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TECHNO-ECONOMIC AND ENVIRONMENTAL PERFORMANCE COMPARISON OF DIFFERENT SYSTEMS FOR SPACE HEATING SYSTEMS IN COLD CLIMATES – CASE OF THE BOW VALLEY MUNICIPALITIES

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ABSTRACT

This study aims to investigate the feasibility of utilizing shallow geothermal systems as a means to meet the heating and cooling needs in the Bow Valley region of Canada. To evaluate the energy usage of a duplex, apartment, and hotel, building energy modelling was conducted using BEopt^{TM}. The study involved analyzing various heating systems, such as forced-air furnaces, air-source heat pumps (ASHP), groundwater heat pumps (GWHP), ground-source heat pumps (GSHP), and electric resistance heaters. The analysis was based on realistic input data, geological information, and location-specific conditions. The results showed that GSHP was the most energy-efficient heating system, followed by GWHP, cold climate ASHP, conventional ASHP, electric resistance heating, and gas furnaces. In terms of CO_2 emissions, GSHP had the lowest emissions. For the duplex, GSHP emitted 44 tCO_2 compared to 289 tCO_2 for high-efficiency gas furnaces. The economic viability of each system varied depending on factors such as location and natural gas prices. This research compared the payback period of different heating systems to high-efficiency gas furnaces. The results showed that the payback period for GSHP and GWHP ranged from 15 to 40 years, while it was 15 to 30 years for ASHP and cold climate ASHP, depending on the incentives and local conditions.

Keywords: Building energy modeling, Heat pumps, Renewable energy, Payback period

NOMENCLATURE

Roman letters

$\dot{V}$	Volumetric fluid usage $[m^3/s]$
HV	Heat value of natural gas $[MJ/m^3]$
q	Heat transfer rate $[W]$
T	Temperature [°C]

Greek letters

λ	Thermal conductivity $[W/m \cdot K]$
ρ	Density $[g/cm^3]$
ω	Moisture content [%]
θq	Quartz content $[g/cm^3]$

Superscripts and subscripts

g	ground
f	fluid
K	Kresten
s	soil
sat	saturated

1. INTRODUCTION

The persistent use of fossil fuels to meet our energy needs is contributing significantly to global warming and climate change by increasing greenhouse gas emissions. This has led to an increase in extreme weather events, diseases, and poverty caused by climate change. Therefore, it is crucial to take immediate action to reduce greenhouse gas emissions and limit the temperature rise of the earth to below 1.5 degrees Celsius above pre-industrial levels. This is necessary to avoid the catastrophic consequences of climate change [1].

Several nations have made commitments to significantly reduce their emissions. Despite Canada's commitment to reduce greenhouse gas emissions as per the Paris Agreement [2], emissions in the country slightly increased from 728 million metric tons of CO2 equivalent in 2018 to 730 metric tons in 2019 [3]. To achieve its emission reduction goals, the country needs to take significant measures to reduce emissions from all sectors. The building sector consumed over 39% of total energy and accounted for approximately 40% of direct and indirect CO_2 emissions in

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2019, making it a prominent contributor to global CO_2 emissions [4]. In 2018, buildings were responsible for over 17% of Canada's CO2 emissions, ranking third behind transportation and the oil and gas industry [5]. Space heating and domestic hot water heating were responsible for over 65% of emissions in buildings [6]. Energy usage in the building sector is expected to increase with urbanization and construction rates on the rise unless there is a significant shift in technology. Canada's Build Smart strategy aims to reduce energy consumption in buildings. It includes the Low Carbon Fund, which supports projects to make homes and buildings more energy-efficient [7]. Heat pumps, especially air-source and ground-source heat pumps, are considered immediate solutions for clean and renewable heating and cooling. Their adoption is increasing rapidly, partly due to government incentives. They have the potential to reduce approximately 500 million tonnes of carbon dioxide emissions [8]. Unlike conventional space heating systems, heat pumps have the potential to provide space heating and cooling with minimum emissions, especially, if powered with electricity from clean sources. They use minimum electrical input to provide heating by moving heat from one place to another. Ground source heat pumps (GSHPs), in particular, are highly efficient and can achieve substantial energy savings, up to 60% compared to electric resistance heating systems [9]. However, they face challenges such as ground thermal imbalances, high initial costs, and limited drilling space in densely populated areas [10]. Researchers have focused on the feasibility of shallow geothermal systems in recent years [11–13]. Hanova et al. [14] evaluated the greenhouse gas (GHG) reduction potential of GSHPs across Canada and assessed the economic cost associated with achieving these reductions. When compared to electric heating, the most substantial GHG reductions occur in regions reliant on coal-based electricity generation, notably Alberta and Saskatchewan. Transitioning from heating oil to GSHP yields annual GHG reductions exceeding 5 tonnes per household in most provinces. Notably, Newfoundland, Nova Scotia, New Brunswick, Ontario, and the Territories experience substantial operating cost savings with GSHPs, reinforcing their economic viability in heating-dominated climates with low electrical costs. The widespread adoption of GSHPs in Canada underscores their economic and environmental benefits. Furthermore, Gunawan et. al [15] considered the potential of Kuujjuaq's shallow geothermal system for residential buildings. They found that the region exhibits a substantial potential, ranging from 5.8 to 22.9 MWh/year, with increased potential at greater borehole depths. In a 50-year life-cycle cost analysis, geo-exchange options, particularly the GSHP system with solar panel-generated electricity, proved economically superior to diesel furnace heating. The most cost-effective scenario, with reduced borehole drilling costs and government incentives, resulted in a 50-year net present cost of \$179,433 for GSHP, compared to \$276,875 for the diesel furnace. Pike and Whitney [16] examined 17 heat pump projects (including GSHP, GWHP, and ASHPs) in Alaska, revealing a wide cost range for geo-exchange systems, from less than \$2000/kW to over \$12,000/kW. The life expectancy of newer heat pumps in Alaska is estimated at 20 to 25 years, with smaller ASHPs having a closer range of 15 years. Compressor replacements are common during the heat pump's lifespan, with larger units potentially requiring a costly overhaul at 12–15 years. Advances in heat pump technology are enhancing efficiency in colder climates. While some ASHPs operate in temperatures as low as -27°C, a backup heating source is recommended in Alaska's cold conditions. In alignment with findings by Healy and Ugursal [17], a study conducted in Halifax, Canada, determined that a GSHP with horizontal borehole heat exchanger is economically more viable than the prevalent oil heating system in the region. The WestJet Campus has implemented an innovative hybrid geo-exchange system that can simultaneously meet the heating and cooling demands. Two dedicated heat pumps are used to efficiently transfer heat between the cooling and heating loops, which reduces the need for a large geo-exchange bore field. The piping is installed within structural piles, which minimizes conventional boreholes. A 13,000 L water tank stores rejected cooling cycle heat, which enhances thermal storage. The building was designed using advanced modelling and optimization, resulting in over \$800,000 in capital cost savings. It is projected that the building will consume 67% less energy than a conventional design [18].

As the above studies show, there is increasing interest in the use of shallow geothermal systems in Canada. However, the performance of these systems is highly dependent on the building energy loads and climatic conditions. This study, conducted in collaboration with the Biosphere Institute of the Bow Valley [19], aims to evaluate the feasibility of using GSHP systems for space heating, cooling, and water heating in the Bow Valley Municipalities. The study compares the performance and cost of GSHP systems with conventional heating systems. Moreover, the available building energy use data is used to develop and validate building energy models. These models determine the energy loads required for a typical residential house in the Bow Valley Municipalities. Based on these energy loads, heat pump systems are designed, and their long-term performance is evaluated, taking into account the local climatic conditions and geology of the Bow Valley Municipalities. Additionally, detailed economic and environmental analyses are undertaken to establish the economic feasibility of such a system, both with and without incentives and their emission reduction potential.

2. METHODOLOGY

The methodology of this work is divided into three main parts: Geology settings, building energy loads modelling, and considered heating and cooling systems.

2.1 Geology Settings

The Bow Valley is located within the Central Rocky Mountains and Foothills of Alberta in Canada and the Bow River flows through it. Banff, Canmore, and Exshaw are population centers located in the Valley, among others. Figure 1 shows the area covered in the geological studies. According to the most updated geological maps produced by the Alberta Geological Survey (AGS), the surficial geology of the area consists of fluvial deposits in the vicinity of the Bow River and glacial till with fluvial deposits in the areas closer to the mountains [20]. Bedrock geology at the bedrock surface consists of inter-beds of Pennsylvanian, Permian, and Triassic strata, and the Jurassic and Lower Cretaceous Fernie Formation and Kootenay Group. The lithologies of these units correspond to limestone, shale, dolomite siltstone, sandstone, shale, and chert [21].

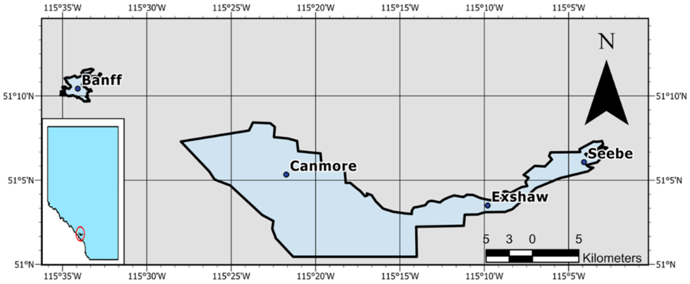


FIGURE 1: Area of coverage of the geological study; Banff and Canmore extending east to Seebe, covering Exshaw

In order to have a better understanding of the geological context and conduct a geologic feasibility study of geo-exchange systems in the area, publicly available information was collected, which included geological, sediment thickness, bedrock topography maps and cross sections, and surface water information. Groundwater information was also sought, but the findings were limited to the Alberta Water Well Information Database (AWWID) [22] and some reports with a general context of the hydrogeology of the area, such as [23].

It is crucial to determine the direction of groundwater flow when exploring shallow geothermal systems. This helps to prevent thermal interference caused by underground water and identify prime locations for GWHP systems [24]. A groundwater flow direction map was generated using static water level data from AWWID, as no such maps existed for the area. A total of 966 wells were discovered in the region and were added to ArcGIS Pro. Out of these, 675 contained data about the static water level. Using these data points, a Triangulated Irregular Network (TIN) was created and then transformed into a raster. This allowed for the flow direction to be estimated using the specific spatial analyst tool available in the software, as shown in Fig 2.

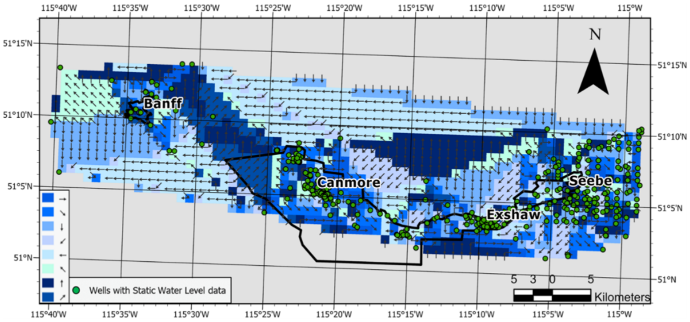


FIGURE 2: Groundwater flow direction map, with static water level data points. Eight flow directions are shown, represented by a shade of blue and arrows

Likewise, no information about the thermal properties of the soils and rocks in the study area was publicly available. This meant that the thermal conductivity of the soil and rocks had to be estimated using empirical equations and reference values from the literature [25, 26]. Equations (1)-(8) are empirical models applied to estimate the thermal conductivity of the soil.

$$\lambda_{K,Fine-grainedsoils} = \left((0.9log(w) - 0.2)10^{0.6242\rho_d - 3.4628}\right)418.6 \tag{1}$$

$$\lambda_{K,Sandysoils} = \left((0.7log(w) + 0.4)10^{0.6242\rho_d - 3.4628}\right)418.6 \tag{2}$$

$$\lambda_s = 7.7^{\theta q} \times 2^{1-\theta q} \tag{3}$$

$$\lambda_{sat} = 0.57^n \times {\lambda_s}^{1-n} \tag{4}$$

$$\lambda_{dry} = \frac{137\rho d + 64.7}{2700 - 947\rho d} \tag{5}$$

$$\lambda_{unsat} = (\lambda_{sat} - \lambda dry)\, K_e + \lambda_{dry} \tag{6}$$

$$K_{e,Sandysoils} = 0.7log\left(\frac{w}{100}\right) + 1 \tag{7}$$

$$K_{e,Fine-grainedsoils} = log\left(\frac{w}{100}\right) + 1 \tag{8}$$

Where λ_K refers to Kersten's thermal conductivity and λ_s, λ_{sat}, λ_{dry}, λ_{unsat}, to Johansen's thermal conductivity of the soil particles, that of the soil in saturated, dry, and unsaturated condition respectively $(W/m \cdot K)$. K_e is the Kersten number, w is the moisture content (%), θq is the quartz content (%), n is the porosity (%) and ρd is the dry density $(\frac{g}{cm^3})$.

After estimating thermal conductivity at different depths, a weighted average was calculated to obtain the effective thermal conductivity values for 300 and 500-foot intervals in the study area. The value of $\lambda_{(unsat25\%)}$ from the different values of thermal conductivity obtained for the surficial soil was used to calculate the weighted average. The thermal conductivity values vary between $1.1 - 2.5\ W/m \cdot K$ and $1.7 - 2.5\ W/m \cdot K$ for distances of up to 300 feet and 500 feet, respectively. However, it is important to note that these calculations do not consider the impact of convection in flowing aquifers.

2.2 Building energy loads modeling

Three different types of buildings are considered: a duplex, an apartment, and a hotel. The energy loads of buildings play a critical role in designing and operating their heating and cooling systems. Firstly, the size and type of the system are determined by the maximum or "design" loads, which ensures that it is compatible with the selected equipment. Secondly, to evaluate the overall performance of commonly used air conditioning alternatives, it is important to calculate the total energy consumption of the building for both heating and cooling purposes. This is crucial in conducting a techno-economic analysis of any selected system for building space heating and cooling.

Building energy modeling is undertaken in Beopt^{TM} software which uses the EnergyPlus^{TM} engine for the computations and the 2014 Building America Housing Simulation Protocols [27] for the simulation assumptions. The input for the building simulation is based on typical outdoor weather conditions in the Bow Valley, formatted in EPW (EnergyPlus Weather). For model validation, the duplex building's actual natural gas consumption was used. The building plan and monthly gas and electricity usage of a detached multi-family house located in, Banff, AB was received from the energy department of the Town of Banff. The building is a front/back Duplex built in 2000 with a total conditioned area of

157 m^2. For the validation case, only the front unit was modeled owing to the symmetrical nature of the building. A 3D CAD model of the unit was developed in Beopt^{TM} using the building plan. Figure 4a shows the CAD model of the duplex building.

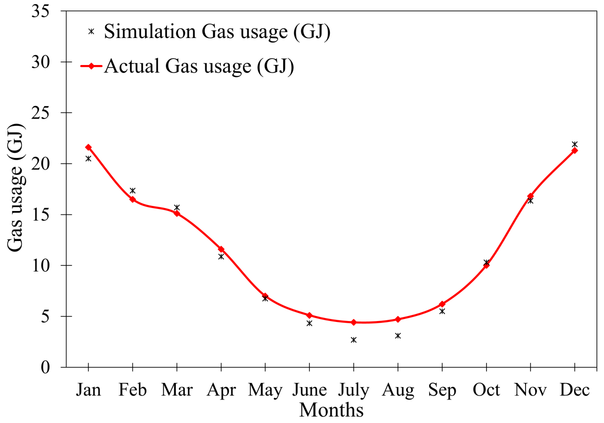


FIGURE 3: Monthly gas usage validation of the duplex building

The comparison between the actual gas usage and the simulation results is depicted in Fig. 3. The figure indicates that there is an excellent agreement between the two datasets. The maximum error observed was 6.2% in heating mode. However, the error is higher in the cooling mode, primarily due to the absence of detailed information regarding the occupants' gas usage behavior within the building in the summer.

After validating the energy model using gas consumption for a duplex building, the model was expanded to calculate energy loads for different building types. The 3D CAD models of all building types are illustrated in Fig. 4. It is worth noting that all the building models are developed based on the building plans received from the Bow Valley municipalities. Table 1 summarizes the heating and cooling peak energy loads of each building type.

TABLE 1: Energy loads in different building types

Building type	Area [m^2]	Peak heating energy load [kW]	Peak cooling energy load [kW]
Duplex	157	13.23	3.23
Apartment	1100	110.06	20.03
Hotel	10150	395.36	126.82

2.3 Considered heating and cooling systems

In this study, five different types of heating and cooling systems have been considered for all types of buildings. These include a forced air furnace, Air Source Heat Pump (ASHP), Ground Water Heat Pump (GWHP) using an underground aquifer, Ground Source Heat Pump (GSHP) with conventional borehole heat exchanger, and electric resistance heating (baseboard heating). Starting from forced air furnace systems, three levels of efficiencies i.e. high (95%), medium (80%), and low (60%) are considered. Using building energy loads and weather conditions throughout the year, the energy (natural gas) consumption for every type of the properties can be calculated using Eq. 9:

$$\dot{V} = \frac{\dot{Q}_{Building}}{\eta \times HV} \tag{9}$$

Where $\dot{V}$ is the volumetric natural gas usage, $\dot{Q}_{Building}$ is building energy loads, η is the efficiency of the furnace, and HV is the heat value of the natural gas in Canada which is about 950 BTU/hr. For the ASHP systems, two types are considered in this study: Conventional and Cold Climate (CC) ASHPs. The performance of ASHPs is analyzed using their coefficient of performance (COP) and heating capacity related to the outdoor ambient temperature. Based on the peak heating loads, the required heat pumps are selected. Figure 5 depicts the heating capacity and COP of the chosen CC ASHP for the duplex building for different outdoor ambient temperatures [28].

Based on the heating COP and capacity of the selected CC ASHP, a second-order equation can be fitted to each dataset. Equations 10 and 11 depict the COP equation for heating and cooling, respectively.

$$COP_{heating} = 0.0007T^2 + 0.1016T + 3.2982 \tag{10}$$

$$COP_{cooling} = 0.0023T^2 - 0.27T + 9.5331 \tag{11}$$

In regards to the apartment, it is assumed that every unit has its own ASHP system with the capacity to handle its peak energy load since there is no commercial ASHP system with the required peak heating load capacity. However, for the hotel building, the ASHP is not taken into consideration as it is assumed that the building has a central air conditioning system.

Furthermore, two geo-exchange systems are considered. Starting with GWHPs, similar to the ASHPs, they also have a performance table that relates the system's COP and capacity to the groundwater temperature. In this study, the underground water temperature for the region under study is constant and equal to 4.5 °C. As a result, the performance of the GWHP is constant during operation throughout the year, with a heating COP of 3.36 and a heating Capacity of 11,400 W for the duplex unit. It is worth noting that the GWHP can be coupled with free cooling during summer since the underground water temperature is at the perfect temperature for space cooling without running the compressor. The GWHP system has been selected for each building type based on its annual peak energy load. For hotel buildings, since the peak heating load is bigger than the commercial GWHP capacities, it is assumed that there are two heat pumps each meeting half the building energy load [29].

Closed-loop vertical geo-exchange systems or vertical GSHPs are also considered in this study. The same heat pump used for the GWHP system is used for GSHPs. However, the working fluid is changed from underground water to an antifreeze solution for the GSHP and the ground heat exchanger (GHE) needs a different design. The most important factor for a GHE is its pipe length. In calculating the required pipe length, it is assumed that the problem is steady-state, and all thermal

(a) Duplex (b) Multifamily (c) Hotel

FIGURE 4: 3D CAD models of considered building types

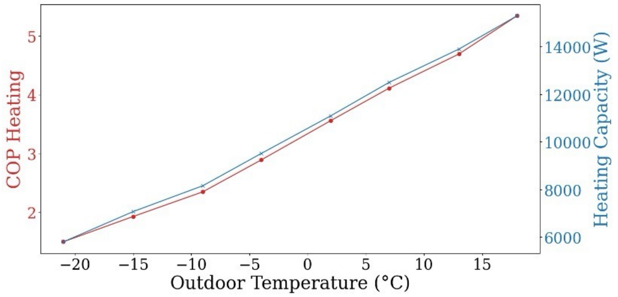


FIGURE 5: Monthly gas usage validation of the duplex building

properties are constant [30]:

$$q = \frac{L(T_g - T_f)}{R_g} \tag{12}$$

Where q is the heat transfer rate (W), L is the required length of the GHE (m), T_g is the ground temperature (°C), T_f is the working fluid temperature (°C), and R_g is the overall thermal resistance of the ground $(m \cdot K/W)$. As the peak heating load is considerably higher than the cooling loads in the Bow Valley region, the length of the GHE pipes is calculated based on the heating operation of the GSHP system. In the heating mode, the heat removed from the ground by the evaporator is:

$$q_{eavp}/q_{lh} = \frac{COP_{heating} - 1}{COP_{heating}} \tag{13}$$

Where q_{evap} is the heat pump evaporator heat extraction rate from ground (W), and q_{lh} is the building design heating block load (W). Assuming high-density polyethylene (HDPE), 0.0254 m (1") diameter pipe, and propylene glycol with a volume fraction of 25%, Table 2 summarizes the required pipe length for different types of buildings. Following the recommendations by [30], the depth of the boreholes and their configuration are assumed 100 m and single U-tube with 6 m separation, respectively.

3. RESULTS

In this section, the performance of each type of heating and cooling system in three different types of buildings is analyzed and compared to each other.

TABLE 2: Required GHE pipe length for different types of buildings

Building type	Required pipe length [m]	Number of boreholes
Duplex	360	2
Apartment	3000	15
Hotel	10500	53

3.1 Energy usage

As a first step, it is important to analyze the energy consumption of each system. The energy consumption of each system in each building type is established by utilizing the building energy loads together with each system's specific performance data.

3.1.1 Gas furnace. Starting from the conventional heating system, the energy consumption of the gas furnace with three efficiencies is summarized in Table 3.

TABLE 3: Annual natural gas usage of different types of buildings

Building type	Annual gas usage [GJ]–high perf.	Annual gas usage [GJ]–mid perf.	Annual gas usage [GJ]–low perf.
Duplex	31.57	37.47	49.78
Apartment	83.08	98.56	131.07
Hotel	436.89	518.91	690.08

3.1.2 ASHP. Using the Eqns. 10 to 13 in the methodology section, the energy usage of heat pumps can be calculated. As the heating capacity of the heat pump changes with outdoor temperature, there are times in a year when the building energy loads are greater than the heating capacity. In these situations, the ASHP needs an auxiliary heater to satisfy the whole building's energy loads. In this analysis, it is assumed that the auxiliary heating system is a gas furnace. Table 4 depicts the energy consumption of ASHP for the duplex and apartment buildings.

TABLE 4: Annual ASHP electricity and natural gas usage for different types of buildings

Building type	CC ASHP electricity [MWh]	CC ASHP auxiliary heater [MWh]	Regular ASHP electricity [MWh]	Regular ASHP auxiliary heater [MWh]
Duplex	8.2	1.7	4.75	10.2
Apartment (per unit)	3.3	0.06	1.41	3.3

3.1.3 GWHP. Based on the heat pump performance characteristics and the hourly building energy loads, Table 5 depicts the annual electricity usage of GWHP units in different types of buildings, together with a mid-efficiency natural gas furnace as the auxiliary heating system. The water flow rate into the heat pump unit is calculated based on the capacity of the heat pump and recommended by the manufacturer [29]. It is important to know the required flow rate to ensure that an aquifer with a sufficient water flow rate is available.

TABLE 5: Annual GWHP electricity and natural gas usage for different types of buildings

Building type	Flow rate [GPM]	electricity [MWh]	Auxiliary heater [GJ]	Average heating COP
Duplex	12	7	4.32	3.36
Apartment	100	27.2	0.43	3.3
Hotel	360	95.5	-	3.91

3.1.4 GSHP. The energy consumption and COP of the GSHP are determined in the same way as for the ASHP and GWHP. Instead of using water from the aquifer, the heat pump unit is connected to the ground heat exchanger through which the working fluid circulates. Table 6 shows the energy consumption of the vertical GSHP systems for different types of buildings.

TABLE 6: Annual GSHP electricity and natural gas usage for different types of buildings

Building type	Flow rate [GPM]	electricity [MWh]	Auxiliary heater [GJ]	Average heating COP
Duplex	12	7.2	0	3.3
Apartment	100	22.5	0	3.14
Hotel	360	122.1	0	3.8

3.1.5 Baseboard heating and cooling. Table 7 summarized the annual electricity consumption by the baseboard heating and cooling system. Furthermore, the comparison of electricity usage per conditioned area of buildings is depicted in Fig. ??.

TABLE 7: Annual baseboard electricity usage for different types of buildings

Building type	Annual electricity usage [MWh]
Duplex	23.5
Apartment	107.1
Hotel	366.75

3.1.6 Comparison of all systems. In this section, an overall summary of the energy consumption of different types of heating and cooling systems in three types of buildings is presented. Figure 6 shows a comprehensive overview of the energy use for each system in each building with their COPs and efficiencies. The results show that all heat pump systems use less energy, whereas the geo-exchange systems use the minimum energy among all other types of systems owing to their high seasonal COP (SCOP). Based strictly on energy usage, this study shows that geo-exchange systems are the best option for space heating and cooling. These are followed by GWHPs and cold-climate ASHPs. Both GSHPs and GWHPs use more stable ground and underground water temperatures, respectively, thus the better performance.

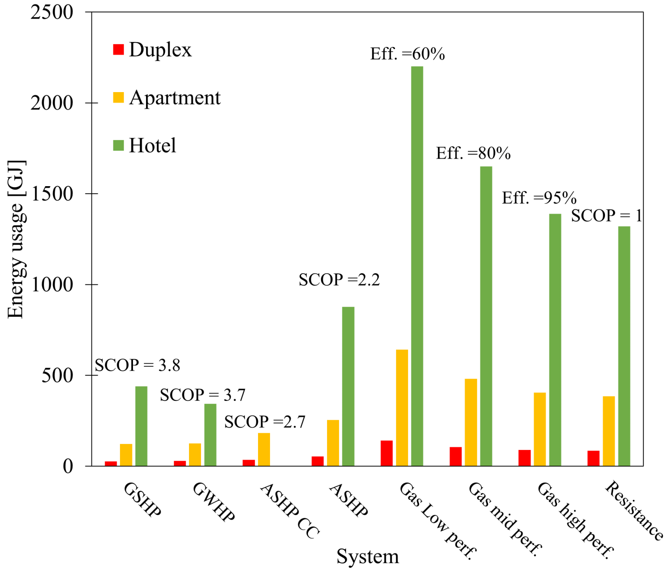


FIGURE 6: Overview of total energy use of each type of system in each type of building

3.2 CO_2 emissions

Environmental considerations are deemed integral to this study, given their pivotal role in shaping contemporary heating system choices. In this assessment, the environmental impact of each system is evaluated concerning greenhouse gas emissions and energy efficiency. Results are presented in the form of CO_2 emissions based on the grid emission factors for Alberta.. The

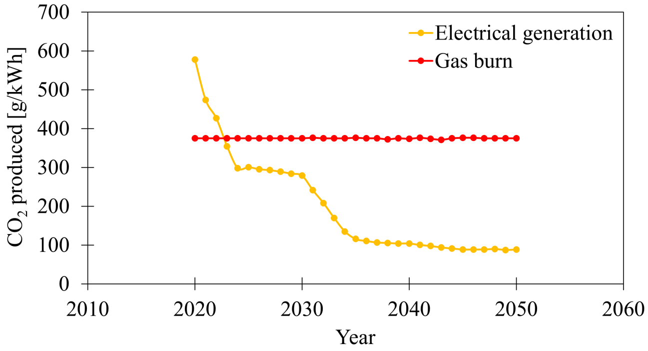
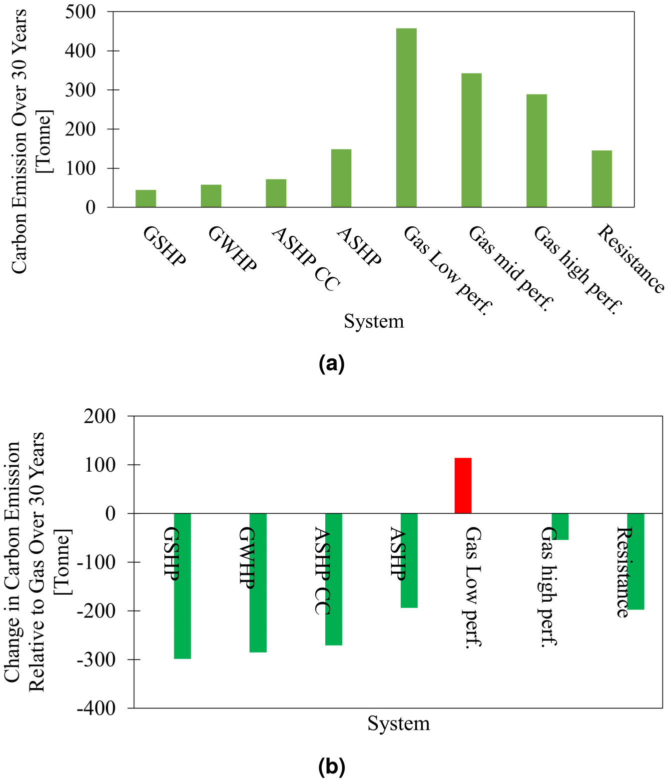


FIGURE 7: CO_2 produced per energy production

amount of CO_2 emitted by different systems was examined by first calculating the CO_2 emissions from the two primary forms of energy (gas and electricity).

Moreover, the cumulative emissions for each system over 30 years are calculated by summing the annual emissions. This calculation provides an understanding of the emissions scale associated with each system. Figures 8 to 10 depict these cumulative emissions for the 30-year duration for each system in each type of building and demonstrate the potential emissions reduction achievable by transitioning from a mid-performance gas furnace. The results indicate that a high-performance gas furnace emits more than 6.5 times the amount of CO_2 compared to a GSHP in the duplex building. Furthermore, the geo-exchange system for the duplex unit emits nearly 300 tonnes less CO_2 over 30 years than a mid-efficiency forced air furnace.



(a)

(b)

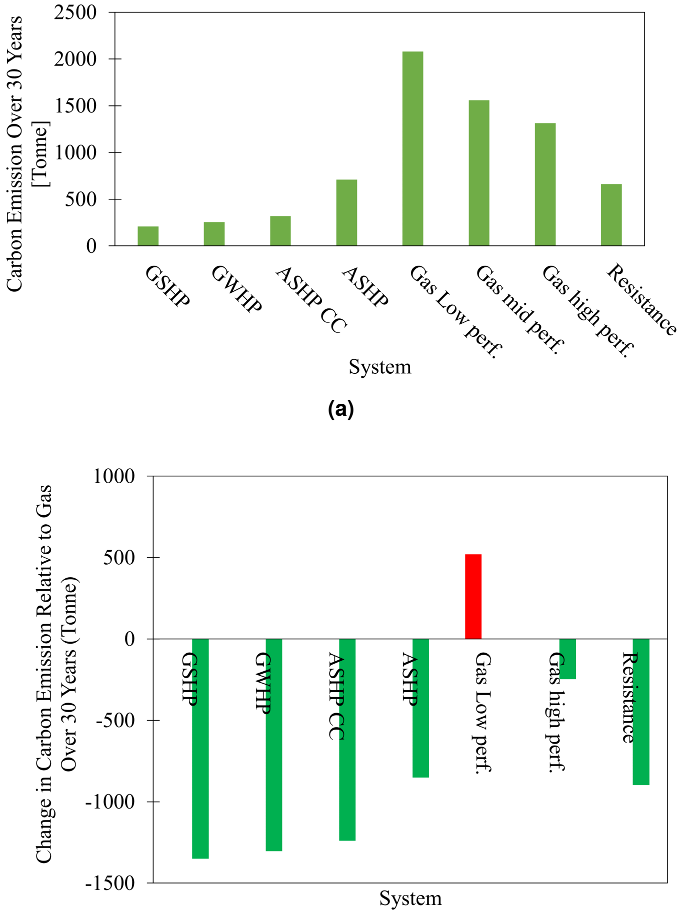
FIGURE 8: 30 years carbon emissions in tonnes and comparison with a mid-efficiency gas furnace for the duplex building

3.3 Capital Costs

Capital cost estimates are based mainly on online quotes, conversations with experts, and case studies in similar situations. For each system, the sources and detailed information are explained. It is recommended that anyone interested in installing any of the systems contact credible and qualified contractors for actual system quotes since these may vary from location to location. The capital cost for GSHP systems was determined through various methods. The most effective method involved looking for the cost of the major components, which include drilling and borehole heat exchanger installation, heat pump, and header installation, and then incorporating an additional percentage to account for ancillary expenses. Regarding permit costs, data from the Alberta government [31] was used. For drilling expenses, extensive efforts were made to solicit quotes from numerous drilling companies in Alberta. However, none were able to provide a comprehensive quote without further detailed information. Rough estimates that were received varied considerably. Nevertheless, a figure of $20 per foot emerged as a middle-ground estimate, aligning with data from other case studies. Cost estimates for heat pumps were predominantly sourced from Hydrosolar company [32], and these quotes were found to be consistent with data extracted from available case studies. Moreover, several case studies and overall estimates were generously shared, contributing to the data used in this study. Databases containing this information are accessible upon request. Furthermore, the inclusion of grants in the estimation process was in accordance with guidelines outlined at the Natural Resources Canada website [33]. The estimation of drilling costs for GWHP was derived from data extracted from various case studies conducted in Canmore, notably including the Spring Creek project [34]. These case studies provided valuable insights into drilling expenses and significantly informed the cost estimates. Additionally, some drilling companies were approached, resulting in rough estimations specifically for open-loop systems. Furthermore, grant-related considerations were integrated into the overall cost estimations. For ASHP, estimations were mainly based on quotes from an expert at Action Furnace as 9,000 CAD for a 2-ton system to 14,000 CAD to 15,000 CAD for a 4-ton system, including installation. This is compared to a variety of sources online and with some case studies. Additionally, the furnace prices website [35] provides an optimistic estimation of costs. For gas furnace systems, it was assumed that each unit in the duplex and apartment configurations had an individual furnace. Conversely, for the hotel setup, a single central heating system was considered to provide heating for all units. Finally, the pricing data for baseboard heaters, sourced from the HomeGuide website [36], indicates a scaling factor of three times the square footage. After converting this pricing information to the appropriate currency and area, it corresponds to approximately 14.67 CAD per square meter. This data serves as a valuable reference for estimating the cost of baseboard heating systems in the analysis. Table 8 shows the breakdown of capital costs for each system and building type. As the table shows, for each building type, heat pumps always emerge as the most expensive system to install.

TABLE 8: Capital costs of each system in Canadian dollars

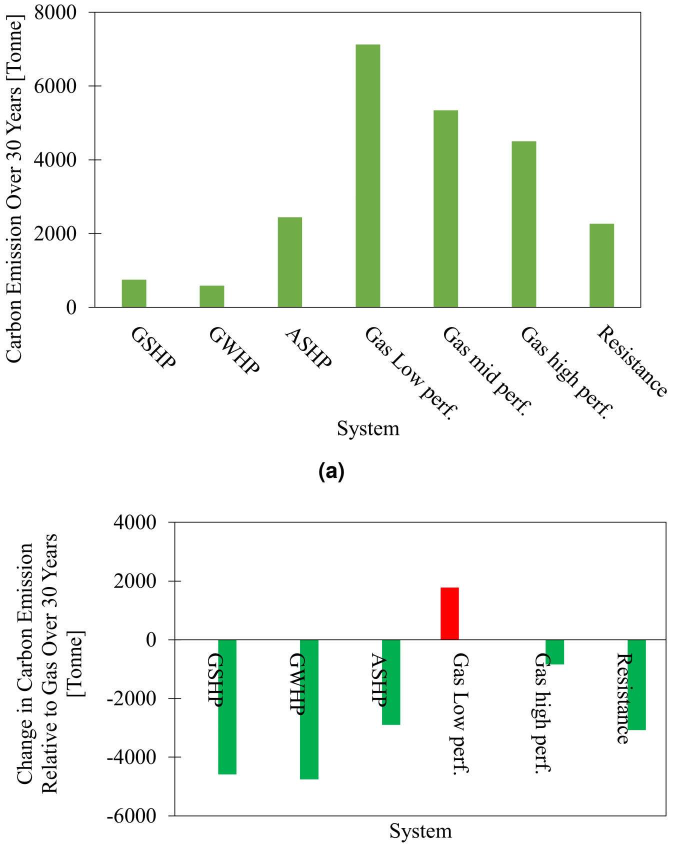
Type of Building	GSHP	GWHP	Regular ASHP	ASHP CC	Gas low eff.	Gas mid eff.	Gas high eff.	Baseboard
Duplex	31,000	31,000	10,500	8,000	N/A	5,000	8,000	2,300
Apartment	13,300	12,700	9,500	7,500	N/A	4,000	6,000	1,200
Hotel	680,000	585,000	N/A	N/A	N/A	200,000	270,000	150,000



(a)

(b)

FIGURE 9: 30 years carbon emissions in tonnes and comparison with a mid-efficiency gas furnace for the apartment building



(a)

(b)

FIGURE 10: 30 years carbon emissions in tonnes and comparison with a mid-efficiency gas furnace for the hotel building

3.4 Operating and energy cost

Fixed rates were determined to be the most practical choice due to their consistent cost profile year-round, as opposed to floating and regulated rates which can exhibit substantial fluctuations. Utilizing a database of fixed rates offered by various providers in Alberta over the last two years, sourced from the Energy Department of Government of Alberta website [37], an annual price per gigajoule was calculated. The annual monthly average of gas and electricity prices per gigajoule (CAD/GJ) is 5.22 and 23.64 CAD/GJ, respectively.

Combining the average monthly rates of gas and electricity with the gas and electrical use of each system, an estimation of the yearly operating costs of each system can be established, as can be seen in Figs. 11, 12 and 13 for a duplex, apartment, and hotel, respectively. The carbon tax is an additional tax levied on sources that emit CO_2, such as the combustion of natural gas, which is considered as the operating cost of gas furnaces. Currently set at 65 CAD per ton of CO_2, this tax is slated to increase by 15 CAD per ton annually for the next seven years, as specified by the Government of Canada [37]. It's important to note that all calculations in this study consider this escalating carbon tax, assuming that once the target is reached, it will remain at that level in subsequent years. Figures 11 to 13 show the annual operating cost of each heating system in 2023. Of the means of electrification, heat pumps emerge as the lowest-cost option in comparison to resistance heating. They also present lower operating costs compared to natural gas.

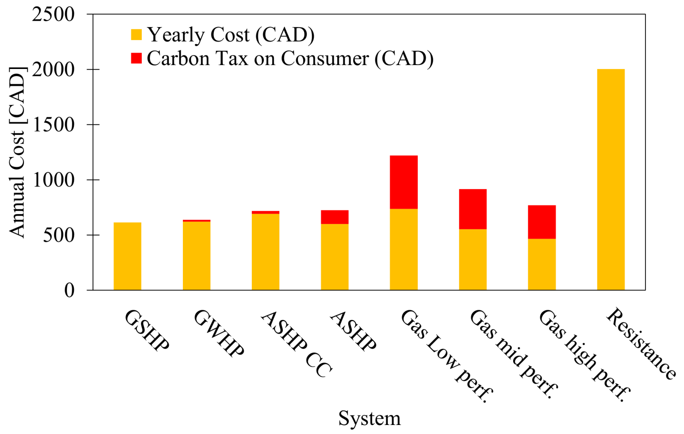


FIGURE 11: Annual operating cost in 2023 for the duplex building

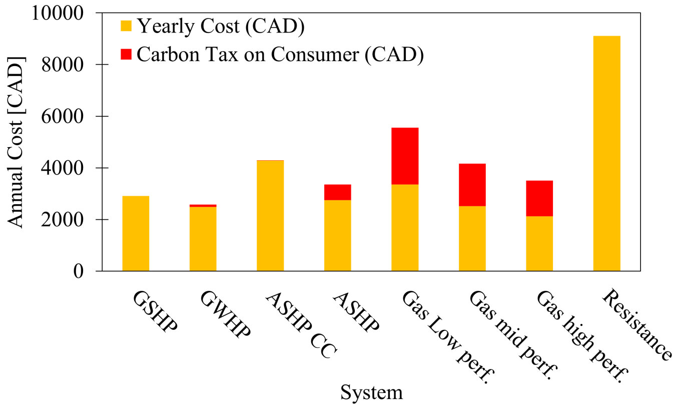


FIGURE 12: Annual operating cost in 2023 for the apartment building

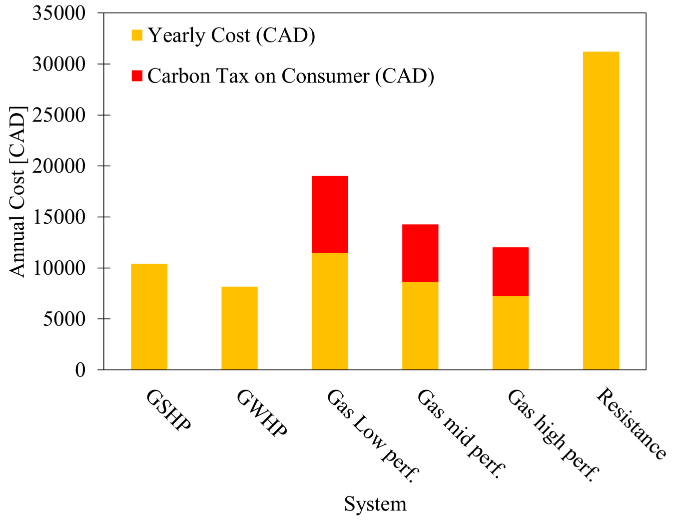


FIGURE 13: Annual operating cost in 2023 for the hotel building

Figures 14 to 16 illustrate the total annual costs for each of the heating systems with the increased carbon tax at the end of the seven years of tax increment. These plots can be compared to the previous graphs to assess the impact of the rising carbon tax on the overall costs of these heating systems. As the carbon tax increases, it will become more cost-competitive to use heat pumps for space heating and cooling. It should be noted that the carbon tax might affect the electricity cost if generated from non-renewable sources. However, the direct cost of the carbon tax on the system user is considered here. The figures show that the systems associated with high emissions (gas-based systems) attract a significant carbon tax. For the electrically powered systems, the use does not directly pay for the carbon tax. However, the Alberta grid is still carbon intensive, meaning that heat pump systems and resistance heating will also be associated with CO_2 emissions.

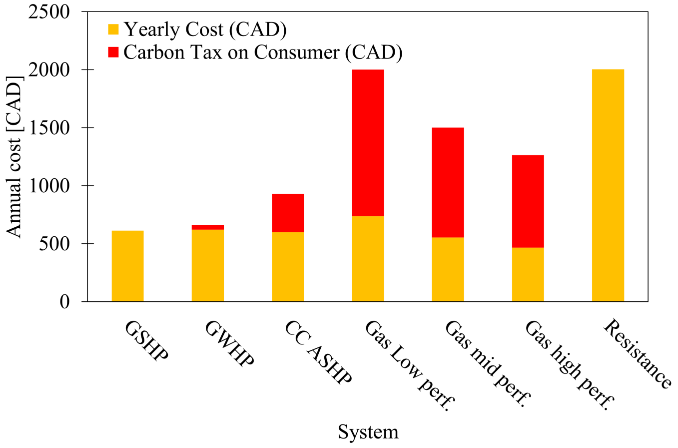


FIGURE 14: Annual operating cost in 2030 for the duplex building

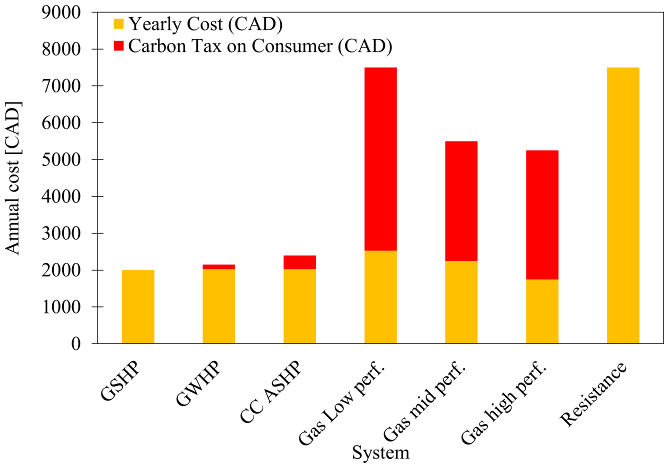


FIGURE 15: Annual operating cost in 2030 for the apartment building

3.5 Payback period

The calculation of the payback period in this study involved comparing each of the heat pump systems against a high-efficiency gas furnace (95% eff.), to determine the point at which the total costs of both systems become equal. Using the simple

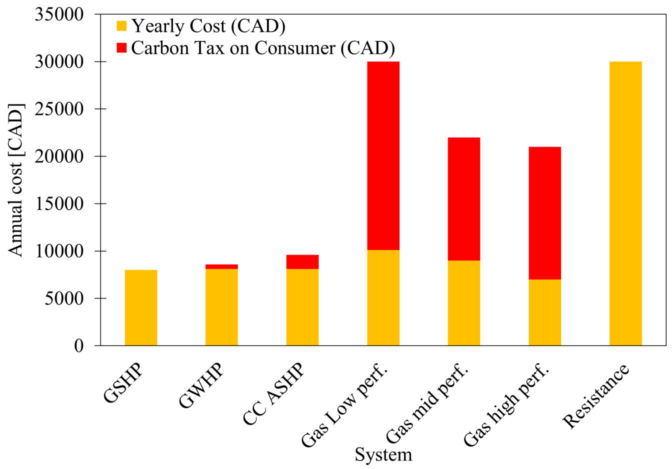


FIGURE 16: Annual operating cost in 2030 for the hotel building

payback period formula, which is the ratio of the system's additional capital investment to the difference in the annual operating cost. In other words, the payback period represents the number of years it takes for the total cost invested in each system to be recovered, signifying that both systems have equal overall costs. Operation cost and capital cost data are utilized to calculate the payback period in years for this specific comparison. Table 9 shows the estimated range of payback period of GSHP, GWHP, and ASHP systems in years when compared to high-performance gas.

TABLE 9: Estimated Payback period range in years when compared to high-performance gas furnace

Building type	Geo-exchange systems [Years]	Air-source systems [Years]
Duplex	15- 40	15-30
Apartment		
Hotel		

It is important to note that the presented range of payback period is based on the electricity and natural gas prices specific to the Bow Valley Municipality, which vary from location to location, and also from year to year, the amount of carbon tax in future years, the location of the system which affects the number of boreholes or the temperature of the underground water, together with all other extra fees that gas companies charge consumers for their services. In addition, the comparison is with a standard gas furnace not taking air conditioning into account. If the cost of an additional air conditioning system is considered as will be needed in the future, the heat pump systems will have favorable payback periods since they are capable of providing both heating and cooling without additional components.

4. CONCLUSION

In this study, the feasibility of shallow geothermal systems for the Bow Valley Municipalities was investigated. The geology of the study area was briefly investigated. The results of the geological study revealed that suitable aquifers with water flow rates ranging from 10 to 400 gallons per minute were identified in the Bow Valley region. Thermal conductivities between 1.1 and 2.7 W/m.K were measured, indicating the viability of utilizing ground-source heat pumps. Further, Building energy loads were determined for a duplex building, a hotel, and an apartment building and used to size different heating and cooling systems. Heating demands exceeded cooling demands in all cases, with heating loads per square meter measuring 0.084 kW/m^2 for the duplex, 0.051 kW/m^2 for the apartment, and 0.032 kW/m^2 for the hotel building. Results underscore the high feasibility of shallow geothermal systems in the Bow Valley. Both ground water source heat pumps and vertical ground source heat pump systems are shown to be viable options, capable of meeting building heating and cooling needs with minimal greenhouse gas emissions and environmental impact. Despite slightly longer payback periods ranging between 15 and 40 years, the substantial environmental benefits translate into reduced greenhouse gas emissions and lower electricity consumption compared to electric resistance heating systems, reducing the need for significant electric grid investments by utilities. Moreover, if the provision of air conditioning together with a furnace-based system is considered, the heat pump system economics will be competitive.

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