel Oil
Initial Cost	5	5	1	4	3	3	3
Operating Cost	5	4	5	3	2	2	2
Ease of Use	4	2	5	1	5	4	3
Efficiency	3	2	5	3	5	3	3
Env. Impact	2	1	5	3	4	2	3
Fuel Availability	1	3	5	4	5	4	3
Total		66	80	58	73	54	55

5 = Best

3 = Good

1 = Poor

Section 4: Conclusions and Future Work

Conclusion

Based on the cost-benefit analysis, the best option was determined to be the geothermal heat pump. Although it has the highest installation cost, it has the lowest operational cost and is among the lowest maintenance costs. Over a period of 20 years, the geothermal system would cost \$537,220-\$960,220. At its highest cost value, it would be \$79,740 cheaper than the next best alternative. Replacing the current coal-fired boiler system with a geothermal heat pump would save the monastery of St. Gertrude a minimum of \$533,780 over a period of 20 years.

Geothermal is, by far, the most environmentally safe option. Not only is the electricity from the grid clean, but there is also opportunity to add solar panels and wind turbines to power the system. It is also the best long term option. The low maintenance and operational costs should save the monastery money over the long term even with the high installation cost. All of the other systems have operational and maintenance costs too high above the status quo to pay off any installation costs.

Future Work

The plan for the remainder of the project is to develop and optimize a geothermal heat pump model using Engineering Equation Solver (EES). EES has built-in thermodynamic properties for many materials and fluids, which allows an entire system and its components to be analyzed. Pumps, compressors, heat exchangers, and piping systems can all be sized based on head loss, heating load, configuration, and other parameters. EES Optimization functions allow maximization or minimization of certain parameters which will be used to optimize cost and other areas of interest.

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Appendix A

Installation Costs using RS Means

Common Costs for all systems:

1. Demo of Coal Boiler (pg. 246)
 - a. Used gas/oil costs due to no numbers available for coal
 - b. Crew: Q-7
 - c. Daily Output: 0.8
 - d. Labor Hours: 40
 - e. Labor Costs: \$2050
 - f. Total Including O&P: \$3075
2. Chapel Radiator work: \$5000
3. Electrical Revisions: \$2000

Total: \$10,075

Individual Costs for each systems

Biomass (pg. 362)

1. Smallest available in RS Means: 1280 MBH
 - a. Materials: \$34,800
 - b. Labor: \$3,375

Total: \$43,300

Electric (pg. 522)

2 boilers required

1. 60 KW, 205 MBH
 - a. Materials: \$8,025
 - b. Install: \$3,725
 - c. Total: \$11,750
2. 120 KW, 410 MBH
 - a. Materials: \$10,300
 - b. Install: \$4,475
 - c. Total: \$14,775

Total: \$26,525

Propane (pg. 524)

2 boiler required

1. 200 MBH
 - a. Material: \$8,975
 - b. Install: \$5,675
 - c. Total: \$14,650

2. 440 MBH
 - a. Material: \$12,800
 - b. Install: \$7,975
 - c. Total: \$20,775
3. Above ground 5000 gallon steel horizontal tank
 - a. Material: \$6,075
 - b. Install: \$515
 - c. Total: \$7475

Total: \$42,900

#2 Fuel Oil (pg. 525)

1. 876 MBH
 - a. Material: \$32,000
 - b. Install: \$14,800
2. Above ground 5000 gallon steel horizontal tank
 - a. Material: \$6,075
 - b. Install: \$515
 - c. Total: \$7475

Total: \$54,275

Storage Tank Cost

Propane: 92 KBtu per gallon

- 6.5 gallons/hr at max heating load
- assume 12 hrs of operation a day
- 78 gallons a day for 30 days
- 2340 gallons a month
- *get a 5000 gallon tank so they only have to refill every other month*

Fuel oil: 140 KBtu per gallon

- 4.5 gallons/hr at max heating load
- assume 12 hrs of operation a day
- 54 gallons a day for 30 days
- 1620 gallons a month
- *get a 5000 gallon tank so they only have to refill every 3rd month*