Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Heat or Power: Proposing Geothermal Development on the Basis of Fossil Fuel Displacement

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Keywords: geothermal, power, heat, binary power plant, fossil fuel, Canada, resource assessment, Monte Carlo

ABSTRACT

This study applies a fossil fuel savings approach to the evaluation of a prospective geothermal reservoir near the town of Hinton in Western Alberta, Canada. The energy content of the resource was estimated and two exclusive development scenarios – power generation and space heating – were analyzed. Monte Carlo simulations were used to estimate the thermal power available in the sample reservoir, resulting in a potential wellhead thermal output of 226 MWth at 95% cumulative probability for a project lifetime of 50 years. The thermal power was converted to a brine flow rate estimate of 540 kg/s at the average reservoir temperature of 118°C.

Using the estimated geothermal flow rate as an input, a binary power plant was modelled and optimized in Engineering Equation Solver (EES). The resulting n-butane power plant model produced 12.1 MWe net power at a thermal efficiency of 9.2%. Colder air temperatures in the winter resulted in an output of 16.1 MWe, while a minimum of 9.5 MWe is produced by the model in summer conditions. A residential district heating system, the second development scenario, was modelled in EES using an 80/40/-20 design criteria. The design resulted in a system capable of heating over 18,000 houses year-round, with excess energy at ambient temperatures above -20°C available to a larger heating system and/or industry partners. The heating system operates at 92.4% energy efficiency under design conditions.

The power plant scenario provides 108 GWh annually, which translates to 649 TJ of fossil fuel energy savings per year. The district heating option provides a total of 3840 TJ of thermal energy annually, resulting in a fossil fuel savings of approximately 4267 TJ – an increase of 557% from the power generation scenario. As the district heating network operates at lower than maximum capacity for much of the year, its project lifetime can be prolonged to 630 years if used exclusively for Hinton residential heating. The prospective heating network would then save 213 PJ (5.76B m^3 NG) of non-renewable energy, more than six times the 32.4 PJ (0.87B m^3 NG) saved under the power generation scenario. Correspondingly, the greenhouse gas emissions avoided in the heating scenario amounts to 10.8 Mt CO_2, compared to just 1.6 Mt in the power generation scenario.

The seminal finding from the study is the conclusion that the fossil fuel energy payback of direct-use heating utilization was 6.6 times that of indirect power generation. Developing available geothermal resources to replace space heating most readily fulfills the objective of displacing the maximum amount of non-renewable energy. The results of this case study analysis are applicable to any similar community with an energy economy dominated by fossil fuels.

1. INTRODUCTION

Globally, energy produced by geothermal power generation is roughly equivalent to that of geothermal direct-use applications – 73.5 GWh and 70.9 GWh in 2015 respectively (Bertani, 2015) (Lund and Boyd, 2016). Both direct and indirect sectors have experienced signification growth in the past two decades, but, as a whole, geothermal development has not kept up with the exponential growth of other renewables; namely wind and solar energy. However, the fact that geothermal energy can be harnessed in two different methods - direct and indirect - makes it unique among renewable energy sources. As a result, individual applications of geothermal energy can be customized to suit different needs across many industries and can also be applied in a cascading manner to maximize energy usage from a geothermal resource.

This study aimed to determine the value of a moderate-temperature reservoir under two exclusive development scenarios - power generation and direct-use space heating – based on the amount of non-renewable energy displaced in each scenario. A case study approach was taken to assess a potential resource in Western Alberta, Canada and evaluate the outcomes of the two development scenarios with respect to the current energy delivery systems in place. The ultimate goal of the study is to quantify the difference between the fossil fuel energy displacement of the power and heating options. The disparity of the fossil fuel savings, or lack thereof, between the development options can then be factored into development decisions of future greenfield geothermal projects, especially those proposed in energy markets saturated with fossil fuels. A depiction of the study progression is shown in Figure 1.

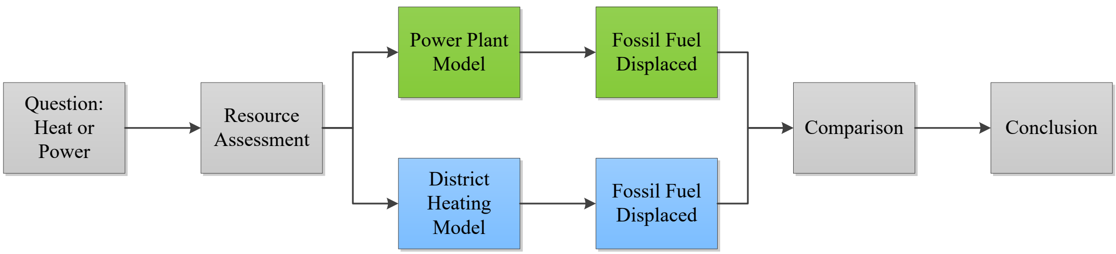

Figure 1: Visual representation of study structure

1.1 Case Study Location

Canada has tremendous potential to reduce its dependence on fossil fuels by employing geothermal energy (Thompson, Bakhteyar and Van Hal, 2015). The country's commercial-scale geothermal resources are available in two forms: high-temperature volcanic regions and a low- to moderate-temperature sedimentary basin. Both types of resources are limited to the western part of the country. See Figure 2 for a summary of Canada's geothermal resources.

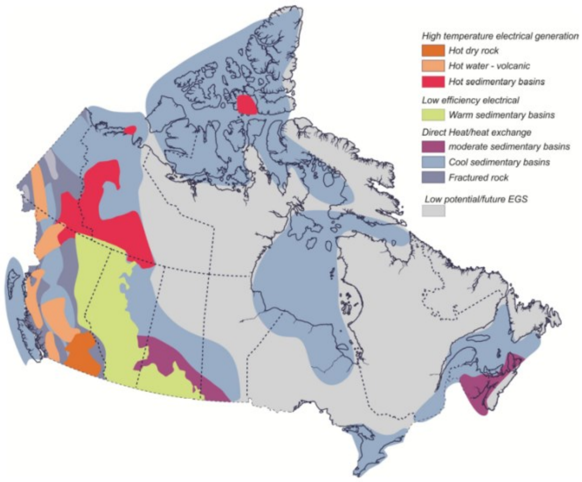

Figure 2: Map of Canada's potential geothermal resources by geology and potential utilization. (Grasby *et al.*, 2012)

The Western Canadian Sedimentary Basin (WCSB) represents Canada's most accessible geothermal resource and contains the area of interest for this study (Jessop, 1998). The town of Hinton, shown in Figure 3 on the western border of the WCSB where the basin is deepest, was chosen as the location for this case study. Recent energy statistics for Hinton and Alberta were used to calculate average household energy consumption and well log data were used to calculate a volume of the WCSB near the town, designated as the prospective geothermal reservoir. The two development options - heating and power - were evaluated based on both their ability to serve the individual town of Hinton and also the maximum amount of deliverable energy over a 50-year project lifetime.

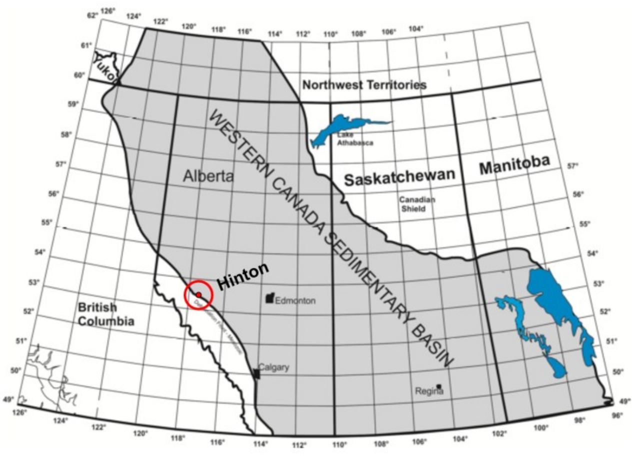

Figure 3: Geographical location of the town of Hinton relative to the WCSB. Adapted from Grasby et al. (2012)

1.2 Alberta Household Energy Consumption

<u>1.2.1 Space Heating</u>

Water and space heating are responsible for over 80% of residential energy consumption in Canada, with heating alone accounting for almost two-thirds (Natural Resources Canada, 2016b). Space heating in Alberta is predominantly achieved through natural gas combustion, with forced-air furnaces as the chosen heating system for 94% of residences in the province (Statistics Canada, 2011). The high heating demand results in an annual natural gas consumption of 119 GJ compared with an electricity consumption of 26 GJ (7200 kWh) (Statistics Canada, 2013). The comparison between household electricity and heating consumption is depicted in Figure 4.

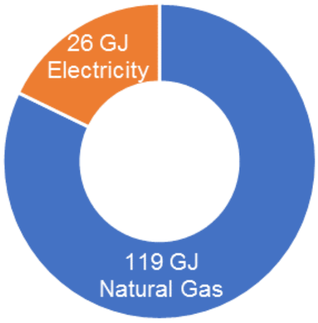

Figure 4: Average annual energy consumption by fuel type in Albertan households. (Statistics Canada, 2013)

There were 3,670 occupied households in Hinton as of a 2016 census. It is assumed, for the purposes of this study, that households in Hinton follow the average Canadian and Albertan heating statistics previously described. An Albertan uses 119 GJ for water heating and space heating combined, with space heating representing 77% (from (Natural Resources Canada, 2016a): 64% / (64% + 19%) = 77%), or 91.8 GJ, of the energy consumption. As of 2009, all furnaces installed in Canada were required to have a minimum efficiency of 90% (Natural Resources Canada, 2017). With this regulation and the provincial heating statistics, it is concluded that the average Albertan household requires 82.6 GJ of thermal energy for space heating, as shown in Table 1.

Table 1: Alberta household heating by natural gas.

Household Usage	119 GJ
Water Heating	27.2 GJ
Space Heating	91.8 GJ
Furnace Efficiency	90%
Space Heating Thermal Energy Required	82.6 GJ

1.2.2 Electricity

While fossil fuel sources are responsible for only 20% of electricity generated nation-wide, they make up the vast majority of Alberta's electricity market (Natural Resources Canada, 2016b). As shown in Figure 5, 90% of the electricity consumed in the province was generated by either coal or natural gas.

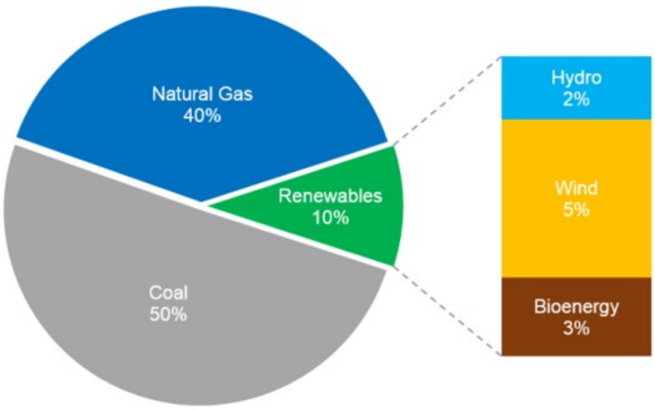

Figure 5: Source of electricity generation in Alberta in 2016. Total generation = 84 TWh. (Alberta Utilities Commission, 2017)

Electricity consumption for the town of Hinton was received from the local utility provider for this study. The consumption data were divided into categories by type of customer and was provided for 2013 through 2015, as shown in Table 2. For the purposes of this study, it is assumed that current residential and total electricity demand of the town is equivalent to that of 2015, where residential consumption was 27.9 GWh, or an average of 3.2 MWe.

Table 2: Hinton Electricity Consumption for 2013-2015

Category	Electricity Consumption (GWh) 2013	2014	2015
Residential	28.1	28.8	27.9
Town Total	116.5	143.6	139.0

2. RESOURCE ASSESSMENT

2.1 Resource Definition

Due to widespread oil and gas exploration in Alberta, existing wells in the WCSB number in the hundreds of thousands, resulting in an extensive database of down-hole data. The University of Alberta Geothermal Energy Group has worked with several industry partners to acquire well log data for the purposes of mapping potential geothermal resources. These data included 70 wells within a 50 km radius of the town of Hinton, which formed the basis of the resource assessment for this study. Well-log data from these wells was used by the University of Alberta to generate a geological model of the formations in the Cretaceous period found between 3 and 4 km depth, and allowed for this study to characterize their geothermal potential. A summary of the formations is given in Table 3 below. Together, these formations constitute the prospective geothermal reservoir for this study.

Table 3: Summary of Cretaceous formations used for resource assessment

Formation	Study Volume (km^3)	Average Depth (km)	Average Temperature (°C)
Viking	4.96	3.33	115
Upper Mannville	168	3.46	115
Middle Mannville	60.8	3.65	125
Cadomin	8.24	3.72	129

2.2 In-Place Method

The available energy in geothermal reservoirs is commonly estimated using the USGS volumetric “heat in-place” method (Williams, Reed and Mariner, 2008). Using measured or estimated values of the reservoir volume, temperature, and thermal properties, the energy stored in the geothermal reservoir is calculated by

$$q_{th} = \overline{\rho c}\,(T_R - T_r) \tag{1}$$

where:

q_{th} = Thermal energy stored in reservoir

$\overline{\rho c}$ = Volumetric heat capacity of fluid-saturated rock (= $\varphi\rho_w c_w + (1-\varphi)\,\rho_r c_r$)

$\rho_w(\rho_r)$ = Density of water (rock)

$c_w(c_r)$ = Specific heat of water (rock)

φ = Rock porosity

V = Reservoir volume

T_R = Reservoir Temperature

T_r = Reference Temperature

These reservoir characteristics are typically estimated through geological and geophysical surveys of the area and proven quantities from previous comparable project. The potential energy recoverable at the well head is then calculated by

$$R = q_{wh} / q_{th} \tag{2}$$

where q_{wh} is the recovered thermal energy, q_{th} is the total thermal energy, and R is the recovery factor. Next, the enthalpy of the geothermal fluid at the wellhead can be calculated by

$$h_{wh} = h_R - Dg \tag{3}$$

where h_R is the enthalpy of the geothermal fluid at the reservoir temperature, D is the average reservoir depth, and g is gravity. Mass flow rate at the wellhead can then be determined from the wellhead power by

$$\dot{q}_{wh} = \dot{m}_{wh} (h_{wh} - h_r) \quad (4)$$

where $\dot{q}_{wh}$ is the recoverable wellhead power (wellhead energy over the defined project lifetime), $\dot{m}_{wh}$ is the brine flow rate, h_{wh} is the wellhead enthalpy from Equation 3, h_r is the enthalpy of the geothermal fluid at the reference temperature.

Following the USGS method would dictate a calculation of the available energy of the geothermal fluid at this point. A measure of the anticipated power plant exergetic efficiency, known as the utilization factor, would then be applied to determine the potential for total electricity production. Amortization of the electricity over a project lifetime, typically 30 to 50 years, provides the size of power plant recommended by the method.

These final steps are omitted from the resource estimate for this study. Modelling of a basic power plant and heating system is used in their place to provide a more detailed estimate of energy efficiency for both options. Therefore, the output of the resource assessment in this case is the annual thermal power at the wellhead and the corresponding geothermal mass flow rate.

2.3 Monte Carlo Simulation

Due to the uncertainty inherent in many of the required parameters, a Monte Carlo simulation is often used in the application of the heat in-place method. This approach allows the parameters of Equation 1 to be represented as a unique distribution (e.g. beta, triangle, uniform) of values across a plausible range. Each iteration of the simulation employs random number generation to select a value for each parameter relative to its user-defined distribution. The wellhead power is then calculated using the equations defined in the previous section. The simulation must run a statistically significant amount of iterations - typically in the thousands for geothermal applications - and the result is a probability distribution of possible outcomes.

Well log data were used to determine accurate ranges and distributions for reservoir temperature and porosity. Literature review of WCSB geological studies and worldwide geothermal power projects were used to characterize the remaining variables. See Table 4 for the input parameters for the Monte Carlo simulation of one formation (Middle Mannville). For more detail on the description of each variable and the selection of its range and distribution, please see Section 2.2 in Lavigne (2018).

Table 4: Input parameters for Monte Carlo simulation for one of the four formations of interest.

Parameter	Unit	Minimum	Most likely	Maximum	Distribution
Reservoir Area	km^2	-	702.6	-	Fixed
Reservoir Thickness	m	-	86.47	-	Fixed
Reservoir Temperature	°C	106	125	140	Triangular
Recovery Factor	%	0%	5%	10%	Even
Porosity	%	0%	2%	7%	Beta
Specific Heat of Rock	kJ/m^3/°C	2125	2277.5	2430	Beta
Average Reservoir Depth	m	-	3500	-	Fixed
Ambient Temperature	°C	-	2.4	-	Fixed
Plant Capacity Factor	%	-	90%	-	Fixed
Project Lifetime	years		50		Fixed

2.4 Thermal Power Estimate

The volumetric assessment was calculated by performing a heat-in-place Monte Carlo simulation for each of the four stratigraphic formations to more accurately capture their geothermal potential using their individual temperature and porosity distributions. A resource estimate for the prospective reservoir was achieved by combining the results from all four Monte Carlo simulations. The thermal power estimates are added together at each cumulative probability interval resulting in the distribution shown in Table 5 below.

Table 5: Results of thermal power Monte Carlo simulation of each formation for a 50-year project lifetime.

Cumulative Probability	Thermal Power (MWth)				
	Viking	Upper Mannville	Middle Mannville	Cadomin	Combined
100%	0	0	0	0	0
95%	4	155	58	8	226
90%	9	309	121	17	455
75%	22	786	302	43	1153
50%	45	1558	606	86	2295
25%	69	2329	904	129	3431
10%	83	2802	1084	155	4123
5%	88	2984	1158	164	4394
0%	106	3619	1408	196	5329

A conservative cumulative probability of 95% was designated for this study. The probability selection, along with the conservative choices for several of the input variables, suggests that the resultant thermal power of 226 MWth over a project lifetime of 50 years represents the absolute minimum production should this reservoir volume be developed.

The estimated thermal power can then be converted into a flow rate of geothermal brine by using the equation for wellhead thermal power, given as

$$\dot{Q}_{wh} = \dot{m}_{wh}(h_{wh}-h_r) \tag{5}$$

where $\dot{Q}_{wh}$ is the estimated thermal power at the wellhead, $\dot{m}_{wh}$ is the brine flow rate, h_{wh} is the enthalpy of the geothermal fluid at the wellhead, h_r is the enthalpy of the geothermal fluid at the reference (ambient) temperature.

The values used for temperature and depth were generated by averaging the formation mean values, weighted by their proportional contribution to thermal power in the Monte Carlo simulation. The enthalpies used in the calculation assumed a geothermal brine with high saline content as is common in the WCSB. The resulting wellhead flow rate of 118°C brine, as found from Equation 5, was determined to be 540 kg/s, or 2.4 kg/s per MWth.

3. SCENARIO METHODOLOGY

3.1 Power Scenario

The completion of the resource assessment results in a defined geothermal fluid flow which can then be considered for utilization. The first utilization scenario presented in this study is the development of a geothermal binary power plant.

A basic sub-critical organic Rankine cycle (ORC) was modelled in Engineering Equation Solver (EES) to estimate the power generation potential of the geothermal resource in this study. A depiction of the power cycle is shown in Figure 6 on a temperature-entropy diagram, and again in Figure 7 in terms of ORC components. States 1 through 5 on the diagram represent the ORC, while states 11 to 13 and 21 to 23 represent the heat source and sink fluids respectively.

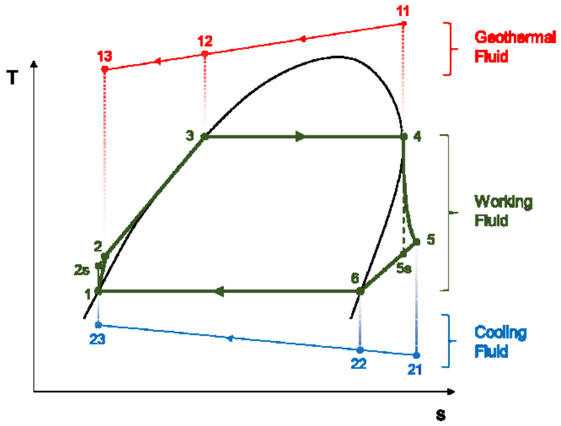

Figure 6: ORC geothermal binary power cycle represented on temperature-entropy diagram along with geothermal fluid and cooling fluid states.

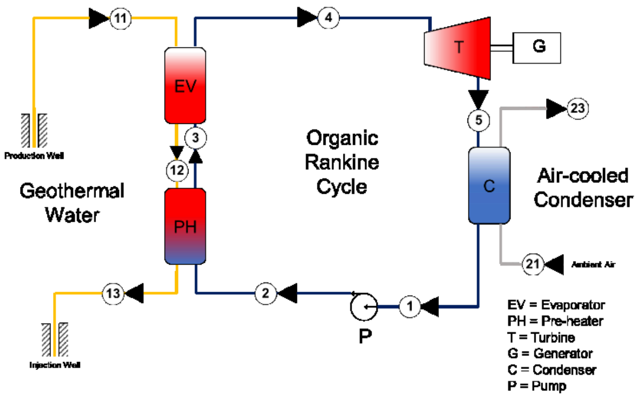

Figure 7: Process flow and components of geothermal binary power plant model.

While the power plant components are not described in detail, it is worth noting that an air-cooled condenser, rather than water-cooled, was chosen for the model. The northern climate and correspondingly low air temperatures year-round are conducive to the use of an air-cooled condenser. The average ambient temperature in the Hinton area is 2.4°C, with monthly average fluctuations between -10.0°C in the winter and 13.7°C in the summer as shown in Figure 8.

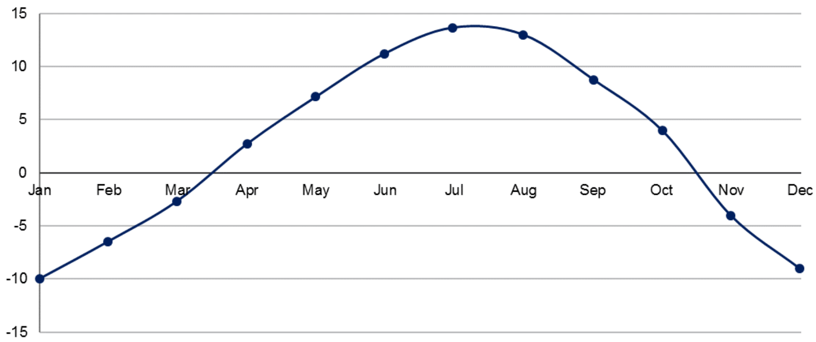

Figure 8: Monthly average temperatures in Hinton for 2017.

Once the power plant was modelled, net power output was optimized for several common ORC working fluids - butane (R600), isobutane (R600a), pentane(R601), isopentane (R601a), and R245fa. The key input parameters for the model and subsequent optimization are listed in Table 6.

Table 6: Input parameters for EES power plant model. (Lavigne, 2018)

Parameter	Value	Units
Brine Flow Rate	540	kg/s
Brine Temperature	118	°C
Brine NaCl Conc'n	6.4	%
Ambient Temperature	2.4	°C
Evaporator Pinch	7.5	°C
Condenser Pinch	5	°C
Turbine Efficiency	0.85	-
Pump Efficiency	0.80	-
Fan Efficiency	0.70	-
Motor Efficiency	0.95	-
Generator Efficiency	0.96	-
Fan Differential Pressure (dP)	0.1	bar
Preheater dP	0.5	bar
Evaporator dP	0.5	bar
Piping Network dP	1.0	bar

3.2 Heating Scenario

The heating scenario consists of a district heating system designed to provide heating to as many homes as possible given the input of geothermal brine determined in the resource assessment. A closed-loop heating design, as opposed to flow-through, was chosen for this study due to the expected high dissolved solids and salinity of the prospective geothermal brine (Connolly *et al.*, 1990). A schematic of the heating system is shown in Figure 9.

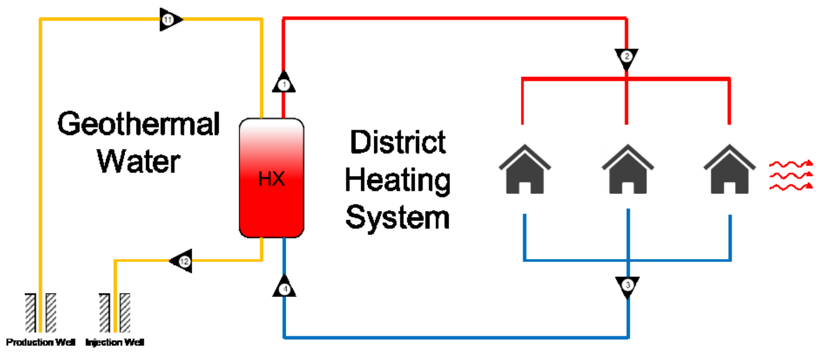

Figure 9: Diagram of closed-loop geothermal district heating system.

To determine a suitable radiator design scenario and its relative supply and return temperatures, heating system design methodology from Iceland was investigated. Systems in Iceland are designed to provide the majority of base-load heating, down to a minimum ambient temperature of -15°C. The Icelandic design scenario is described, in terms of the system temperature parameters (°C), as 80/40/-15/20 (Radiator supply / return / ambient / room temperatures) (Karlsson and Ragnarsson, 1995). This study takes a similar approach to the design scenario, but accounts for a slightly lower minimum ambient temperature due to the colder Canadian prairie winters. The flow rates and heat exchanger sizes were designed to a standard of 80/40/-20/20 for this study. Key inputs and assumptions are described in Table 7, with more detail provided in Lavigne (2018).

Table 7: Input parameters and assumptions used in district heating model.

Parameter	Value	Units
Household Thermal Energy Demand	82.6	GJ/year
Heat Transfer Coefficient of Radiator	5.6	$W/m^2°C$
Heat Transfer Coefficient of Central Heat Exchanger	1000	$W/m^2°C$
Overall Heat Transfer Coefficient of a Household	165	W/°C
Radiator Supply Thermal Energy Loss	3	%
Radiator Return Thermal Energy Loss	2	%

3.3 Scenario Comparison

3.3.1 System Efficiencies

Thermal efficiency, as derived from the first law of thermodynamics, was used to evaluate the performance of the geothermal binary power plant. The thermal efficiency is defined as

$$\eta_P = \frac{\dot{W}_{net}}{\dot{Q}_{geo}} \tag{6}$$

where η_P is the thermal efficiency of the geothermal power plant, $\dot{W}_{net}$ is the net power output of the plant, and $\dot{Q}_{geo}$ is the energy input from the geothermal brine.

As the heating system does not perform work, it is evaluated on its ability to transfer heat from the geothermal fluid to individual households and its efficiency is calculated by

$$\eta_H = \frac{\dot{Q}_H}{\dot{Q}_{geo}} \tag{7}$$

where η_H is the energy efficiency of the geothermal heating system, $\dot{Q}_H$ is the total thermal energy delivered to the households, and $\dot{Q}_{geo}$ is the energy input from the geothermal brine.

3.3.2 Fossil Fuel Displacement

While the calculation of energy efficiency is a valuable comparison for the two development scenarios, the objective of the study is to determine which of the scenarios results in more fossil fuel displaced. In other words, the comparison of the scenarios is dependent not only on the output of the geothermal models, but also on the efficiency of those non-renewable energy systems that would be supplanted in each case.

As shown previously in Figure 5, natural gas power plants supply approximately 40% of Alberta's electricity. Due to operational advantages and environmental concerns, natural gas would be the likely fuel source over coal for any new non-renewable power plant in Alberta. Combined cycle natural gas plants can reach thermal efficiencies of 60% (International Energy Agency, 2017).

As described previously, heating for the vast majority of households in Alberta is provided by forced-air natural gas furnaces, with a minimum thermal efficiency of 90%. Therefore, the fossil fuel displacement for the two geothermal development options are calculated using fossil fuel system efficiencies of 60% and 90% for power and heating respectively.

Non-renewable energy savings of the systems are calculated in Joules, as per

$$q_D = \frac{q_i}{\eta_{FF,i}} \tag{8}$$

where q_D is the fossil fuel energy displaced by the geothermal system, q_i is the energy provided by the geothermal system over its lifetime (where $i \in P, H$), and $\eta_{FF,i}$ is the efficiency of the existing fossil fuel energy system to be replaced.

Displaced fossil fuel energy was also converted to an equivalent volume of natural gas. Natural Resources Canada lists natural gas with an energy content of 37.3 MJ/m^3 (Natural Resources Canada, 2015). Note that both power and heating efficiencies are end-user efficiencies and do not include the energy used in the current extraction and transportation of natural gas for use in space heating and power generation. These additional inefficiencies are assumed to be equivalent across the scenarios.

4. SCENARIO RESULTS

4.1 Power Scenario

The EES power plant model was optimized to maximize net power output for all five working fluids. Condenser and evaporator temperatures were identified as the independent variables and adjusted until a global maximum within the constraints was found. Primary results from the optimization are listed in Table 8.

Table 8: System parameters of optimized power plant model for selected working fluids.

Working Fluid	Condenser Temp (°C)	Evaporator Temp (°C)	Working Fluid Flow Rate (kg/s)	Gross Power (MWe)	Net Power (MWe)	η
Isopentane	14.0	66.7	302	14.3	12.0	9.17%
n-pentane	14.0	66.4	284	14.1	11.8	9.15%
Isobutane	14.0	68.2	332	15.2	12.4	9.10%
n-butane	14.0	67.3	296	14.7	12.1	9.20%
R245fa	14.0	67.5	565	14.7	12.2	9.22%

It is shown that, with the given model assumptions, the working fluids perform similarly in their respective optimized plants. Other factors, such as specific power (power output per unit area of heat exchanger), operating pressures, and working fluid volumetric flow rate, were used to select the design working fluid. These factors have a substantial effect on the capital cost, operating and maintenance costs, and operational logistics of a prospective plant. The criteria and subsequent rankings are given in Table 9, with n-butane as the highest-ranked working fluid.

Table 9: Secondary evaluation parameters for optimized power plants. (Lavigne, 2018)

Working Fluid	Condenser Pressure (bar)	Evaporator Pressure (bar)	Specific Power Output (kW/m^2)	Volumetric Flow Rate (m^3/s)	Piping Diameter Ratio	Final Ranking
Isopentane	0.61	3.26	0.625	169.6	1.79	4
n-pentane	0.45	2.57	0.625	216.8	2.02	5
Isobutane	2.51	10.45	0.610	52.9	1.00	2
n-butane	1.71	7.61	0.622	70.8	1.16	1
R245fa	0.97	5.70	0.622	104.5	1.41	3

4.1.1 n-Butane Model

A visual representation of the net power optimization of the n-butane model is depicted in Figure 10. The optimization maximum was found at a condenser temperature of 14.0°C (P_{sat} = 1.71 bar) and evaporator temperature of 67.3°C (P_{sat} = 7.61 bar) and resulted in a maximum net power of 12.1 MWe.

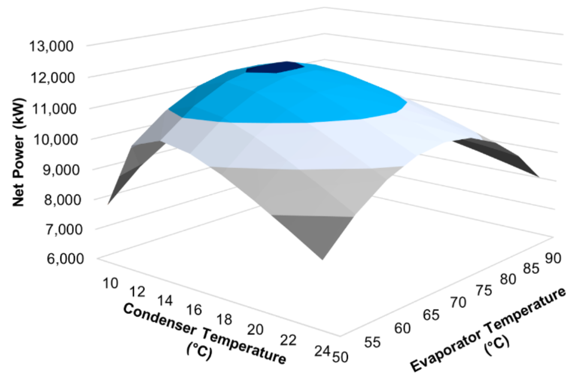

Figure 10: Net power optimization of n-butane power plant model.

Due to the selection of an air-cooled condenser, the power plant net output would fluctuate throughout the year with changes in ambient air temperature. Seasonal variation of the model was evaluated by allowing the evaporator and condenser to migrate to optimized temperatures for average winter and summer conditions, while holding the power plant infrastructure constant. The highest and lowest average monthly temperatures in Hinton, 13.7°C and -10.0°C, produced average monthly net power outputs of 9.47 MWe in summer conditions, and 16.1 MWe in winter.

An approximation of monthly power output (based on average monthly temperatures shown in Figure 8) was calculated by generating a polynomial expression for net power output as a function of ambient temperature using the summer, winter, and design models. Monthly average power outputs estimated by this method are shown in Figure 11 along with the estimated total monthly generation.

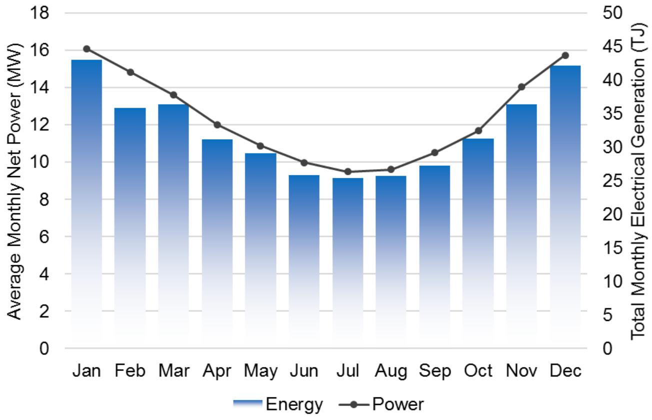

Figure 11: Average net power and total monthly generation of geothermal power plant

The total annual energy output of the power plant model can then be approximated by combining the output from each month. The power plant is estimated to provide 390 TJ (108 GWh) of electricity annually from the geothermal reservoir over the project lifetime of 50 years.

4.2 Heating Scenario

The district heating network was designed to serve the maximum number of typical Albertan households at the coldest expected daily average temperature. The system was designed from the household radiator side, using an 80/40/-20/20 (supply/return/ambient/room) standard, as explained in Section 3.3.

The design of the district heating system is constrained by the amount of energy transferred from the geothermal brine. The outlet temperature of the geothermal fluid from the central heat exchanger was set to match the outlet temperature of the preheater in the power plant model to ensure the energy input was equal for each scenario. This constraint, along with the 80/40/-20/20 parameters, allowed the model to be solved for its design configuration. The central heat exchanger area was established at 5258 m^2, resulting in a total radiator fluid flow of 728 kg/s, as shown in Table 10.

Table 10: Fluid type and stream temperatures of the district heating system central heat exchanger.

Heat Exchanger Side	Fluid	Flow Rate (kg/s)	Inlet Temp (°C)	Outlet Temp (°C)
Geothermal	NaCl Brine	540	118	56.1
Radiators	Water	728	39.2	82.6

With the design constraints described, the resulting heating network model was able to provide over 18,000 households with their space heating requirements at worst case design conditions. The radiator heat transfer details of the heating system are summarized in Table 11.

Table 11: Summary of household radiator parameters for heating network design.

Parameter	Value	Units
No. of Households	18447	
Design Load per Household	6.6	kW
Radiator Area per Household	32.37	m^2
Supply Temperature	80	°C
Return Temperature	40	°C
Flow Rate per Household	0.0395	kg/s

The heating system, as modelled, provides up to 3840 TJ of thermal energy annually over the 50-year life of the geothermal reservoir.

5. DISCUSSION / FOSSIL FUEL DISPLACEMENT

5.1 Total Energy Delivered

It is assumed that either system – power plant or heating system – would be throttled according to demand throughout the project lifetime such that little to no energy output would go unused. Total energy provided by the power and heating scenarios over the project lifetime was calculated to be 19.5 PJ and 192 PJ respectively. This, almost ten-fold, disparity is to be expected by noting their vastly different system efficiencies of 9.2% and 92.4%, along with the fact that the input geothermal energy was equal in both scenarios. Figure 12 provides a visual comparison of the total energy delivered by the scenarios.

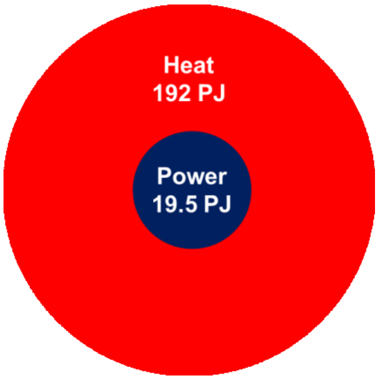

Figure 12: Total energy delivered by space heating and power plant models. Energy is proportional to circle area.

5.2 Hinton-specific Scenario Lifetimes

The development scenarios for this study are evaluated on two criteria. One criterion is the magnitude of displaced fossil fuel energy based on the total energy output of each scenario, given an equivalent amount of input geothermal energy. Another criterion is how effectively each scenario could serve the residences of the nearby town of Hinton.

As designed, the power plant would provide 108 GWh annually with an output of 12.1 MWe at the average annual ambient temperature. However, the Hinton residential power consumption in 2015 was just 27.9 GWh. Assuming the demand follows roughly the same seasonal fluctuation as the plant net power output, the plant could be theoretically downsized to serve only the residential demand of the town (AESO, 2016). In this scenario, if demand remains constant at 2015 levels, the power plant could provide the entirety of the residential power demand for 193 years.

The same approach can be taken with the heating system. Households in Hinton number 3,670 - far less than the maximum number of houses that could be served by the design heating network. If the design network was modified to match the heating demand of residential Hinton alone, it would output 301 TJ annually, extending the lifetime of the heating network to 638 years. This timeline would surely qualify the heating network as a sustainable enterprise.

5.3 Fossil Fuel Displacement

While the heating scenario provides almost ten times the energy of the power generation scenario, this does not tell the whole story. Thermal energy is low-grade energy that has limited applications, whereas electricity is higher-grade, organized energy which can be used for a multitude of applications and is thus more valuable. The method of fossil fuel energy displacement is used to evaluate the scenarios on equal footing.

Energy efficiency of displaced non-renewable energy systems was determined to be 60% and 90% for power and heating respectively, as detailed in Section 3.4.2. Using these system efficiencies, the displaced non-renewable energy of the power scenario was determined to be 32.4 PJ, compared with 213 PJ in the heating scenario. The heating scenario provides over 6 times the fossil fuel savings of the power plant scenario, with 5.72 billion m^3 and 0.87 billion m^3 natural gas displaced respectively, as depicted in Figure 13.

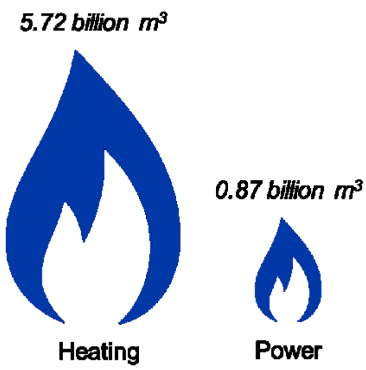

Figure 13: Total natural gas volume displaced by development options.

It is the greater than 6 to 1 (6.6:1) ratio regarding displaced fossil fuel that is the most instructive comparison of this study. Knowledge of the difference in energy payback, relative to regional markets, will allow for resource owners (governments, communities, private companies, etc.) to focus on the most productive development of geothermal resources.

5.4 Greenhouse Gas Emissions Avoided

The greenhouse gas emissions avoided as a result of the non-renewable energy savings can also be taken into consideration in project planning stages. Approximately 50.3 kg of CO_2 is emitted per GJ of natural gas (International Energy Agency, 2017). Following the non-renewable energy and natural gas savings ratios, the heating network results in 6.6 times more avoided emissions at a total of 10.8 Mt of CO_2.

6. CONCLUSION

The objective of this study was to estimate the magnitude of geothermal energy available in a sample region in Alberta and quantify, at a high level, the energy payback of two different development options based on displaced non-renewable energy.

The resource assessment with largely conservative parameter choices proves there is significant geothermal energy potential present in the WCSB, even at relatively shallow depths. With reasonable alternative selections of key assessment variables and cumulative probability, a thermal power estimate of an order of magnitude higher than the study value of 226 MWth could be justified. This assessment adds to numerous analyses in previous studies which have purported the WCSB to be a massive source of geothermal energy.

A basic EES-modelled geothermal binary power plant produced a net power output of 12.1 MWe and thermal efficiency of 9.2% with n-butane as its working fluid. Designed with an air-cooled condenser, the model power output dropped to 9.5 MWe at average summer temperatures and increased to 16.1 MWe in winter. The power plant, over its lifetime, was found to produce 19.5 PJ (5.4 TWh) of energy and displace a potential 0.87B m^3 of natural gas.

Next, with the same geothermal input, a district heating network was designed to provide heating to as many houses as possible at a design condition of 80/40/-20 (supply/return/ambient temperature in °C). It was found that over 18,000 houses could be serviced by the network for a 50-year lifetime. Alternatively, if the network was restricted to only the households in Hinton, it could provide heating for the residences for over 600 years.

Under the constraints of the study, the heating network provided 192 PJ of energy, representing 5.72B m3 of displaced natural gas, and most notably, outperformed the power scenario on a higher than 6:1 basis with respect to fossil fuel energy displacement, as summarized in Table 12. While one may have predicted that geothermal heating would provide the higher non-renewable energy payback, due to the disparity between the energy efficiencies of these types of systems, a case study comparison clearly quantifies the difference between the development options.

Table 12: Comparison of development scenario results

	Geothermal		Fossil Fuel		
Development Scenario	System Energy Efficiency*	Energy Delivered (PJ)	Energy Displaced (PJ)	Energy Displaced (billion m^3 Natural Gas)	Emissions Avoided (Mt CO_2)
Power	9.2%	19.5	32.4	0.87	1.6
Heating	92.4%	195	213	5.76	10.8

*Efficiency calculation described in Section 3.4.1

The comparisons performed in this study were completed on purely an energy basis, with no consideration given to the economics of the two development options. Obviously future geothermal projects will have to be evaluated on their individual economic feasibility. For example, it may be cost effective to develop a central geothermal heating system for a new residential development, but would likely not feasible to convert an existing community with household furnaces to a central geothermal district heating system. Likewise, it is unlikely that geothermal plant would be feasible in most areas in the province without heavy subsidies, but could potentially be viable in remote communities whose electricity is supplied by diesel generators.

The basis of this study was the application of the novel approach of fossil fuel displacement to evaluate a greenfield geothermal reservoir. The objective was not to provide specifics of development scenarios, but rather the recommended utilization method. Therefore, the conclusion, in general, is that in markets where fossil fuels supply the majority of heating and electricity, all efforts to implement geothermal energy should be focused on displacing fossil fuels in the space heating infrastructure prior to entertaining large-scale power generation projects.

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