Feasibility of Shallow Geothermal Systems for Three Bow Valley Municipalities

BIOSPHERE INSTITUTE OF THE BOW VALLEY

UNIVERSITY OF CALGARY

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Executive Summary

Buildings are a significant energy consumer, accounting for approximately 13% of Canada's total energy consumption and over 12% of the country's total CO_2 emissions in 2020. Given Canada's ambitious emissions reduction goals, aiming to reduce emissions by 45% by 2030 and achieve net-zero emissions by 2050, there is a pressing need to transition away from the current fossil fuel-based heating systems used in buildings. The buildings sector is seen as a promising area for achieving significant reductions in CO_2 emissions. One promising technology for providing efficient heating and cooling with minimal emissions is shallow geothermal with heat pumps. Ground source heat pumps harness the stable temperatures found deep below the ground to deliver heating with remarkable efficiencies. They are capable of achieving efficiencies higher than 400% depending on the location. In other words, for every unit of electrical energy consumed, these systems can produce four units of heating, in contrast to electric resistance-based heating, where one unit of electricity generates only one unit of heat. Despite the clear benefits of ground source heat pump systems, their adoption remains limited owing to high upfront costs, ground thermal imbalance in heating dominant climates, and lack of drilling space in densely populated locations. As such, care is needed to appropriately design and size these systems, taking into account realistic building energy loads and site-specific geological conditions.

This study investigated the feasibility of implementing shallow geothermal systems in the Bow Valley municipalities, including the cities of Canmore, Banff, and Bighorn. The study considered (i) hydrogeological characteristics in the Bow Valley using available well data, generating groundwater flow direction, together with calculating soil and rock thermal properties, (ii) building energy loads for three building types, i.e., multi-family complex, an apartment building, and a hotel, and (iii) detailed economics of installing and operating the systems. Besides, a comparison of different systems for space heating and cooling, including air source heat pumps, natural gas furnaces with ground source heat pumps was undertaken. This exploration aimed to understand how these systems can be effectively utilized to provide heating and cooling while minimizing emissions in these specific regions.

Results show that ground source heat pump systems are technically feasible in this region with the lowest annual operating costs and the lowest environmental impact compared to other systems. Furthermore, it is found that open loop geoexchange systems are the best option for the Bow Valley region owing to the great number of underground aquifers and their low operating costs.

Limitations

This study was completed by student interns funded by Mitacs over a period of 4 months from June – September 2023. The recommendations as presented are the opinions of the authors of this report considering the duration of the study, assumptions made as stated and scope. Any use of the report, decision based on the report by the third part are the responsibilities of those parties. The authors are not liable for any direct and indirect damages or losses related to the contents of this report. The report is not intended to be used a design guide or reference.

1. Introduction

1.1. Background

The persistent reliance on fossil fuels for meeting our energy needs has significantly exacerbated the issue of global warming and climate change by increasing greenhouse gas emissions. This has led to a rise in extreme weather events, diseases, and poverty linked to climate change. As such, urgent action is needed to curb greenhouse gas emissions and limit the earth's temperature increase to less than 1.5 degrees Celsius above pre-industrial levels to avoid catastrophic consequences of climate change (Masson-Delmotte et al., 2019).

Several nations have made commitments to significantly reduce their emissions. Despite Canada's commitment to reduce greenhouse gas emissions as per the Paris Agreement, the emissions slightly increased from 728 million metric tons of CO_2 equivalent in 2018 to 730 metric tons in 2019 (Canada. Environment and Climate Change Canada, 2023). As such, significant efforts are still required to curb emissions from all sectors if the country is to achieve its emission reduction targets.

Globally, buildings are a major contributor to CO_2 emissions, consuming over 39% of total energy and accounting for approximately 40% of both direct and indirect CO_2 emissions in 2019 (IEA, 2019). In Canada, buildings contributed to over 17% of total CO_2 emissions in 2018, ranking third behind the oil and gas industry and transportation in terms of emissions (SenCanada, 2018). Space heating and domestic hot water heating were the biggest culprits, accounting for more than 65% of emissions in buildings (Natural Resources Canada, 2020).

With urbanization and construction rates on the rise, energy usage in the building sector is expected to increase unless there is a significant shift in technology. Various initiatives, such as Build Smart: Canada's Building Strategy aim to reduce energy consumption in buildings. The Low Carbon Fund (Ministers, 2017), part of Build Smart's strategy, supports projects to make homes and buildings more energy efficient.

To further Canada's emission reduction goals, it is crucial to invest in research, development, and deployment of sustainable energy technologies for space heating and cooling. Heat pumps, particularly air source and ground source heat pumps, are viewed as immediate solutions for clean and renewable heating and cooling. Their adoption has been growing rapidly, partly due to government incentives, and they have the potential to reduce around 500 million tons of CO_2 emissions, according to the International Energy Agency (IEA, 2023). 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.

Heat pumps can be categorized as air source, ground source, or water source, each with varying performance depending on local climate conditions. Ground source heat pumps, in particular, are highly efficient and can achieve substantial energy savings, up to 60% compared to electric resistance heating systems (Energy.GOV, 2020). However, they face challenges such as ground thermal imbalances, high initial costs, and limited drilling space in densely populated areas (Law & Dworkin, 2016).

This study, in collaboration with the Biosphere Institute of the Bow Valley, aims to assess the feasibility of ground source heat pump systems (shallow geothermal systems) for space heating, cooling, and water heating in the Bow Valley Municipalities.

1.2. Objectives

The general objective of this project was to assess the technical and economic viability of implementing ground source heat pump systems in the Bow Valley municipalities of Canmore, Banff and Bighorn. To achieve this overarching goal, several specific objectives were outlined:

i. **Survey and document existing systems:** Gather information on the performance and characteristics of existing ground source heat pump systems in the Bow Valley Municipalities and nearby areas.
ii. **Develop building energy models:** Create and validate building energy models representative of typical residential structures in the Bow Valley Municipalities.
iii. **Evaluate hourly energy use:** Utilize the validated building energy models to assess the hourly energy consumption for heating, cooling, and hot water production in residential buildings.
iv. **Design and optimize ground source heat pump systems:** Design and optimize ground source heat pump systems suitable for residential or community-level applications in the Bow Valley municipalities.
v. **Conduct detailed economic analysis:** Perform a comprehensive economic analysis of ground source heat pump systems and compare their costs and benefits with conventional and other types of heating systems.

1.3. Outline of the report

This report is divided into four main sections, each addressing distinct aspects of the proposed project. In the first section, the current ground source heat pump systems are surveyed and presented, in the next section, the hydrogeological study is presented, offering insights into the hydrogeological characteristics of the Bow Valley region. It covers topics such as the water well database, the groundwater flow direction map, and soil and rock thermal properties (thermal conductivity, specific heat capacity, and soil diffusivity).

In the mechanical analysis section, the report delves into a comprehensive examination of various elements related to heating and cooling systems in Bow Valley. In this section, different types of buildings considered are described, precise building energy models are developed and presented, and various heating and cooling systems tailored to each building category are scrutinized. Moreover, this section presents the long-term simulations of these systems, offering a glimpse into their performance and efficiency over one year of operation.

The final section, the economic evaluation, tackles the financial aspects of the project. This section considers both environmental factors, such as reduced CO_2 emissions, and economic factors, including potential cost savings derived from ground source heat pump systems. The section further presents an assessment of the capital costs associated with system implementation and an analysis of the payback period, indicating the time required to recover the invested capital. In the concluding section, the report presents a holistic assessment of the feasibility of ground source heat pump systems for the Bow Valley municipalities, drawing upon findings from the geological, mechanical, and economic perspectives to offer a comprehensive view of the technology's potential benefits and challenges in the region.

2. Geological and lithology studies

To establish the feasibility of shallow geothermal systems, an understanding of the geology and lithology of a given area is important to ensure that the systems are designed and sized optimally. In this section, the geology and lithology of the Bow Valley is presented.

2.1. Study area

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 (Fenton et al., 2013). Bedrock geology at the bedrock surface consists of interbeds 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 (Prior et al., 2013).

2.2. Importance of geological data in geothermal system design

Understanding geology is the first fundamental step in geo-exchange feasibility evaluations. It is important to understand both hard and unconsolidated rock thermal properties as thermal conductivity, geological structures, aquifers, and others. This helps in the selection and design of an optimal system, as well as estimating the extractable heat, and improving geo-exchange efficiency.

The purpose of this part of the project is to evaluate the subsurface potential to meet the heating and cooling demands of existing buildings within the Bow Valley communities mentioned above. To reach this goal, a list of the necessary geological data is gathered, including publicly and privately held information. The available data is loaded into ArcGIS Pro software, a groundwater flow direction map is generated and the thermal conductivity of the soil and rocks up to 300 and 500 feet is calculated and mapped, based on empirical equations. Depth intervals of 300 and 500 feet are common for regional drillers closed-loop borehole completion standards.

2.3. Methodology

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 and 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) (Government of Alberta, 2023a) and some reports with a general context of the hydrogeology of the area, such as that of (Toop & de la Cruz, 2002).

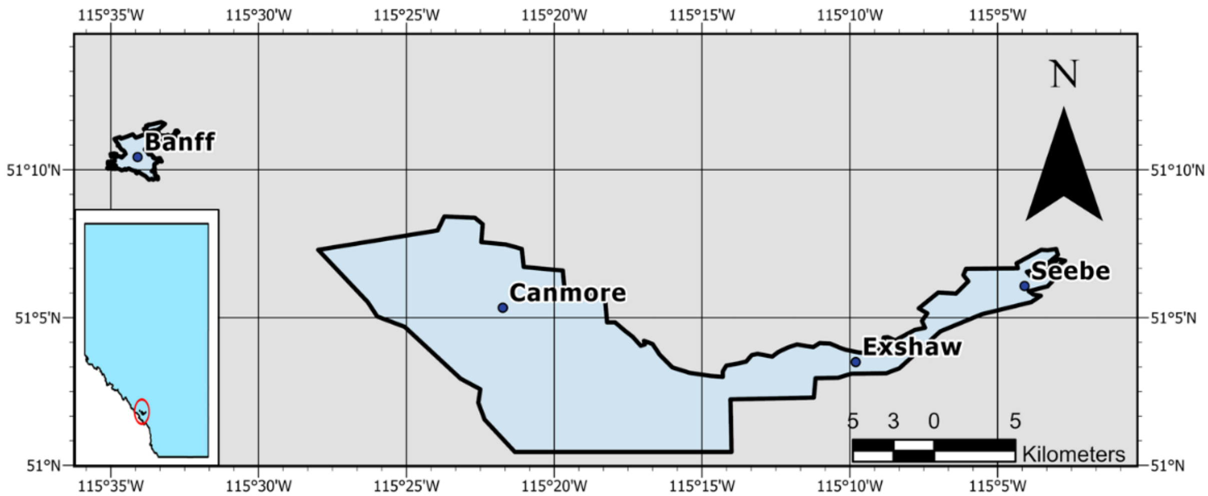


Figure 1. Area of coverage of the geological study; Banff and Canmore extending east to Seebe, covering Exshaw.

Understanding groundwater flow direction is important for shallow geothermal exploitation as it ensures the system's efficiency by preventing thermal interference caused by the presence of underground water and helps in identifying optimal locations for open loop systems (Li et al., 2023). For this reason and due to the absence of such maps for the area, a groundwater flow direction map was generated based on the static water level data found in AWWID (Government of Alberta, 2023a). 966 wells were found in the area and were uploaded to ArcGIS Pro, of which 675 contain static water level data. With those data points, a Triangulated Irregular Network (TIN) was generated and then converted to raster, to estimate the flow direction with the spatial analyst tool designated for that in the software shown in Figure 2.

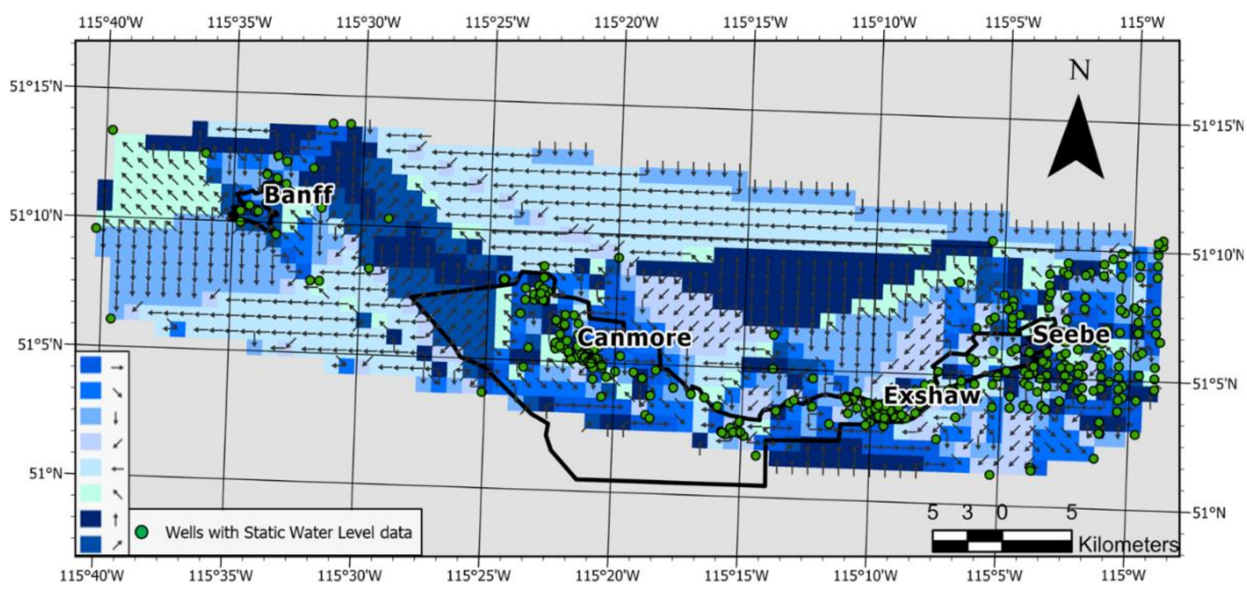


Figure 2. Groundwater flow direction map, with static water level data points. Eight flow directions are shown, represented by a shade of blue and arrows.

Likewise, no public information regarding measurements of the thermal properties of the soils and rocks located within the study area was found. This necessitated the estimation of the thermal conductivity of the soil and rocks using empirical equations and reference values found in the literature.

For estimating the thermal conductivity of the soil, empirical models were applied (Equations 1-8) (Miles S. Kersten, 1949; O. Johansen, 1977). Thermal conductivity calculations with (Miles S. Kersten, 1949; O. Johansen, 1977) unsaturated equations were performed for moisture contents of 10%, 25%, 50% and 70%.

$$\lambda_K = \left((0.9 log(w) - 0.2)10^{0.6242\rho_d - 3.4628}\right) 418.6 \quad (fine - grained\ soils) \tag{1}$$

$$\lambda_K = ((0.7 log(w) + 0.4)10^{0.6242\rho_d - 3.4628})418.6 \quad (Sandy\ soils) \tag{2}$$

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

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

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

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

$$K_e = 0.7 log\left(\frac{w}{100}\right) + 1\ (Sandy\ soils) \tag{7}$$

$$K_e = log\left(\frac{w}{100}\right) + 1 \quad (Fine - grained\ soils) \tag{8}$$

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 $\left(\frac{W}{m.K}\right)$. 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 $\left(\frac{g}{cm^3}\right)$.

The information available in the (Agricultural Regions of Alberta Soil Inventory Database (AGRASID), 2023) was used except for Banff, due to its location in the National Park. Instead, version 3.2 of the Soil Landscapes of Canada dataset was used for Banff. Both databases provide information up to a depth of 1.1 meters, and they contain the soil grain size distribution, which is useful for defining the nature of the soil (sandy or fine-grained soils) and applying the appropriate (Miles S. Kersten, 1949) equation. In addition, as there is no information regarding the densities and quartz content of the soils, the soil grain size distribution of each type of soil in the area was compared with that measured by (Tarnawski et al., 2015), who measured the physical properties and thermal conductivity of 40 Canadian soils. From there, the densities and quartz content of the soils with the most similar grain size distribution were used and applied to the empirical equations. Additionally, a porosity value of 35% was assumed for all types of soil, taking as reference the common ranges of porosity in soils described by (Nimmo, 2013). For the unconsolidated and consolidated rocks deeper than 1.1 metres, the main source of information were the lithological logs from the wells in the area (813 wells contained this information) and the geological maps available for the area (Map 600 and 560 produced by the AGS). From the lithologies and their respective established depths, reference thermal conductivity values were taken from various databases available in the literature, which included (Bagdassarov, 2021; Dalla Santa et al., 2020; Midttømme & Roaldset, 1999; Nimmo, 2013; Santa et al., 2017a, 2017b; Tarnawski et al., 2015).

Finally, after having estimated thermal conductivity values at different depth ranges, a weighted average was taken, and effective thermal conductivity values were obtained for 300 ft and 500 ft intervals in the study area. From the different values of thermal conductivity obtained for the surficial soil, $\lambda_{unsat25\%}$ was used in the calculation of the weighted average. Figure 3 shows the results obtained for the 300 ft interval, and Figure 4 shows the ones for the 500-foot interval.

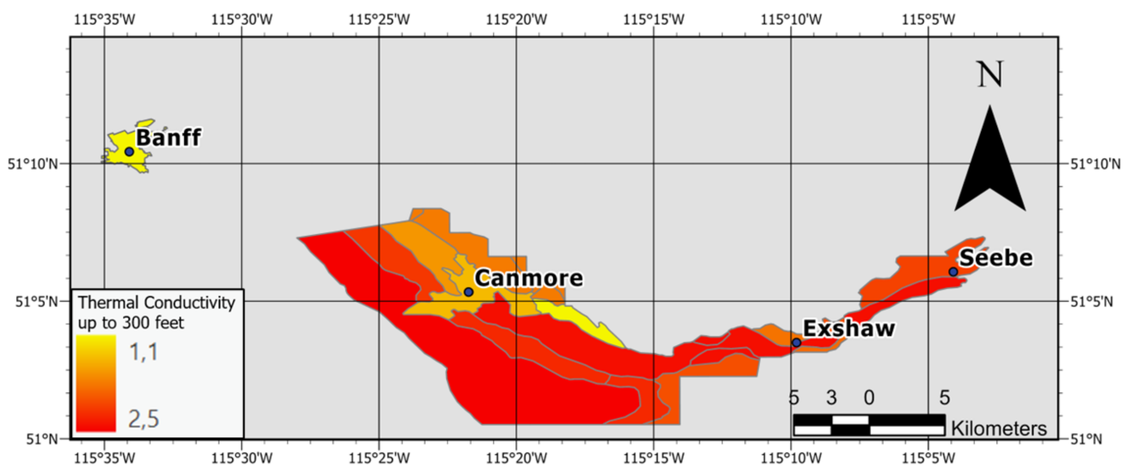


Figure 3. Thermal conductivity results for up to 300 feet. Values given in W/mk.

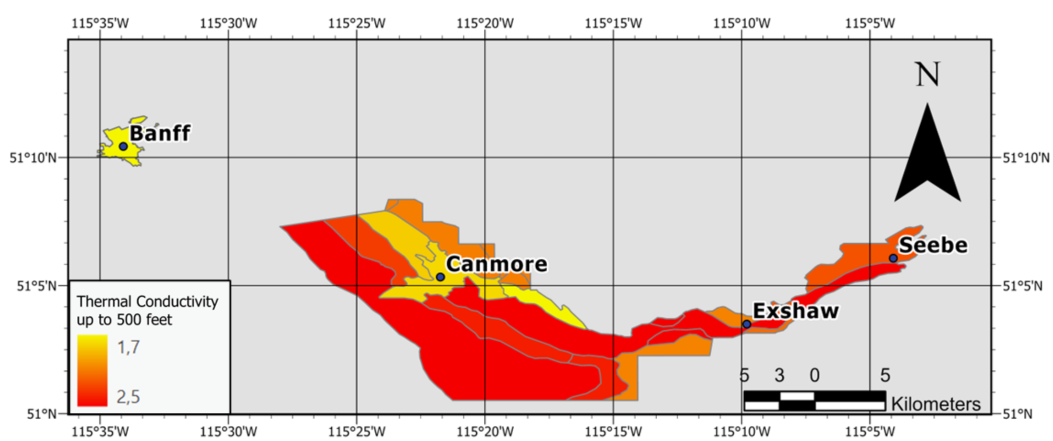


Figure 4. Thermal conductivity results for up to 500 feet. Values given in W/mk.

2.4. Summary and Recommendations

From the analysis of the generated groundwater flow direction map, it can be observed that the flow direction varies depending on the area; in Banff the groundwater flows predominantly to the northeast and east, while in Canmore and Exshaw areas it flows mainly to the south and east. It is important to note that areas with higher data density are more accurate. From Figure 2, it can be seen that the data points concentrate towards Banff, Canmore and Exshaw, meaning that the groundwater flow direction estimation is more reliable there.

The values of ground thermal conductivity range between 1.1 – 2.5 W/m K and 1.7 – 2.5 W/m K up to 300 feet and 500 feet, respectively. It is important to mention that the presented calculations do not consider the effect of convection (i.e., flowing aquifers). For this, thermal response tests (TRT) are required. The present calculations provide an overview of the effective thermal conductivity values at a regional scale. However, in situ tests or sample collections for laboratory measurements of thermal conductivity are highly recommended.

Results of the geology studies show that there is potential for the use of shallow geothermal in the Bow Valley municipalities. There are existing wells up to 500 ft, pump tests from the existing wells showed significant flow rates to support open loop water source heat pump systems. Besides, the ground thermal conductivities in the range 1.1 – 2.5 W/m K are suitable for closed loop geothermal systems.

It is important to note that the conclusions presented based on a regional study by an undergraduate geology student; a useful next step would to be to secure support of a hydrogeologist for comprehensive investigations. In order to further advance hydrogeological investigations in this area and guide the next phase of research, we recommend the following key steps and terms of reference:

1. Extent of Alluvial Aquifer: Conducting a comprehensive hydrogeological assessment to determine the full extent of the thick alluvial aquifer identified in certain areas of Canmore. Investigating whether this aquifer extends downstream to the town of Exshaw, which is of particular importance due to significant proposed future developments.
2. Implications for Exshaw Development: Assessing the potential presence of the identified alluvial aquifer under the large industrial sites in the Exshaw area. Determining the aquifer's properties and its relevance to groundwater supply and thermal characteristics for geoexchange systems, especially in the context of proposed industrial development.
3. Thermal conductivity and geoexchange: As a critical component of geoexchange systems, initiating a study or analysis to understand how thermal conductivity factors into the equation. Explore the influence of varying thermal conductivities in the subsurface on the design and performance of geoexchange systems, and how it impacts energy efficiency and heat exchange in the region's geological context.

These recommendations will serve as a solid foundation for future hydrogeological work in the Bow Valley region, providing valuable insights into the extent of aquifers and their applicability to geoexchange systems.

3. Comparative performance of different systems for space heating and cooling

3.1. Overview

In this section, detailed building energy models for selected building types located in the Bow Valley municipalities are presented. Furthermore, using the obtained building energy loads, various heating and cooling systems are analyzed, and their performance assessed through long-term simulations. The energy consumption of each type of heating and cooling system are discussed and compared, and the importance of this for the feasibility of shallow geothermal systems emphasized.

3.2. Building types

In consultation with stakeholders from the Bow Valley municipalities and the Biosphere Institute of the Bow Valley, three types of buildings were selected based on the planning needs of each city. These include a multi-family duplex, an apartment complex, and a hotel. Building energy loads assume a pivotal role in the design and functioning of heating and cooling systems. Firstly, the determination of the system's size and type is influenced by maximum or "design" loads, ensuring compatibility with the selected equipment. Secondly, in the techno-economic analysis aimed at assessing the overall value of the ground source heat pump relative to commonly employed air conditioning alternatives, it is imperative to compute the total building energy consumption for both heating and cooling purposes. Thirdly, the building energy load significantly impacts system performance and energy utilization, particularly in the context of the Bow Valley, where the prevalent energy load primarily pertains to heating, with considerably lower cooling demands during the summer season.

As part of the broader project investigating the feasibility of shallow geothermal systems in the cold climate of the Bow Valley, this part of the study is dedicated to the calculation of hourly building energy loads over the course of a typical year.

3.3. Building energy modeling methodology and validation

The building energy modeling is done by utilizing the Beopt™ software. BEopt™ (Building Energy Optimization Tool) is a front-end user interface software using EnergyPlus™ engine for the computation and 2014 Building America Housing Simulation Protocols (Wilson et al., 2014) for the simulation assumptions.

The typical ambient weather conditions for the Bow Valley in EPW (EnergyPlus Weather) format are utilized as the building simulation input. EPWs were formulated by the United States Department of Energy (DoE) with the intention of establishing a standardized weather data format that can serve as a common reference for converting various other data formats. Other considered parameters are listed in Table 1. These parameters are considered as inputs to the building energy models.

For model validation, the duplex building’s natural gas consumption as availed by the home owner was used. The natural gas consumption was supplied by the occupants of the building and represented the monthly usage over one year.

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. In 2011, the basements of both halves were developed into a unit each (now in total 4 units). 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™ using the building plan. Figure 5 shows the CAD model of the building in two different views.

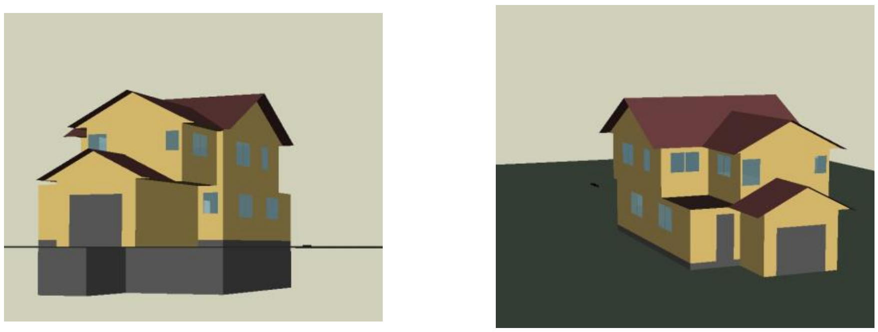


Figure 5. CAD model of the duplex building

As Fig.5 shows, the unit has three storeys, including the basement suite, and there are two bathrooms and three bedrooms in this house. Additionally, the basement suite features one bedroom and one bathroom.

Beopt™ calculates the number of occupants from the number of bedrooms (N_{br}) using the equation:

$$\text{Occupants} = 0.59 \times N_{br} + 0.87 \tag{9}$$

For appliance gains, it considers major appliances such as refrigerator, cooking range (electric), dishwasher, clothes washer, and clothes dryer. The benchmark recommendation for refrigerator load is 434 kwh/yr whereas for other appliances, it follows this equation ($a + b \times N_{br}$), depending on the number of bedrooms. The interior lighting loads depend on furnished floor area (FFA) in ft^2:

$$\text{Interior lighting} = \text{FFA} \times 0.542 + 343 \text{ (kWh/yr)} \tag{10}$$

Figure 6 showcases the comparison between the actual gas usage and the simulation results. As indicated in this figure, an excellent agreement has been achieved between these two datasets. The maximum error observed was 6.2% in heating mode. However, in the cooling mode, the error is higher, primarily due to the absence of detailed information regarding the occupants' gas usage behavior within the building in the summer.

Table 1 List of parameters used in energy load modelling for duplex building

Parameter	Values
Exterior Finish (Vinyl, Light) R-value	0.6
Ceiling R-Value	49
Wall R-Value	21
Basement Wall R-Value	R-15 XPS
Thermal mass	BA Benchmark
Window U-factor*	0.35
Window SHGC	0.44
Airtightness (ACH@50Pa)	7
Window to Floor Area Ratio	0.15
Furnace AFUE (gas)	78%
Air conditioner SEER	13
Cooling set point (°F)	76
Heating set point (°F)	71
HRV Sensible recovery efficiency (%)	NA **
Ventilation rate (cfm, continuous)	NA **
Natural Ventilation	BA values
DHW EF (gas)	0.59
Distribution	uninsulated, copper
Lighting CFL%	34
Appliance & Fixtures	B10 values
Duct location	15% leakage, R-8

*The available window with the closest U-factor (0.29) was selected.
** The default mechanical ventilation in BA Benchmark is not HRV, it's a 2010 exhaust with 85 cfm.

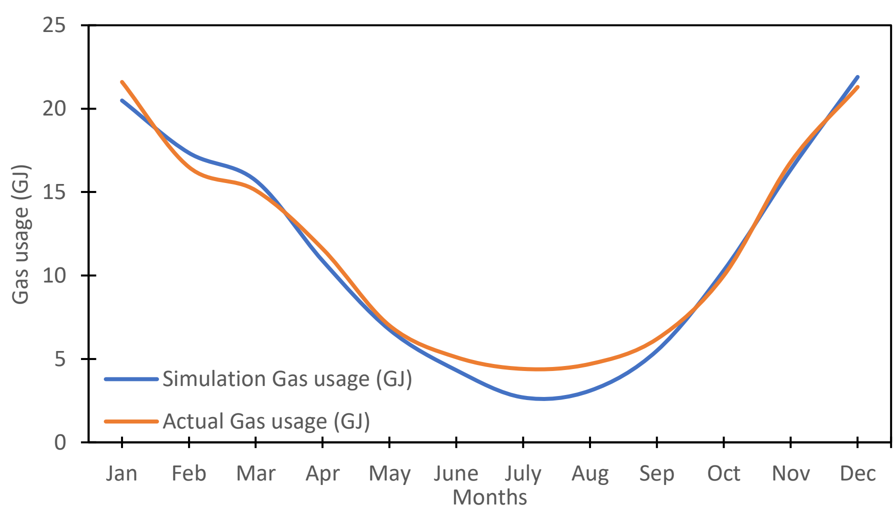


Figure 6. Monthly gas usage validation of the duplex building

3.3.1. Building energy loads for the duplex building

After validating the building energy model using the gas usage for the duplex, the model was extended to the determination of energy loads for the different building types. Figure 6 shows the hourly building loads for the duplex building. The front unit area is 205.6 m^2 splitting 67.7 m^2 for the basement suite and the main floor, and 70.2 m^2 for the upper floor. As expected, the heating energy loads are found to be significantly higher than the cooling loads, an important factor in the design of heating and cooling systems. Furthermore, Table 2 displays the peak heating and cooling loads for the studied unit in the detached multi-family building. This building has an annual heating demand of 84.7 GJ and a cooling demand of 1.45 GJ in a typical year.

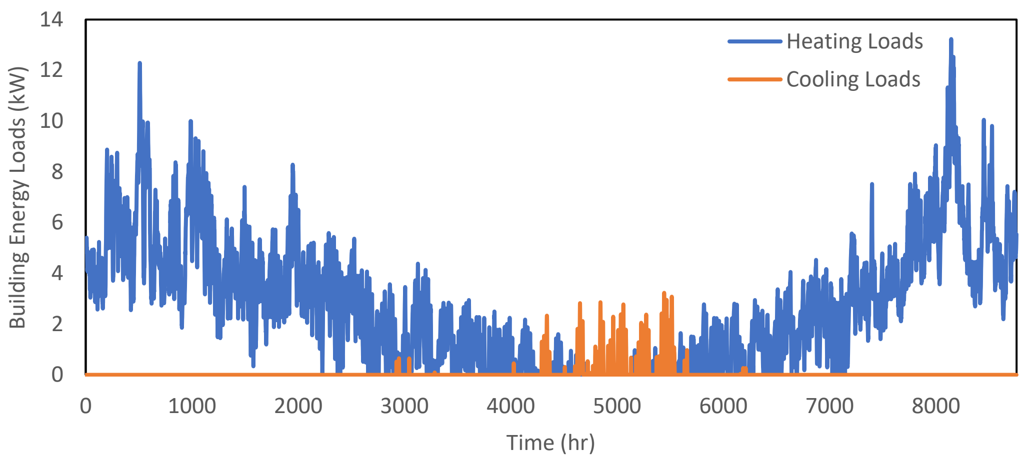


Figure 7. Hourly heating and cooling energy loads for the detached multi-family building

Table 2 Annual natural gas usage for the duplex building

Peak energy load	Value (kW)
Heating	13.23
Cooling	3.23

3.3.2. Building energy loads for the apartment building

The apartment building information and plan was received from the town of. The property is in Palliser village, Canmore and has three stories with 15 units. The site area is 397.2 m^2 which includes 397.1 m^2 on level 1, 366.8 m^2 on level 2, and 366.8 m^2 on level 3. The total area for all the units is 960 m^2. Summing up the corridors and storage areas, the total area of the apartment is 1100 m^2. The building's frame is wood, and the construction involves concrete foundations and a slab-on-grade structure. The exterior features a combination of finishes, including Eldorado stacked stone, prefinished wood clapboard siding, prefinished wood plank siding, and wood trim and fascia with a cedar stain finish. Additionally, there are wood handrails with a cedar stain finish, timber columns, and prefinished aluminum soffits. The windows and doors are constructed from prefinished PVC material, and the roofing consists of asphalt shingles in a midnight black color. It is assumed that the building has a central air conditioning system. Table 3 shows the assumed parameters for the energy loads simulation. Figure 8 illustrates the CAD model of two views of the apartment building.

Table 3 List of parameters used in energy load modelling for apartment

Parameter	Values
Exterior Finish (Vinyl, Light) R-value	0.6
Ceiling R-Value	49
Wall R-Value	21
Basement Wall R-Value	R-15 XPS
Thermal mass	BA Benchmark
Window U-factor*	0.35
Window SHGC	0.44
Airtightness (ACH@50Pa)	7
Window to Floor Area Ratio	0.15
Furnace AFUE (gas)	78%
Air conditioner SEER	13
Cooling set point (°F)	76
Heating set point (°F)	71
HRV Sensible recovery efficiency (%)	NA **
Ventilation rate (cfm, continuous)	NA **
Natural Ventilation	BA values
DHW EF (gas)	0.85
Distribution	uninsulated, copper
Lighting CFL%	50
Appliance & Fixtures	B10 values
Duct location	20% leakage, R-8

*The available window with the closest U-factor (0.29) was selected.
** The default mechanical ventilation in BA Benchmark is not HRV, it's a 2010 exhaust with 85 cfm.

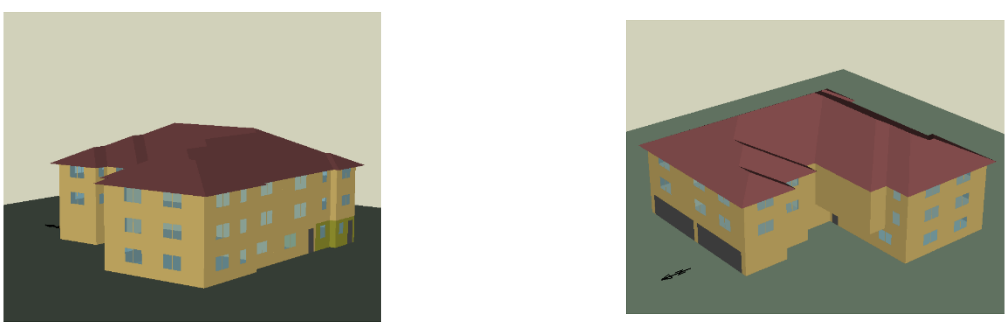


Figure 8. CAD model of the apartment building

The building energy model uses the same weather conditions as those of the duplex with the new input parameters specific to the apartment building as shown in Fig. 8. Figure 9 depicts the hourly heating and cooling loads for one year and Table 4 summarizes the peak heating and cooling loads. This building has an annual heating demand of 385.3 GJ and an annual cooling demand of 16.02 GJ in a typical year.

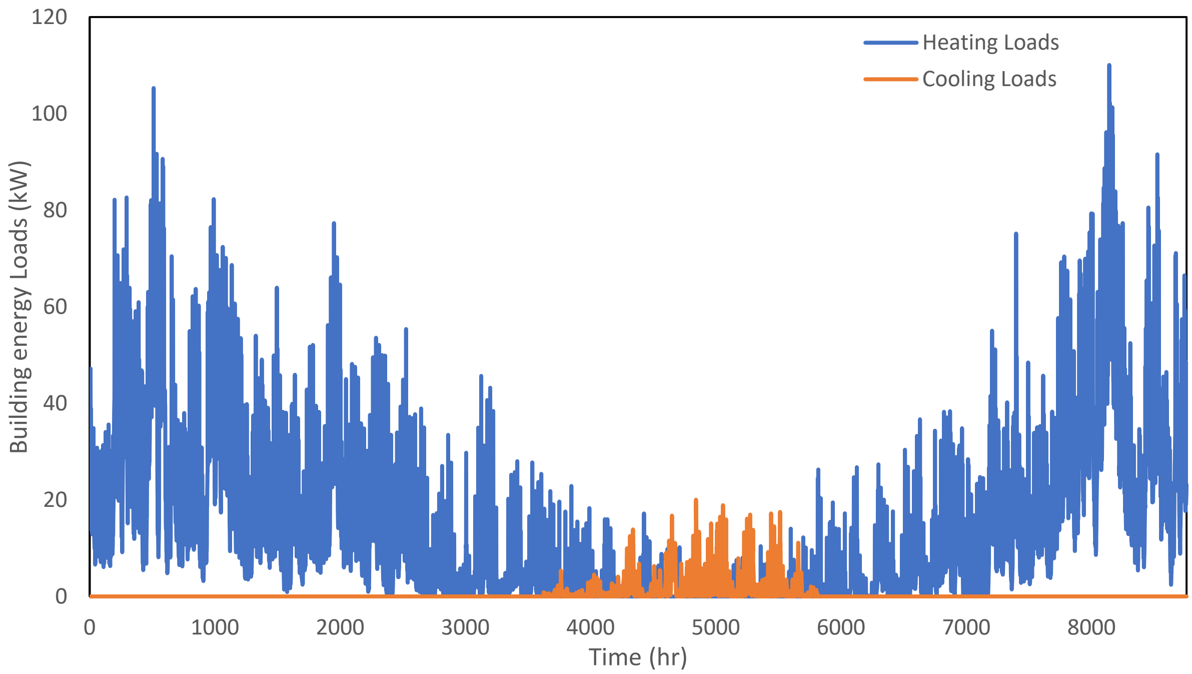


Figure 9. Hourly heating and cooling energy loads for the apartment building

Table 4 Energy loads in the apartment building

Peak energy load	Value (kW)
Heating	110.06
Cooling	20.03

3.3.3. Building energy loads for the hotel

The hotel building information and details were also received from the town of Canmore. The building is located on Bow Valley Trail and still is under construction. It consists of 4 levels with 99 units. The total area of the hotel units is 10,150 m^2. As the hotel occupancy is different from time to time, analyzing the hotel's occupancy patterns to optimize energy usage is one of the most important factors in the building energy loads modeling. However, in this study, it is assumed that all the units are full, and peak heating and cooling loads are calculated based on this assumption. Table 5 shows the assumed parameters as the input for the building energy modeling. Figure 10 depicts the CAD model of the building in two separate views.

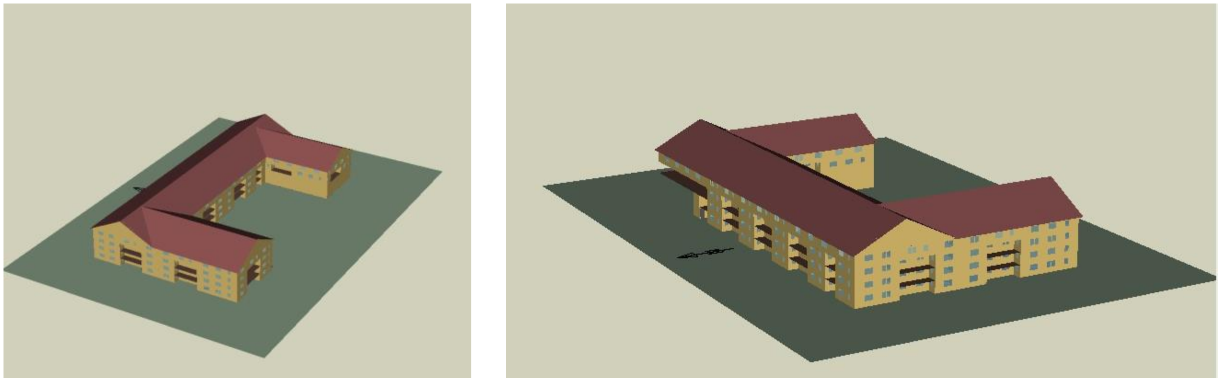


Figure 10 CAD model of the hotel building

Table 5 List of parameters used in energy load modelling for hotel

Parameter	Values
Exterior Finish (Vinyl, Light) R-value	0.6
Ceiling R-Value	49
Wall R-Value	21
Thermal mass	BA Benchmark
Window U-factor*	0.35
Window SHGC	0.44
Airtightness (ACH@50Pa)	7
Window to Floor Area Ratio	0.15
Furnace AFUE (gas)	78%
Air conditioner SEER	13
Cooling set point (°F)	76
Heating set point (°F)	71
HRV Sensible recovery efficiency (%)	NA **
Ventilation rate (cfm, continuous)	NA **
Natural Ventilation	BA values
DHW EF (gas)	0.59
Distribution	uninsulated, copper
Lighting CFL%	34
Appliance & Fixtures	B10 values
Duct location	15% leakage, R-8
*The available window with the closest U-factor (0.29) was selected. ** The default mechanical ventilation in BA Benchmark is not HRV, it's a 2010 exhaust with 85 cfm.	

The building energy loads were obtained using the same weather conditions as the duplex and apartment building to model the building energy loads with the same weather conditions, but, new input parameters for the hotel building were used. Figure 11 shows the hourly heating and cooling loads during one year and Table 6 summarizes the peak heating and cooling loads. As was shown for the duplex building and the apartment building, the heating loads are also significantly higher than the cooling loads. This building has 1320.27 GJ of heating demand and 178.48 GJ of cooling demand in a typical year.

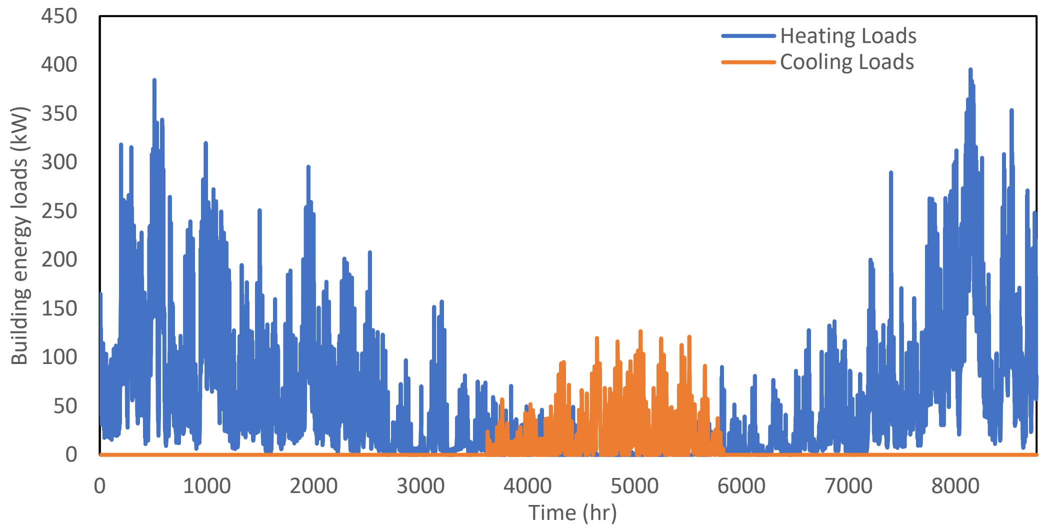


Figure 11 Hourly heating and cooling energy loads for the hotel building

Table 6 Energy loads in the hotel building

Peak energy load	Value (kW)
Heating	395.36
Cooling	126.82

Overall, all the building types show the same trend of the building energy loads. They all have significantly higher heating than cooling loads owing to the cold climate experienced in the Bow Valley. On a per square ft basis, the duplex has a heating load of 0.084 kW/m^2, the apartment building has a heating load of 0.05 kW/m^2, and the hotel 0.03 kW/m^2. From this, it is clear that the duplex has a higher intensity given the number of exposed walls compared to the apartment and hotel as well as different heat gains.

3.4. 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, an air source heat pump, a ground water heat pump, a ground source heat pump, and an electric resistance heating system (baseboard heating). In the following sub-sections, each system is studied in detail.

3.4.1. Heating with a forced air furnace

A forced air furnace is a central heating system commonly used in residential and commercial buildings to provide warmth during colder months. It operates by circulating warm air throughout the building via a network of ducts and vents. This type of furnace is renowned for its efficiency, reliability, and ability to distribute heat quickly and evenly. Forced air furnaces are often powered by various energy sources, including natural gas, propane, electricity, or oil, depending on regional availability and the user's preference. In this project, natural gas was chosen as the energy source for this type of heating systems.

The main drawbacks of such systems are no cooling ability during hot seasons, emission production, and lower efficiencies in comparison to modern heat pump systems. In order to analyze the performance of forced air furnaces, three levels of efficiencies i.e. high (95%), mid (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 has been calculated using Equation 11. Table 7 shows the summary of the yearly natural gas usage in each building.

$$\dot{Q} = \frac{\dot{Q}_{Building}}{efficiency \times \, heat\ value\ of\ natural\ gas} \tag{11}$$

Where $\dot{Q}$ is the volumetric natural gas usage, $\dot{Q}_{Building}$ is the building energy load, and the heating value of the natural gas in Canada is about 950 BTU/hr.

Table 7 Annual natural gas usage of different types of buildings

Building type	Area (m^2)	Yearly gas usage (GJ) – high perf.	Yearly gas usage (GJ) – mid perf.	Yearly gas usage (GJ) – low perf.
Duplex	157	31.57	37.47	49.78
Apartment	1100	83.08	98.56	131.07
Hotel	10150	436.89	518.91	690.08

To facilitate a comparison of the annual natural gas usage for each building, the values are normalized by the building area. Figure 12 provides a visual representation of this comparison, illustrating the gas consumption for various building types in Gigajoules per square meter (GJ/S.M) and different efficiency levels.

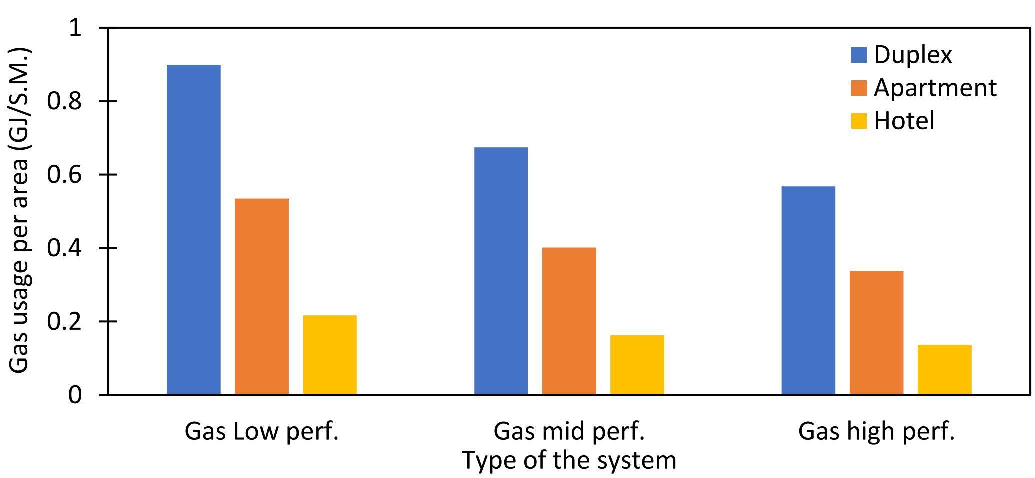
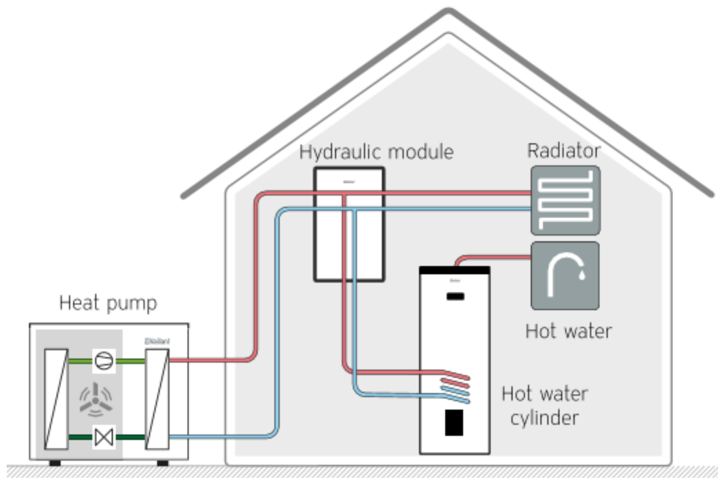


Figure 12 Gas usage comparison of different types of buildings and three levels of efficiencies

3.4.2. Heating and cooling with air source heat pumps

Air source heat pumps (ASHPs) are innovative and energy-efficient heating and cooling systems that have gained significant popularity for their ability to provide both heating and cooling functions in residential and commercial buildings. These systems work by transferring heat between the indoor and outdoor environments, using the principles of refrigeration technology. ASHPs are known for their versatility, cost-effectiveness, and reduced environmental impact compared to traditional heating and cooling systems. They come in two main categories: regular ASHPs and cold climate ASHPs.



(a)

Figure 13. (a) Schematics of an ASHP system (BioSun Energy, 2023)

- Regular ASHPs:

Regular ASHPs are designed for moderate and milder climates, where winter temperatures typically stay above freezing. They operate by extracting heat from the outdoor air and transferring it indoors to heat the building during the colder months. In the summer, they reverse the process, removing heat from indoors to provide cooling.

- Cold Climate ASHPs:

Cold climate ASHPs, on the other hand, are specifically engineered to perform efficiently in colder regions where temperatures frequently drop below freezing. These systems incorporate advanced technology, including improved insulation, larger heat exchangers, and variable-speed compressors, allowing them to maintain their heating capacity even in extremely low temperatures. Cold climate ASHPs have expanded the reach of this technology, making it feasible for areas that experience harsh winters to benefit from the energy efficiency and sustainability advantages of air source heat pumps.

ASHPs are selected based on their maximum heating and cooling capabilities. In the Bow Valley region, where the primary energy demand is for heating, the choice of an ASHP is primarily determined by its peak heating capacity. Each ASHP comes equipped with its capacity chart, which relates the system's heating and cooling capacity to the outdoor air temperature. Essentially, this chart outlines how much heat the heat pump can generate at various outdoor temperatures. As a result, a specific metric can be defined, which correlates the heating or cooling output of the heat pump to its energy consumption, and this metric is referred to as the "Coefficient of Performance" or COP. A sample of this chart is shown in Figure 14.

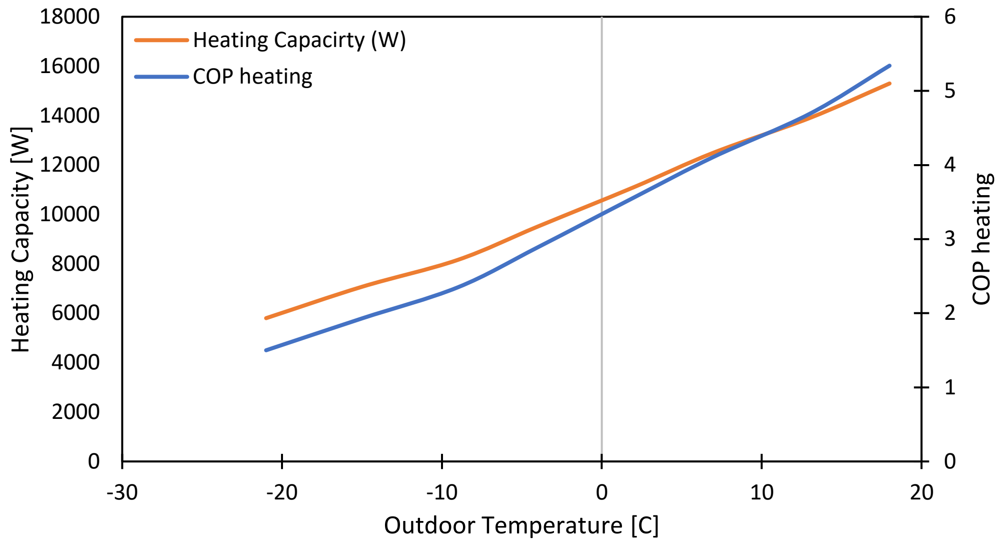


Figure 14. COP heating and heating capacity of the chosen ASHP vs. outdoor temperature

The coefficient of performance (COP) is a measure of the efficiency of a heat pump system. It is defined as the ratio of the desired output or heat transfer (typically heating or cooling) to the input energy or work required to achieve that output. COP is used to quantify how effectively a system can move heat from one location to another, such as from a colder environment to a warmer one.

For a heating system, the COP is calculated as:

$$COP_{heating} = \text{Desired Heating Output} / \text{Input Electrical Energy} \quad (12)$$

For a cooling system, the COP is calculated as:

$$COP_{cooling} = \text{Desired Cooling Output} / \text{Input Electrical Energy} \quad (13)$$

A higher COP value indicates greater efficiency, it means that more heating or cooling is achieved with a given amount of energy input. In practical terms, a COP greater than 1 indicates that the system is more efficient at transferring heat than a simple electric heater, which has a COP of 1 because it converts all input electrical energy into heat. Heat pumps have COP values greater than 1, making them more energy-efficient for heating and cooling applications.

Depending on the building energy loads, an ASHP is chosen to meet the building's peak load. For the duplex unit, when the peak energy load is 15 kW, an air-to-water ASHP is selected (Nordicghp, 2023a). This is a cold climate ASHP, which has been chosen as an example. The minimum operating temperature for this ASHP is -21 ^{o}C and the indoor flow rate is 12 gpm. Tables 8 and 9 show the ASHP heating and cooling capacity, COP, and compressor work based on the outdoor temperature.

Table 8 Heating capacity and heating COP of the ASHP (Nordicghp, 2023a)

Outdoor Temperature (C)	COP heating	Heating Capacity (W)	Compressor work Input (W)
-21	1.5	5800	3866.67
-15	1.93	7070	3663.21
-9	2.35	8160	3472.34
-4	2.89	9510	3290.66
2	3.56	11100	3117.98
7	4.11	12500	3041.36
13	4.69	13900	2963.75
18	5.34	15300	2865.17

Table 9 Cooling capacity and cooling COP of the ASHP (Nordicghp, 2023a)

Outdoor temperature (C)	COP cooling	Cooling Capacity (W)	Compressor work input (W)
10	7.14	14500	2030.81
16	5.77	13000	2253.03
21	4.69	11800	2515.99
27	3.96	11000	2777.78
32	3.22	10100	3136.65
38	2.67	9350	3501.87
43	2.13	8450	3967.14
49	1.7	7520	4423.53

Based on Table 8 and Table 9, a second order equation can be fit to each dataset (COP, Capacity, and Compressor Work). Using that equation, the system's performance can be analyzed throughout the year. The equations for heating and cooling COPs are given by Eqns. (14) and (15), respectively

$$COP_{heating} = 0.0007\,T^2 + 0.1016\,T + 3.2982 \quad (14)$$

$$COP_{cooling} = 0.0023\,T^2 - 0.27\,T + 9.5331 \quad (15)$$

Where T is the ambient dry bulb temperature. As the result, Figure 14 visualizes the ASHP performance in one chart.

Next, the hourly COPs and heating and cooling capacities of the ASHP are calculated based on the weather conditions and building energy loads. Since the heating capacity of the heat pump changes with outdoor temperature, there are times of the year when the building energy load is greater than the heating capacity. In these situations, the ASHP needs an auxiliary heater to satisfy the whole building's energy loads. It is assumed that the auxiliary heating system is a gas furnace. Table 10 shows the results of the cold climate ASHP performance for the duplex unit.

Table 10 Cold Climate ASHP performance for the duplex unit

Performance parameters	Values
Average COP heating	2.7
Average COP cooling	4.7
Compressor work (Electricity Consumption) (MWh)	8.2
Auxiliary heater Energy Consumption (Natural Gas) (MWh)	1.7

For the apartment building, as there is no ASHP with the peak heating load capacity, it is assumed that each unit has a separate ASHP with the capacity of their peak energy load. Furthermore, for the hotel building, the ASHP is not considered because it is assumed that the building has a central air conditioning system and no ASHP is able to meet the entire building's load. Table 11 depicts the energy consumption of an ASHP for the duplex and apartment buildings. Figure 15 shows the comparison of energy consumption of ASHPs in the duplex and apartment building types.

Table 11 ASHP performance for all building types

Building type	Building Area (m^2)	ASHP CC electricity consumption (MWh)	ASHP CC Auxiliary heater energy consumption (Natural Gas) (MWh)	ASHP Regular electricity consumption (MWh)	ASHP Regular Auxiliary heater energy consumption (Natural Gas) (MWh)
Duplex	157	8.2	1.7	4.75	10.2
Apartment (per unit)	1100	3.3	0.06	1.41	3.3
Hotel	10125	-	-	-	-

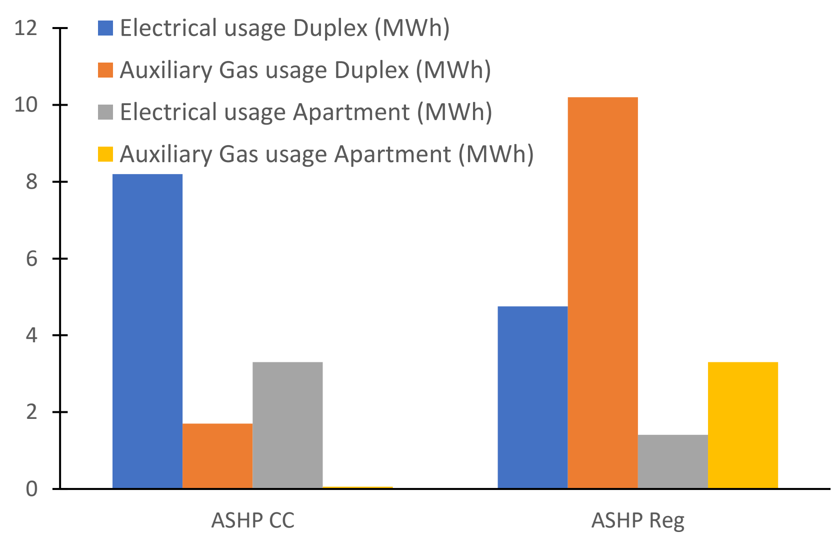


Figure 15. ASHPs performance comparison

3.4.3. Heating and cooling with ground water heat pumps

Ground water heat pumps (GWHP) or open-loop ground source heat pumps are a specialized type of geothermal heat pump system that utilizes underground water as the working fluid to exchange heat with the Earth's subsurface. These systems are particularly well-suited for regions with abundant underground water resources. Open-loop systems directly draw water from a well, use it to extract or dissipate heat, and then discharge it into another well or a suitable water body.

The operation of open-loop ground source heat pumps relies on two main components: production wells and injection wells. A production well draws groundwater from the underground aquifer and passes it through a heat exchanger within the heat pump system. As the groundwater flows through the heat exchanger, it exchanges heat with the refrigerant in the heat pump, either extracting heat for heating purposes or dissipating heat for cooling. Once the heat exchange process is complete, the now-cooler or warmer groundwater is discharged into an injection well or returned to the aquifer. The process is highly efficient because the groundwater's temperature is relatively stable and close to the desired temperature for the heat pump to operate efficiently.

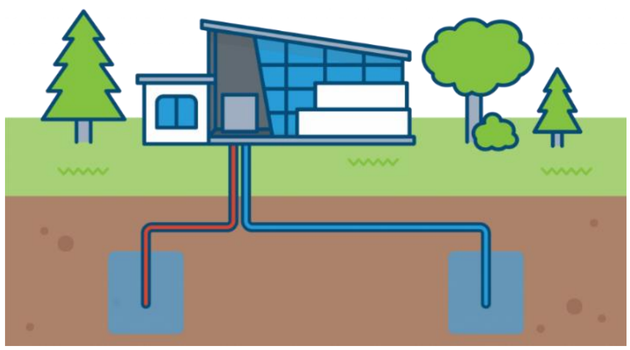


Figure 16. Schematics of an open loop ground source heat pump system or ground water heat pump system (Efficiency Manitoba, 2021)

The underground water temperature in Bow valley region is approximately 4.5°C based on the conversation between our team and local contractors at the Spring Creek Village in Canmore. Similar to ASHPs, the capacity of the heat pump is determined by the building energy loads. As a result, an appropriate GWHP has been chosen. It is suitable for the duplex unit. The required flow rate for the heat pump is 12 gpm (Nordicghp, 2023b).

Similar to the ASHPs, GWHPs also have a performance table which relates the system's COP, and capacity to the ground water temperature. In this study, it is assumed that the underground water temperature is constant and equal to 4.5 C. Thus, the heat pump always draws 4.5 °C underground water to the system, and the COP of the system and capacity of the GWHP is constant throughout the year. It is worth noting that GWHPs can bring free cooling during summer. The underground water temperature is at the perfect temperature for space cooling without running the heat pump. Table 12 depicts the heat pump performance information.

Table 12 GWHP performance table for the duplex unit

Underground water temperature (C)	COP heating	Heating Capacity (W)	Compressor work input (W)
4.4	3.36	11400	3405

As mentioned before, there are times when the heat pump capacity is less than building energy loads. In these situations, it is assumed that the gas furnace helps the system as an auxiliary heater. For hotel building, since the peak heating load is bigger than the commercial GWHPs capacities, it is assumed that there are two heat pump units connected to each other in series ((Nordicghp, 2023b). As such, the overall capacity will be sufficient to handle all the building energy loads, and no auxiliary heater will be needed for the hotel building. Table 13 gives useful information about the GWHP requirements for each building type.

Table 13 GWHP energy consumption and loop flow rate in each building type

Building type	**Area of the building (m^2)**	**Flow rate (GPM)**	**Yearly electricity consumption (MWh)**	**Yearly auxiliary (gas) heater consumption (GJ)**	**Average heating COP**
Duplex	157	12	7	4.32	3.36
Apartment	1100	100	27.2	0.43	3.91
Hotel	10125	360	95.5	-	3.91

It is important to know the heat pump's required flow rate and ensure that there is an aquifer with the sufficient water flow rate. Figure 17 shows the comparison of GWHP performance in different building types per area of the building. The hotel has a lower energy usage per unit area and requires no auxiliary heating since it has the lowest energy demand intensity as discussed earlier.

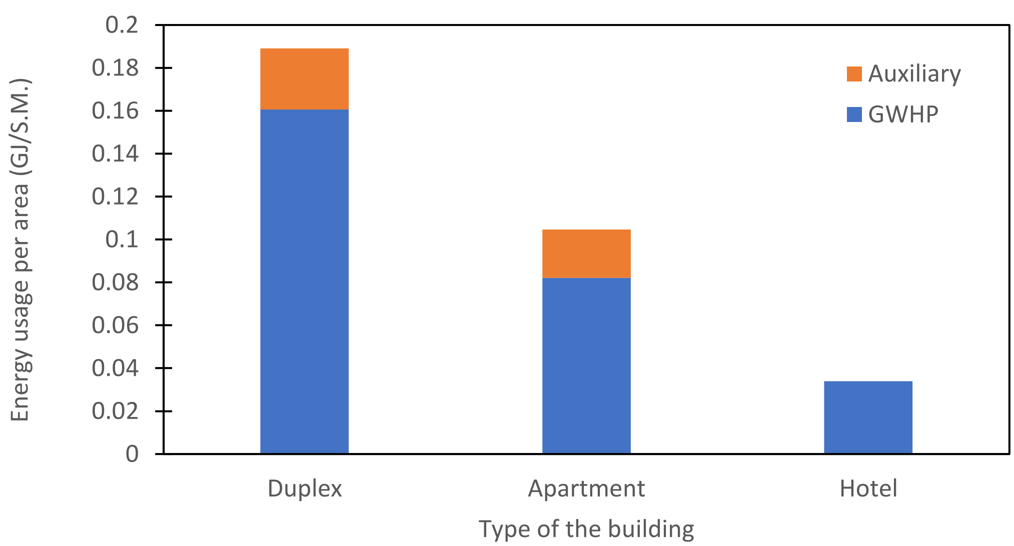
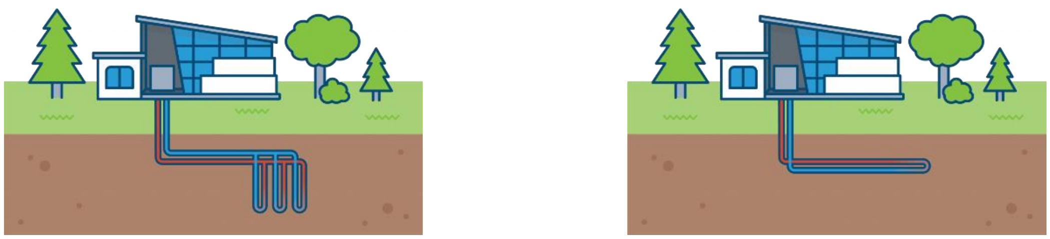


Figure 17. Performance comparison of GWHP in different building types

3.4.4. Heating and cooling with ground source heat pumps

Closed-loop ground source heat pump systems are another type of geothermal heating and cooling system that use a closed network of pipes to circulate a heat-transfer fluid, typically a mixture of water and antifreeze. These systems are versatile and can be installed in various geographical areas, making them suitable for regions with limited access to underground water resources. Closed-loop systems come in two main configurations: horizontal and vertical.

Horizontal closed-loop systems consist of pipes buried in shallow trenches, typically several feet below the surface. This design is cost-effective to install and is well-suited for areas with ample space. In contrast, vertical closed-loop systems involve drilling boreholes deep into the ground and inserting vertical loops of pipes. This design is ideal for locations with limited surface area but higher drilling costs. Both configurations utilize the Earth's relatively stable subsurface temperature to exchange heat with the heat pump.



(a) (b)

Figure 18. Schematics of a closed loop ground source heat pump system: (a) vertical (b) horizontal (Efficiency Manitoba, 2021)

Closed-loop systems offer several benefits. They are less dependent on the availability of underground water, making them a reliable choice for a wider range of geographic regions. They are also less vulnerable to contamination or mineral scaling issues that can affect open-loop systems. Additionally, closed-loop systems tend to require less maintenance over time.

However, closed-loop systems also have some drawbacks. The initial installation cost can be higher due to the excavation or drilling required, and this cost may vary depending on the chosen configuration. Horizontal systems require more space, which may not be practical for small properties, while vertical systems require specialized drilling equipment. Additionally, closed-loop systems may be less efficient than open-loop systems in regions with abundant groundwater because they rely on the heat-transfer fluid to transport heat to and from the ground, which may have a lower heat exchange efficiency compared to direct groundwater contact.

The same heat pump as used in GWHP systems can be used for GSHP with an antifreeze solution as the working fluid. However, the underground heat exchanger needs a different design. The most important factor for the ground heat exchanger is its pipe length. To calculate the required pipe length, it is assumed that the problem is steady-state and all thermal properties are constant.

$$q = \frac{L\,(T_g - T_f)}{R_g} \quad (16)$$

Where q is the heat transfer rate (W), L is the required length of heat exchanger pipe (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.K/W).

The heat rate delivered to the ground in the cooling mode by the condenser includes the heat of the heat pump and auxiliary equipment. Thus, q_{cond} can be calculated to be:

$$q_{cond/lc} = \frac{COP_c + 1}{COP_c} \quad (17)$$

Where COP_c is the cooling coefficient of performance (W/W), q_{cond} is the heat pump condenser heat rejection rate to ground (W), q_{lc} is the building design cooling block load (W).

However, the heat of the heat pump and auxiliary equipment in heating mode is delivered to the building. Thus, the heat removed from the ground by the evaporator is:

$$q_{evap/lh} = \frac{COP - 1}{COP} \quad (18)$$

Where q_{evap} is the heat pump evaporator heat extraction rate from the ground (W), q_{lh} is the building design heating block load (W), and COP is the heating coefficient of performance (W/W).

Assuming high-density polyethylene (HDPE), 1-inch diameter pipe, and propylene glycol with a volume fraction of 25%, Table 14 summarizes the required pipe length for different types of buildings considering the type of the ground heat exchanger.

The depth of the horizontal ground heat exchanger is 2 meters below the ground surface, while the depth of the borehole for the vertical ground heat exchangers is 100 meters. Moreover, the vertical configuration is assumed to be a single U-tube with 6-meter separation, and the horizontal configuration is assumed to be the serpentine configuration.

Table 14 Required pipe length for different types of buildings and types of heat exchangers

Type of the building	Vertical heat exchanger (m)	Number of boreholes	Horizontal heat exchanger (m)
Duplex	360	2	1200
Apartment	3000	15	-
Hotel	10500	53	-

As Table 14 shows, the required length for horizontal configuration is significantly higher than the vertical configuration. Even for the duplex building, the horizontal configuration is not applicable since it utilizes a significant amount of land area, which is not available in Bow Valley population centers.

The calculations for energy consumption and COPs are the same as the ASHP and GWHP. The heat pumps are chosen as discussed in the GWHP section. Instead of connecting to the aquifers, the heat pump unit connects to the ground heat exchanger, which circulates the working fluid into the ground. Table 15 shows the energy consumption of the vertical GSHP systems for different types of buildings. Figure 19 shows the comparison of GSHP performance in different building types per unit area of the building. As shown, the apartment building has the lowest energy use per unite area and highest COP given the lowest load intensity as discussed earlier.

Table 15 Vertical GSHP energy consumption and loop flow rate in each building type

Building type	Area of the building (m^2)	Flow rate (GPM)	Yearly electricity consumption (MWh)	Yearly auxiliary (gas) heater consumption (MWh)	Average heating COP
Duplex	157	12	7.2	0	3.30
Apartment	1100	100	22.5	0	3.14
Hotel	10125	360	122.1	0	3.80

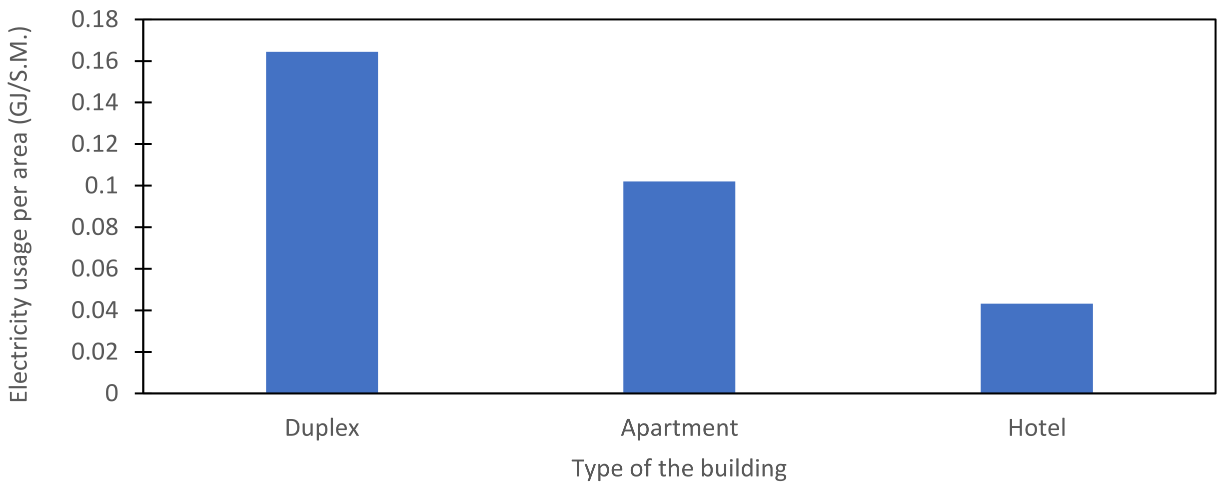


Figure 19 Performance comparison of GSHP in different building types

3.4.5. Heating with electric resistance (baseboard heating)

Resistance heating, often referred to as baseboard heating, is a straightforward and common method of providing warmth or coolness to indoor spaces. It relies on the principle of electrical resistance, where electricity flows through a resistive element, typically made of a heating wire or coil, and generates heat as a byproduct. Baseboard heaters are usually installed along the baseboards of rooms and are controlled by thermostats to maintain a desired temperature. One of the key advantages of resistance heating is its simplicity and ease of installation, as it requires minimal equipment and no fuel storage. However, it is generally considered less energy-efficient compared to other heating methods like heat pumps or gas furnaces because it directly converts electricity into heat, which can be relatively costly, especially in regions with high electricity rates. Nevertheless, resistance heating remains a practical and reliable option for providing localized heat in homes, apartments, and other spaces where more complex heating systems may not be feasible. Table 16 shows the energy consumption of the vertical GSHP systems for different types of buildings. Figure 20 shows the comparison of baseboard system performance in different building types per area of the building.

Table 16 Baseboard energy consumption in each building type

Building type	Area of the building (m^2)	Yearly electricity consumption (MWh)
Duplex	157	23.5
Apartment	1100	107.1
Hotel	10125	366.75

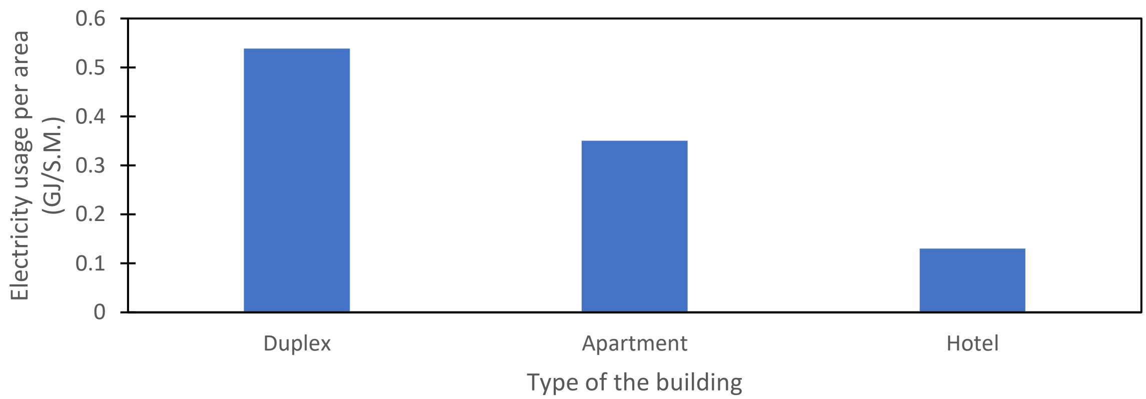


Figure. 20 Performance comparison of baseboard heating and cooling in different building types

3.5. Summary

In this section, an overall summary of energy consumption of different types of heating and cooling systems in three types of buildings has been presented. Figure 21 shows a comprehensive overview of the energy use of each system in each building with their coefficient of performance and efficiencies. The results show that heat pumps use less energy than other systems. The shallow geothermal heat pump systems use the minimum energy among all other types of systems owing to their high seasonal COPs. As such, the energy usage study of the different systems shows that the geo-exchange systems are the best option for heating and cooling. They have the most efficient performance in places where the ambient temperatures fluctuate significantly, such as the Bow Valley region. Although these systems show excellent performance, their initial costs are higher than their counterpart ASHP, furnace and resistance-based heating systems. The cost of installing and operating these systems, as well as the environmental effects of each system, will be discussed next.

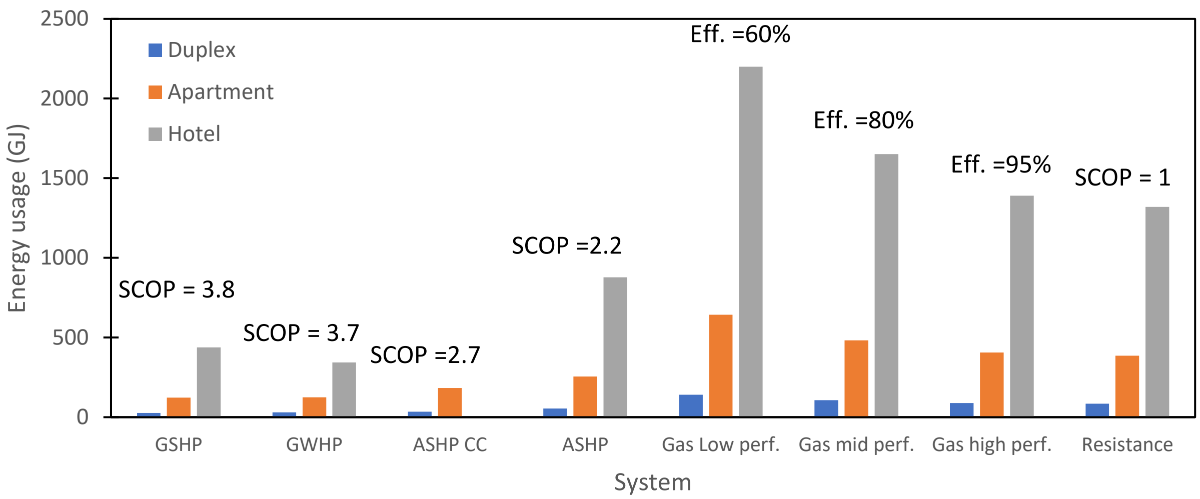


Figure 21. Overview of total energy use of each type of system in each type of building

4. Economic and environmental comparison of different systems

4.1. Overview

The economic study conducted here is intended to assess the financial aspects of various heating systems to enable informed decision-making by individuals and organizations concerning their heating requirements. Five heating options are taken into consideration: gas furnaces, air source heat pumps, ground water heat pumps, ground source heat pumps, and baseboard heating. In this study, both environmental and economic factors associated with each system are examined, with capital costs, payback periods, and overall economic viability being estimated.

4.2. Environmental and economic factors

Environmental considerations are deemed integral to this analysis, 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, parallel to their economic feasibility. By assessing the interplay between environmental and economic factors, a comprehensive perspective is offered on the sustainability and cost-effectiveness of these heating options, with particular attention to the of CO_2 emissions, a critical aspect in the context of climate change mitigation.

The amount of CO_2 emitted by different systems was examined by first calculating the CO_2 emissions from the two primary forms of energy. Predictions for Alberta's electricity generation over the next 30 years (Canada Energy Regulator, 2017), in conjunction with emission data from gas and various types of electricity generation, were used to generate the graph in Figure 22. Figure 22 illustrates the grams of CO_2 emitted per kilowatt-hour (kWh) of energy and how this emission rate changes over the next 30 years. The figure considers the increasing share of renewable energy in the electricity grid and thus reduced carbon dioxide intensity.

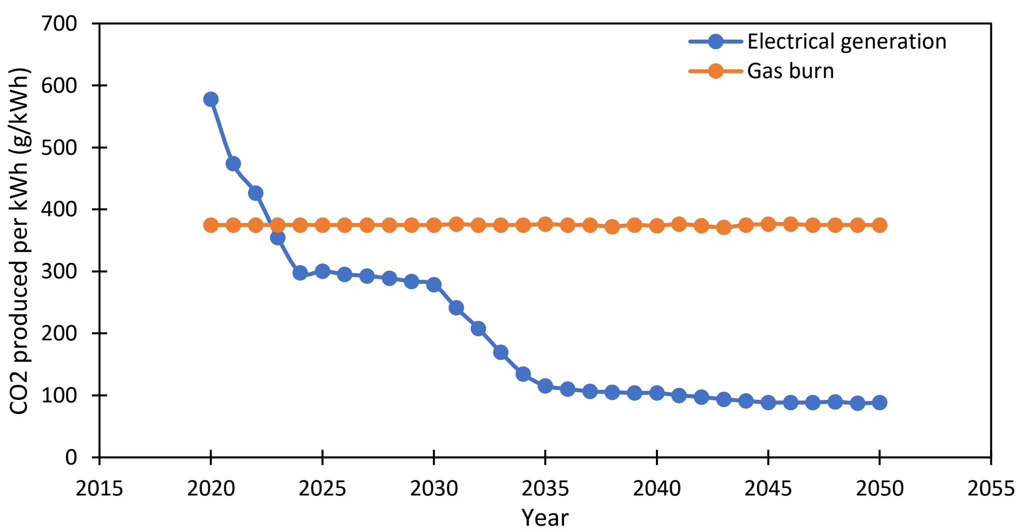


Figure 22. CO_2 produced per energy production

When the emission factors in Figure 22 are applied to the energy consumption of specific systems, it becomes evident how emissions from each system exhibit varying trends over time. The emissions for gas furnace-based systems stay relatively constant, while the costs for systems using electricity reduce with time.

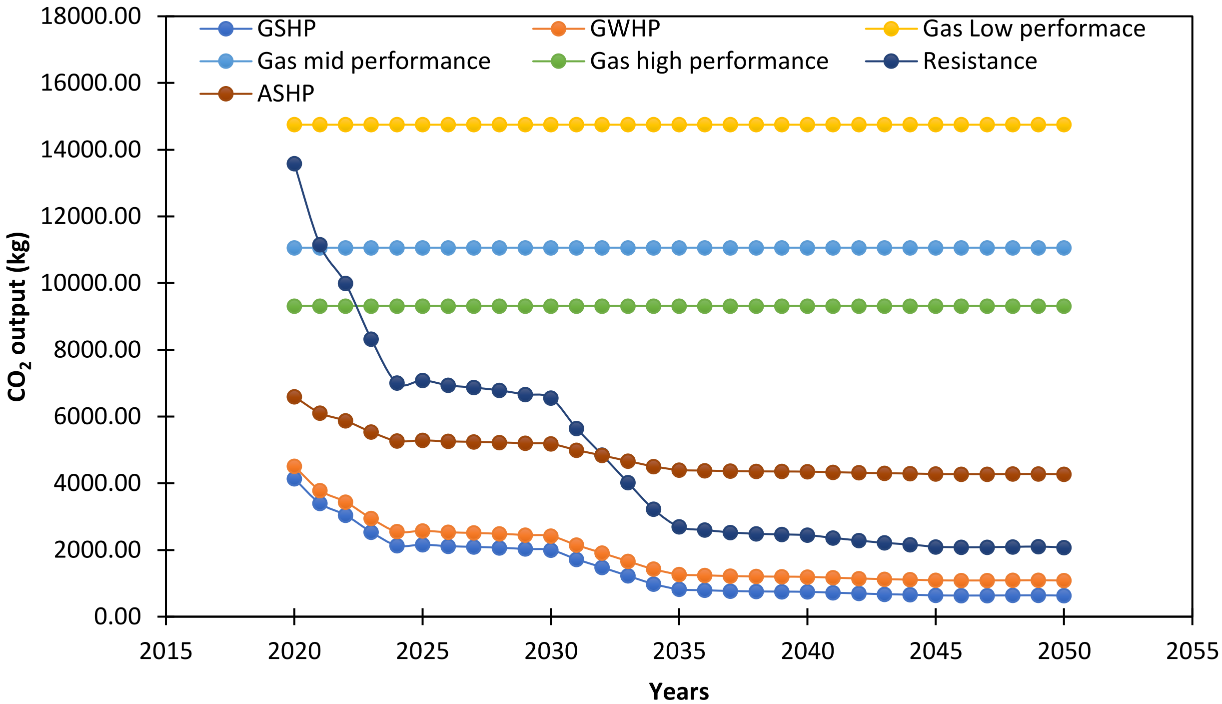


Figure 23 Overall CO_2 emissions from different Systems

The cumulative emissions for each system over a 30-year period are calculated by summing the annual emissions. This calculation provides an understanding of the emissions scale associated with each system. Figures 24 to 26 depict these cumulative emissions for the 30-year duration for each system in each type of the building and demonstrate the potential emissions reduction achievable by transitioning from a mid-performance gas furnace. In line with the energy usage, the efficiency of each system, and the reduction of emissions with time, the electrically powered systems have the lowest CO_2 emissions compared to the gas-powered furnaces. GSHPs and GWHPs show the best environmental performance of all the systems studied.

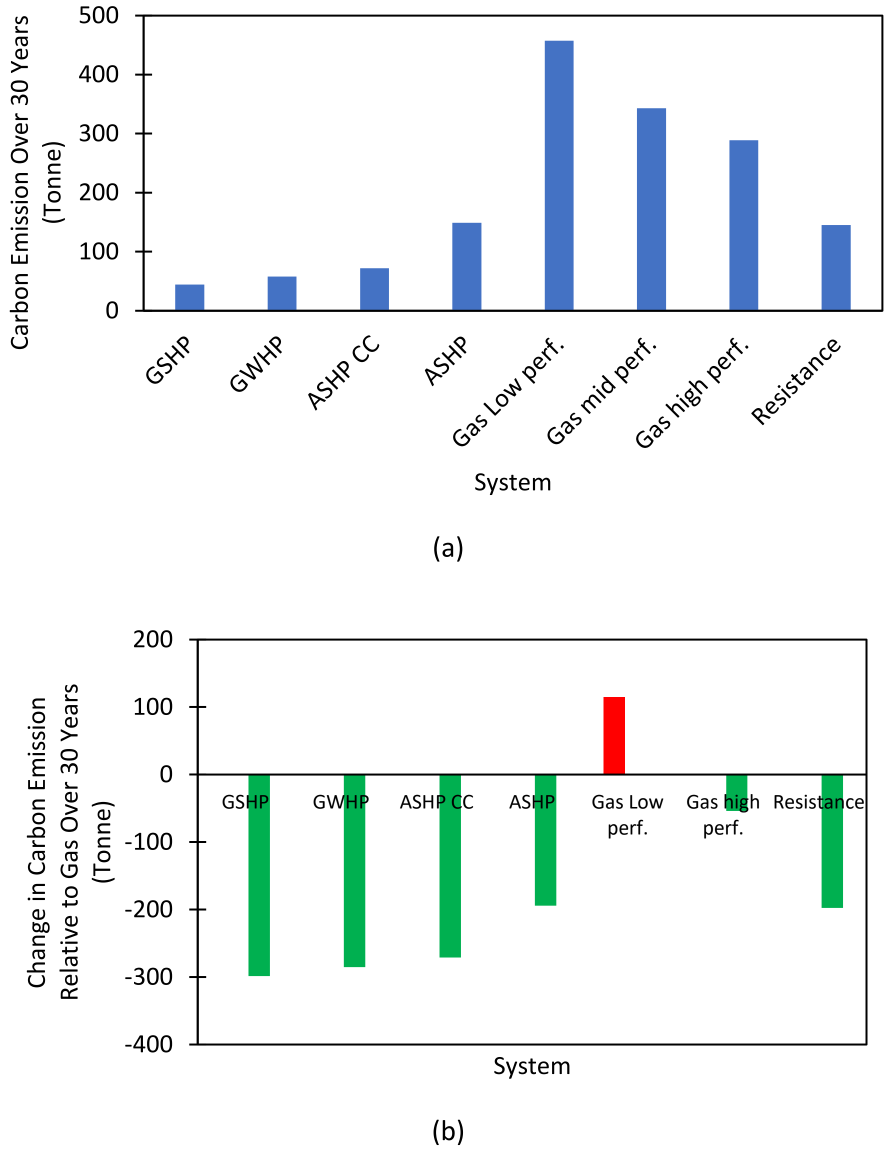
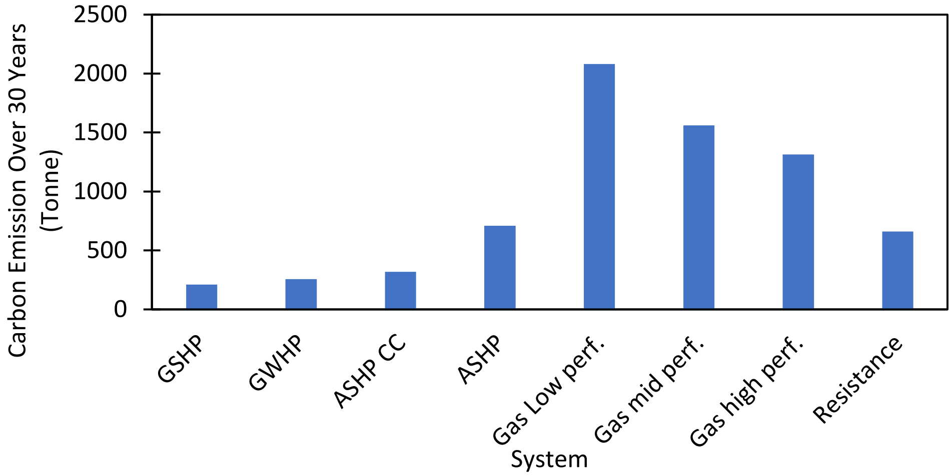
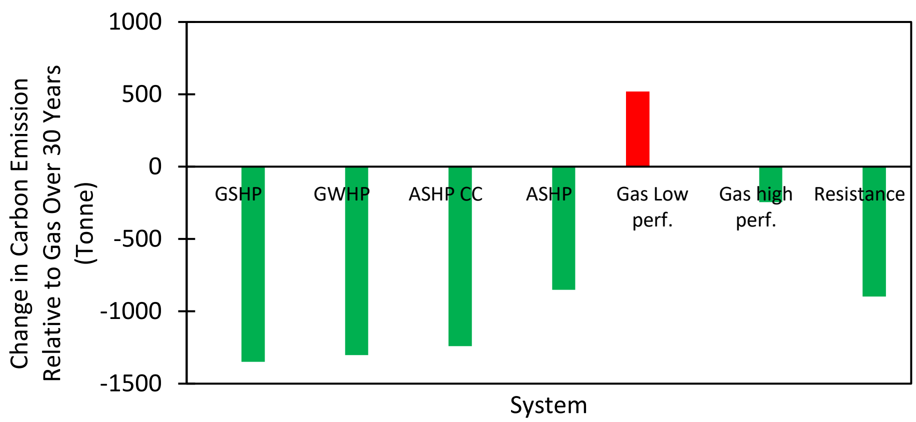


Figure 24. 30 years carbon emissions and comparison with a mid-efficiency gas furnace for the duplex building

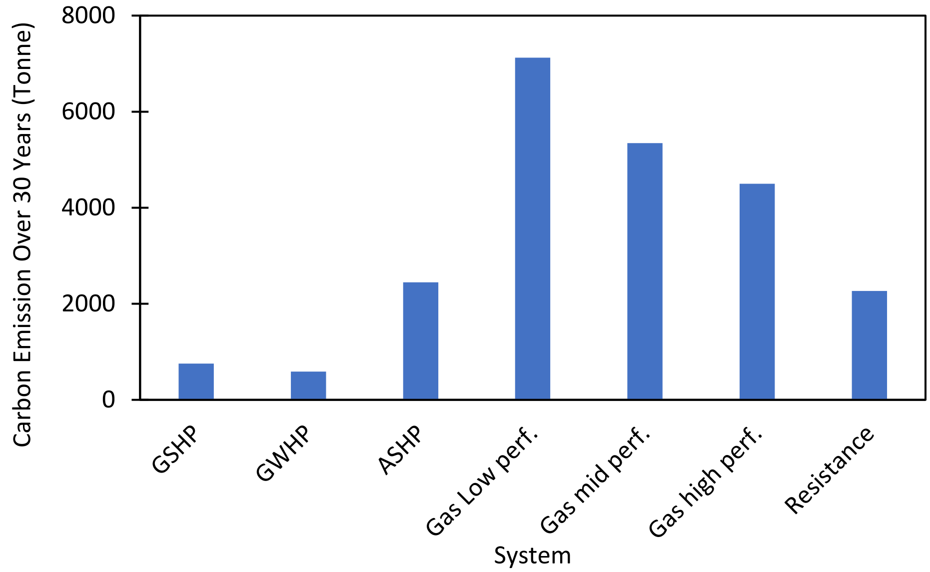


(a)

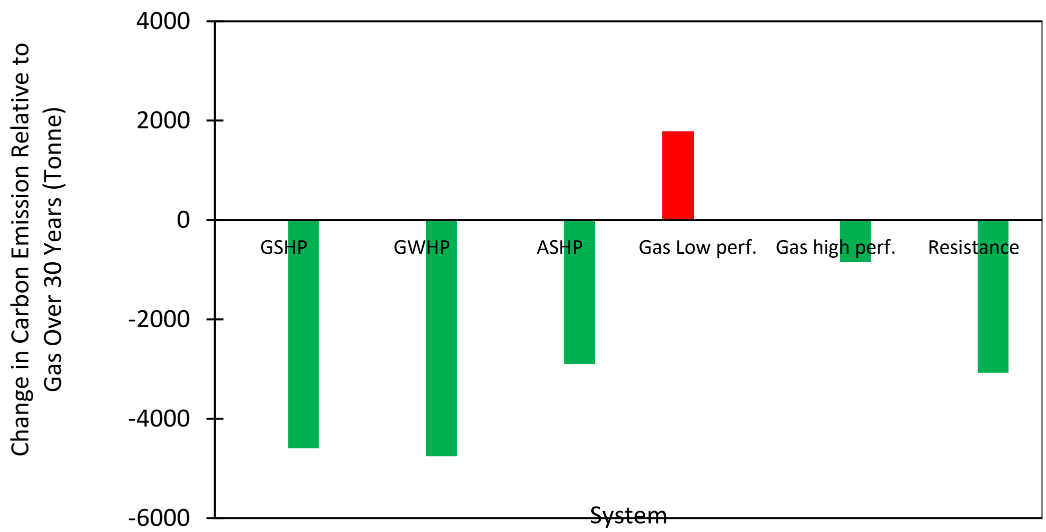


(b)

Figure 25. 30 years carbon emissions and comparison with a mid-efficiency gas furnace for the apartment building



(a)



(b)

Figure 26. 30 years carbon emissions and comparison with a mid-efficiency gas furnace for the hotel building

The results indicate that a high-performance gas furnace emits more than 6.5 times the amount of CO_2 compared to the ground source heat pump in the duplex building. Furthermore, the geoexchange system for the duplex unit emits nearly 4000 tones less CO_2 over a 30-year period than a mid-efficiency forced air furnace. Table 17 summarizes the amount of CO_2 emissions reductions for each system and building type.

Table 17 30-year CO_2 reduction per square meter of buildings summary

Type of the building	GWHP (CO_2 Tones)	ASHP CC (CO_2 Tones)	ASHP (CO_2 Tones)	GSHP (CO_2 Tones)
Duplex	1.81	1.72	1.23	1.9
Apartment	1.18	1.13	0.77	1.22
Hotel	0.47	N/A	N/A	0.45

4.3. Estimated capital costs

Capital costs estimates are based mainly on online quotes, conversations with experts, and case studies in similar situations. For each system, the sources and detailed information is explained. It is recommended that anyone interested in installing any of the systems contact credible and qualified contractors for actual system quotes.

The capital costs for ground source heat pumps (GSHP) were determined through various methods. The most effective method involved looking at the major components, which encompassed drilling, heat pump, and header installation, and then incorporating an additional percentage to account for ancillary expenses. Regarding permit costs, data from the Alberta government (Alberta Environment and Protected Areas, 2021) 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. The 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 (Hydrosolar, 2023), 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 (NRCan, 2023). The analysis assumes that for the duplex configuration, each unit operates as an entirely independent system. In a future study, the use of a shared system for the duplex could be explored. For apartment and hotel scenarios, a shared system is already implemented, including a communal heat pump.

The calculation of costs for groundwater heat pumps (GWHP) closely paralleled that of ground source heat pumps (GSHP). However, drilling costs notably diverged. 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 (SPRING CREEK, 2021). 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 9,000CAD for a 2 ton system, to 14,000CAD to 15,000CAD for a 4 ton system, including installation. These were comparable to those from a variety of online sources. Additionally, furnace prices website (Simon Bernath, 2023) provides optimistic estimations of furnace costs. We assumed that the duplex and apartment have completely individual system per unit. As already mentioned, the hotel is considered too large and, therefore, not suitable for individual units.

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. The estimations for Gas Furnace systems were compiled from a wide array of online data points. Notably, the furnace prices website (Simon Bernath, 2023) presented estimations based on available information. While these estimations appeared slightly conservative, they consistently aligned with data from other sources. It is important to note that the provided information primarily pertained to high-performance furnaces. References used in the analysis specify that estimations were computed for mid and high-performance furnaces, with data for low-performance furnaces not being readily available.

Finally, the pricing data for baseboard heaters, sourced from the HomeGuide website (Tamatha Hazen, 2023), 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 18 shows the breakdown of capital costs for each system and building type. As the table shows, for each building type, geothermal heat pumps always emerge as the most expensive system to install. However, as will be shown later, they have the lowest operating costs of all the systems.

Table 18 Capital costs of each system in Canadian dollars

Type of the building	GSHP	GWHP	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 (Per Unit)	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

4.4. 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 the Government of Alberta website (Government of Alberta, 2023b), an annual price per gigajoule was calculated. Figure 26 represents the average of these rates over the past two years, offering valuable insights into the annual cost of energy per gigajoule. It should be noted that electricity and gas prices are prone to fluctuations. For simplicity, these fluctuations were not considered in the analysis.

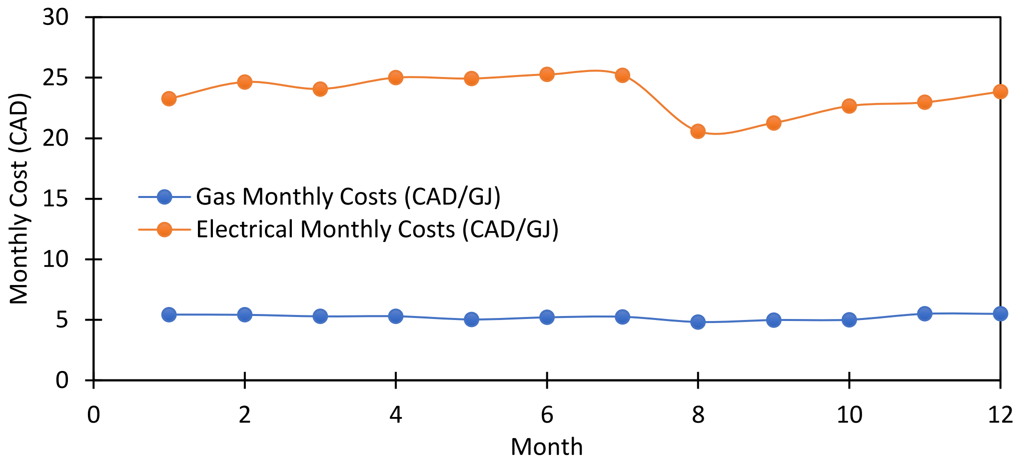


Figure 27 Monthly cost of gas and electricity for a general home per GJ

Combining Figure 27 with the gas and electrical use of each system, an estimation of the yearly operating costs of each system can be established as shown in Figures 28, 29 and 30 for a duplex, apartment, and hotel, respectively. The carbon tax is an additional tax levied on sources that emit carbon dioxide (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 (Government of Canada, 2023). 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 28 to 30 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.

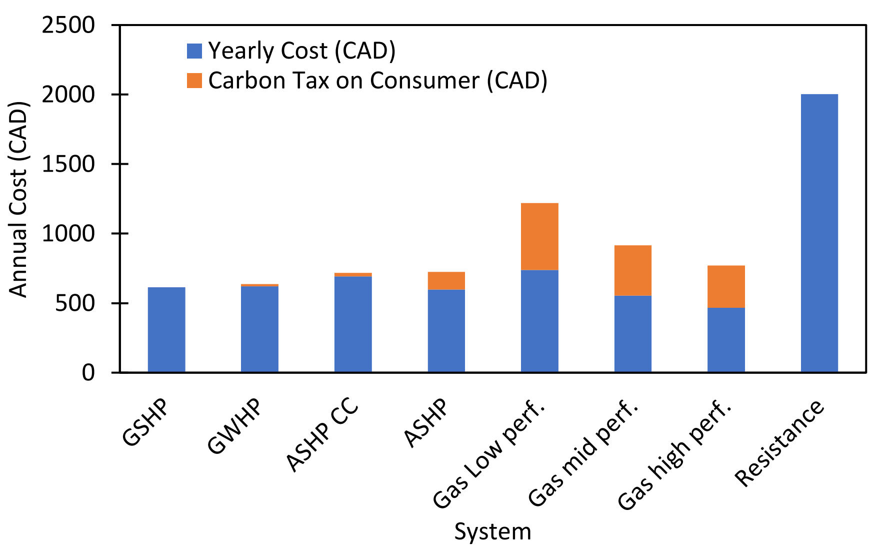


Figure 28. Annual operating cost in 2023 for the duplex building

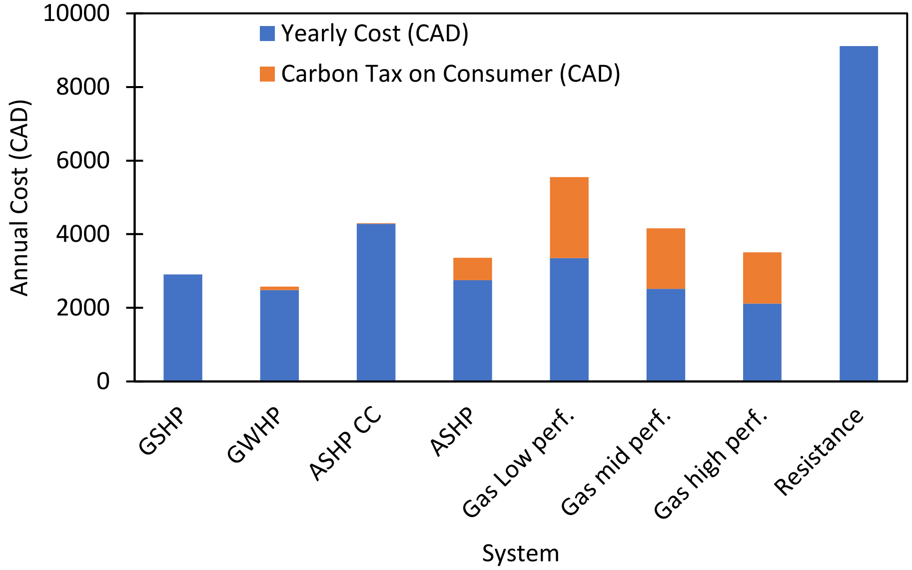


Figure 29. Annual operating cost in 2023 for the apartment building

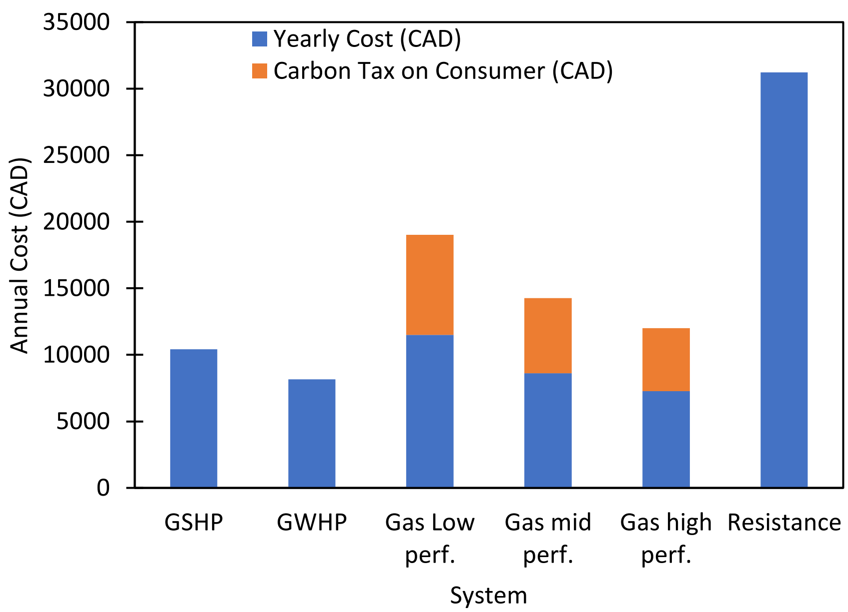


Figure 30. Annual operating cost in 2023 for the hotel building

Figures 31 to 33 illustrate the total annual cost 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 the heating systems. As the carbon tax increases, it will become more cost-competitive to use heat pumps for space heating and cooling. However, it should be noted that the carbon tax might affect the electricity cost if generated from non-renewable sources.

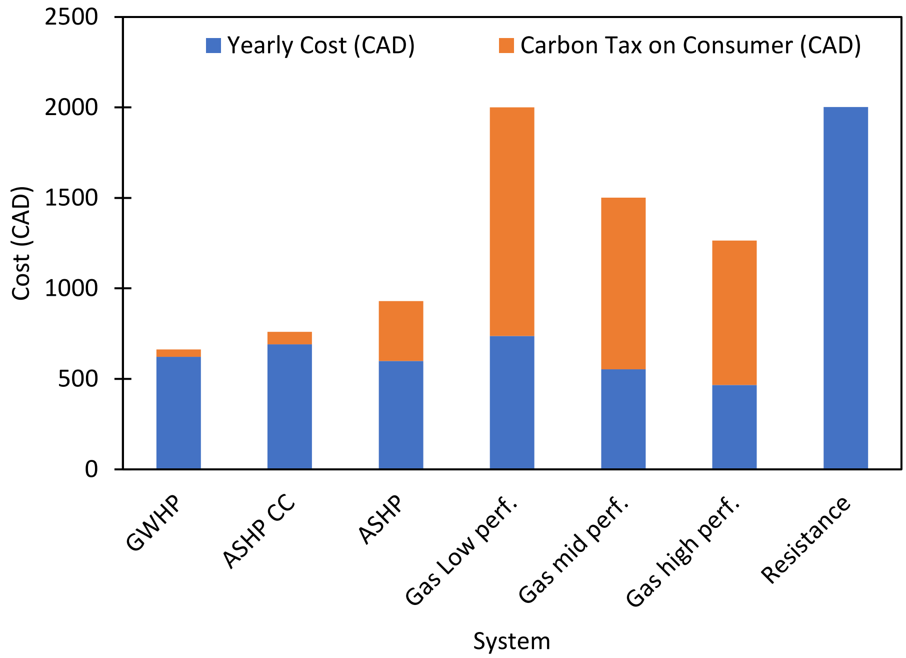


Figure 31. Annual operating cost in 2030 for the duplex building

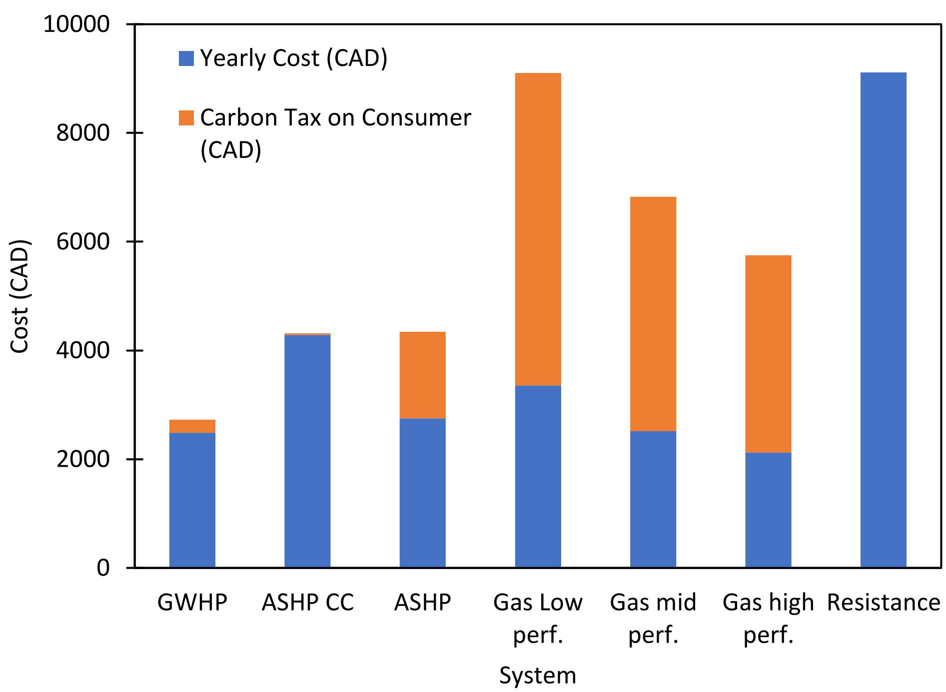


Figure 32. Annual operating cost in 2030 for the apartment building

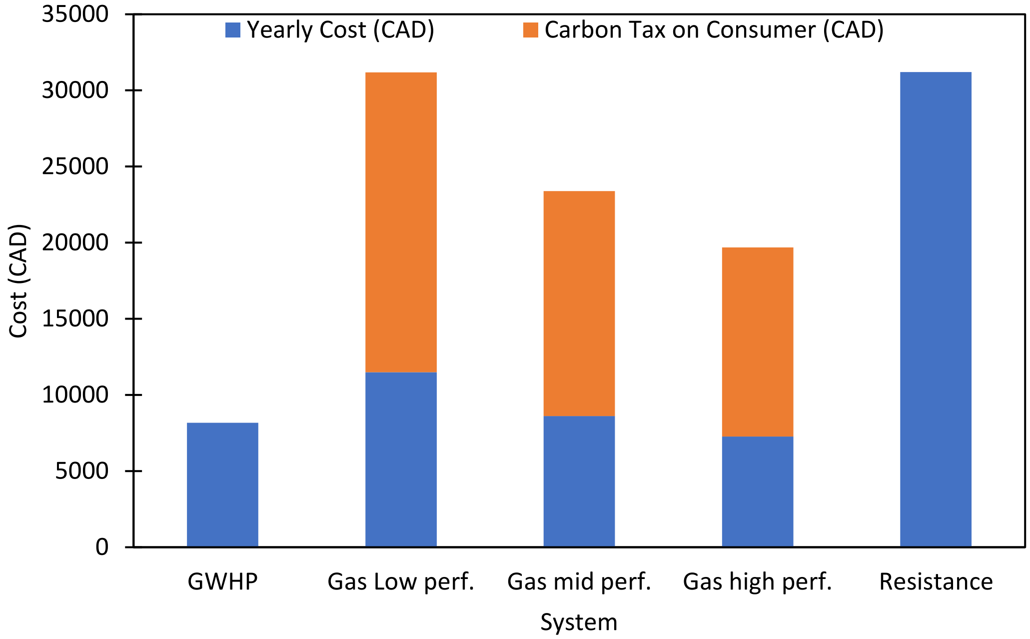


Figure 33. Annual operating cost in 2030 for the hotel building

4.5. Payback Period

The payback period is a financial metric used to assess the time it takes for an investment or a particular system to generate returns equal to the initial capital cost. It represents the point at which the cumulative gains or savings from the investment balance or surpass the total upfront expenses. In essence, the payback period provides insights into the timeframe required for an investment to recoup its initial financial outlay, rendering it a critical tool for evaluating the cost-effectiveness and viability of various projects, systems, or technologies. Shorter payback periods are generally more favorable as they indicate a quicker return on investment, while longer payback periods may be less attractive, suggesting a more extended duration to realize cost recovery. The payback period is a valuable metric for decision-making, helping individuals and organizations determine the profitability and efficiency of their investments or projects.

The calculation of the payback period in this study involved comparing two different systems, such as a ground source heat pump and a high-efficiency furnace, to determine the point at which the total costs of both systems become equal. This was achieved by dividing the difference in capital cost by the difference in 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 reach an equilibrium, signifying that both systems have equal overall costs. The method involved comparing the system in question directly to a high-performance gas furnace. Operational cost and capital cost data were utilized to calculate the payback period in years for this specific comparison.

Table 19 Estimated Payback period range in years when compared to high performance gas

Type of the building	GSHP (Years)	GWHP (Years)	ASHP CC (Years)	ASHP (Years)
Duplex	15 - 40		15-30	
Apartment (Per Unit)				
Hotel				

The presented range of payback period is based on the electricity and natural gas prices, which vary from location to location, and from year to year, the amount of carbon tax in future years, the location of the system which determines 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.

The concept of life cycle cost is introduced in a scenario where all expenses are allocated on an annual basis, rather than the typical practice of having a substantial upfront payment followed by smaller yearly costs. In this alternative method of comparison, it is presumed that all financial commitments are evenly distributed across each year. To calculate this, the capital cost is divided by the anticipated product lifetime and subsequently added to the yearly operational expenses. This approach provides a more balanced assessment of the total cost of ownership, making it easier to evaluate the financial implications of various systems over their entire operational lifespan.

In conclusion, to facilitate a meaningful and equitable comparison of the diverse data presented above, a standardized approach was adopted. This involved expressing all the information on a per-square-meter basis, making it possible to overcome the variations in property sizes. For instance, if the duplex unit encompasses 157 square meters, dividing all the data by 157 permits us to derive specific information tailored to the size of that particular property. This method enables a more uniform and comprehensive assessment of the different heating and cooling systems across properties of varying dimensions, ensuring a fair and accurate comparison.

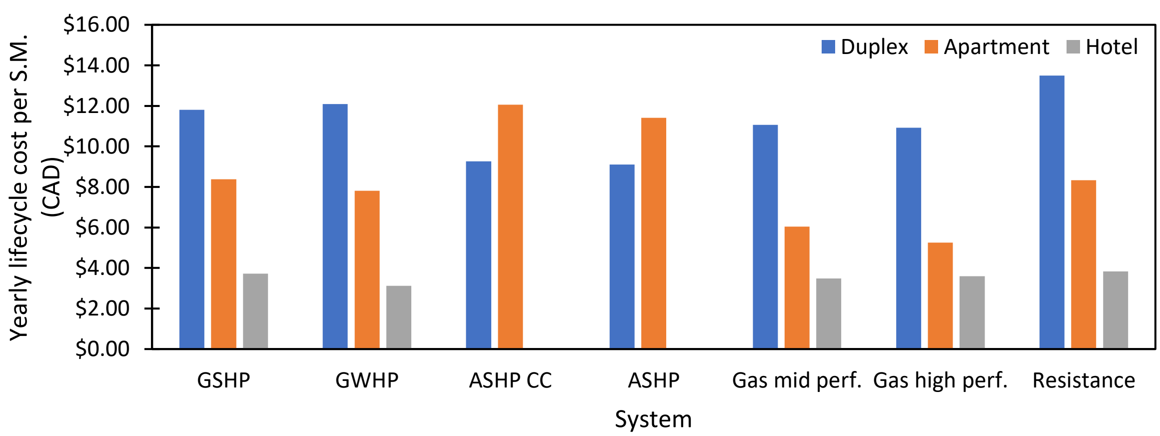


Figure 34 Estimated annual lifespan and operation cost per square meter

4.6. Summary

To summarize the economic analysis of different heating and cooling system, Tables 23 to 25 show all the calculated data and information gathered in this chapter.

Table 23 Summary of economic analysis for the duplex building

Costs	GSHP	GWHP	ASHP CC	ASHP
Capital Cost (CAD)	31,000	31,000	10,500	8,000
Operational Cost (CAD)	613	658	753	895
Carbon Reduction (Ton)	298	285	271	194
Subsidy for 15 years (CAD)	14,500	15,000	0	0
Lifecycle Cost (CAD)	1,853	1,898	1,453	1,429

Table 24 Summary of economic analysis for the apartment building

Costs	GSHP	GWHP	ASHP CC	ASHP
Capital Cost (CAD)	13,300	12,700	9,500	7,500
Operational Cost (CAD)	194	180	288	279
Carbon Reduction (Ton)	90	87	83	57
Subsidy for 15 years (CAD)	4,800	4,000	2,400	300
Lifecycle Cost (CAD)	726	688	921	779

Table 25 Summary of economic analysis for the hotel building

Costs	GSHP	GWHP	ASHP CC	ASHP
Capital Cost (CAD)	680,000	585,000	N/A	N/A
Operational Cost (CAD)	10,420	8,170	N/A	N/A
Carbon Reduction (Ton)	4,590	4.753	N/A	N/A
Subsidy for 15 years (CAD)	290,000	161,000	N/A	N/A
Lifecycle Cost (CAD)	37,620	31,570	N/A	N/A

5. Conclusions

This study conducted a comprehensive evaluation of the cost-effectiveness, energy conservation, and reduction in greenhouse gas emissions resulting from the adoption of ground source heat pump systems in residential properties throughout the Bow Valley region, encompassing Canmore, Banff, and Bighorn. It rigorously compared the operational costs of ground and air source heat pump systems with those of electric resistance, gas, and oil furnaces across various building types, including duplexes, apartments, and hotels. The primary aim was to provide valuable insights into the economic and environmental advantages of implementing these systems within the specific regional context.

A key finding of this study is that the Ground Water Heat Pump (GWHP) emerged as the most advantageous option, considering both initial costs and environmental considerations, while also yielding favorable payback periods.

Furthermore, based on each section of this study, the following conclusions were drawn:

1. An assessment of geological and lithological data in the Bow Valley revealed the potential for both open-loop water source heat pumps and closed-loop ground source heat pump systems. 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 closed-loop ground source heat pump systems.
2. A detailed analysis of building energy demands demonstrated a consistent variation in energy requirements across duplexes, apartments, and hotels due to the region's similar climate. Heating demands exceeded cooling demands in all cases, with heating loads per square meter measuring 0.084 kW/m^2 for duplexes, 0.051 kW/m^2 for apartments, and 0.032 kW/m^2 for hotels.
3. An extensive economic analysis was carried out, taking into account various factors, including capital costs, carbon tax implications, annual operating expenses, monthly gas and electricity consumption, and their influence on the overall cost-effectiveness. The study revealed that the payback period for geo-exchange systems in the Bow Valley region varies widely, ranging from 15 to 40 years. This significant variation can primarily be attributed to soil properties affecting the heat exchange efficiency, the fluctuations in monthly gas and electricity bills, and the available grants and incentives. Carbon tax considerations further underscored the importance of adopting eco-friendly heating and cooling solutions.

In summary, this study underscores 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 viable options, capable of meeting building heating and cooling needs with minimal greenhouse gas emissions and environmental impact. Despite slightly longer payback periods, the substantial environmental benefits translate into reduced greenhouse gas emissions and lower electricity consumption compared to electric resistance heating systems, thereby reducing the need for significant electric grid investments by utilities.

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