

Article

Comparative Assessment of Energy and Emission Costs for Geothermal Heat Pumps and Fossil-Fuel Heating Systems Across U.S. Climatic Zones

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Abstract

In response to growing concerns over global warming and energy sustainability, transitioning from fossil-fuel-based heating systems to renewable alternatives is essential. This study evaluates the economic and environmental performance of geothermal heat pumps for building heating and compares it with conventional coal-fired boilers, natural-gas boilers, and diesel furnaces. Using the heating degree-day (HDD) method, heating energy demand was analyzed for four U.S. cities—Anchorage (AK), San Francisco (CA), Salt Lake City (UT), and Las Vegas (NV)—representing diverse climatic zones. The analysis integrates thermodynamic and economic parameters, including the coefficient of performance (COP = 2–5) and annual fuel-utilization efficiency (AFUE = 80–97%), to evaluate heating-system performance and operational cost across different climatic regions. Sensitivity analysis with $\pm 10\%$ variations in fuel and electricity prices and system efficiencies demonstrates that geothermal heating remains the most stable and emission-efficient option under all scenarios. Results indicate that geothermal systems, despite higher reported initial investment, achieve lower operational and emissions-related costs and offer a robust and sustainable solution for decarbonizing building-heating systems. For example, the estimated seasonal geothermal heating cost is \$370.59 in Anchorage compared with \$646.48 for coal heating and \$3375.65 for diesel systems. Furthermore, policy evaluation indicates that federal and state incentives, such as investment tax credit under the Inflation Reduction Act and rebate programs, can reduce installation costs by 25–40%, improving economic feasibility, particularly in colder regions. The analysis focuses exclusively on energy and emissions-related costs and does not explicitly model capital investment or leveled cost metrics.

Keywords: geothermal heat pump; coal-fired boiler; natural-gas boiler; diesel furnace; operating costs; emissions reduction; comparison; degree-days; cost reduction



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1. Introduction

Geothermal energy, a form of thermal energy that stores heat in the rocks and fluids in the Earth's crust, is becoming appealing and dependable as a clean energy and sustainable heat source for utilities, consumers, and government authorities [1]. As a renewable resource derived from the Earth's internal heat and the natural circulation of groundwater, it offers a sustainable, low-emission alternative to fossil fuels and provides stable, long-term energy with minimal environmental impact [2].

Based on data from the U.S Energy Information Administration (EIA), twenty-four countries, including the United States, generate energy through geothermal energy, amounting to approximately 92 billion kWh worldwide. In 2023, the U.S. generated 17 billion kWh of geothermal energy, about 0.4% of total U.S. energy generation. Although geothermal resources are geographically concentrated, several states, such as California, Nevada, Utah, and Alaska, possess significant potential for direct-use heating and electricity generation applications [3].

Several studies have been conducted in the literature related to geothermal energy generation and its various applications. The authors in [4] conduct a feasibility study analysis for a 1 MW geothermal power plant in Hasbaya, Lebanon. They also perform a cost analysis to check the feasibility of this plant. The authors in [5] discuss various criteria for selecting suitable locations for geothermal power plants. It mainly analyzes how location selection is essential for energy use, such as heating and cooling or generating electricity. The authors in [6] analyze the wide geothermal energy generation technology and corresponding barriers. The authors in [7] suggest policies for the feed-in price of geothermal energy in Taiwan, concentrating on the internal rate of return and net present value.

In addition to energy generation, geothermal energy is widely used for building heating and cooling. Numerous residential and commercial buildings worldwide, including the USA, China, Iceland, etc., are efficiently heated using geothermal heat pumps. Among them, Iceland used geothermal heat pumps to heat about 70 percent of its homes [8]. The authors in [9] assessed the application of ground-source heat pump systems for building heating and cooling in northern China. The findings indicated that geothermal heat pumps can achieve considerable reductions in primary energy consumption and carbon emissions when compared with conventional heating methods. The authors in [10] discuss how geothermal heat pump is a key renewable resource for reducing carbon emissions in developing countries, illustrated through case studies from Europe and Lebanon. The authors in [11] discuss the application of geothermal energy for building cooling purposes without the grids' power to enhance cooling efficiency in hot climates. The results demonstrated that coupling geothermal energy with desiccant cooling can significantly reduce conventional electrical consumption while maintaining acceptable indoor thermal comfort. More recently, national laboratories and energy agencies, including Oak Ridge National Laboratory (ORNL) and the National Renewable Energy Laboratory (NREL), have emphasized the role of geothermal heat pumps in achieving the U.S. carbon-neutral goals by 2050 through residential and commercial decarbonization [12].

While prior studies have examined geothermal heating performance, most focus on single-region evaluations or emphasize power generation rather than direct heating economics and environmental trade-offs. As a result, systematic comparisons of geothermal heat-pump systems with conventional fossil-fuel heating technologies, such as coal-fired boilers, natural-gas boilers, and diesel furnaces, under a unified framework across diverse U.S. climate zones remain limited. To address this gap, the present study performs a comprehensive cost–emission–efficiency comparison of geothermal heat pumps and fossil-fuel heating systems using a consistent analytical framework combined with fuel-price, efficiency, and policy sensitivity analysis. The evaluation is conducted for four representative U.S. cities—Anchorage (AK), San Francisco (CA), Salt Lake City (UT), and Las Vegas (NV)—covering distinct climatic conditions and enabling a comparative assessment of building-heating performance across diverse climate zones.

In this study, the term geothermal heat pump refers to a ground-source heat pump system used for building space heating. For clarity, the analysis focuses specifically on geothermal heat pump technology when comparing heating performance, cost, and emis-

sions with conventional fossil-fuel heating systems. The analysis applies the degree-day method to evaluate building-heating demand and integrates thermodynamic and economic parameters such as the coefficient of performance (COP) and AFUE. AFUE is a dimensionless ratio representing the seasonal thermal efficiency of combustion-based heating systems. COP represents the rated or instantaneous heat pump performance, whereas the seasonal performance factor (SPF) reflects performance over an entire heating season; in this study, a representative COP is used for consistent cross-technology comparison. Furthermore, a sensitivity analysis is conducted to examine the impact of $\pm 20\%$ variations in energy prices and system efficiencies, and the influence of state and federal incentive programs, such as the Inflation Reduction Act (2022) [13], on system feasibility.

By combining environmental, economic, and policy perspectives, this work provides a unified framework for evaluating the practical viability of geothermal heating in comparison with traditional fossil-fuel-based heating systems. The outcomes are intended to guide policymakers, energy planners, and building designers in advancing cost-effective and low-emission heating solutions within the United States.

The main contributions of this research are summarized as follows:

- A consistent, building-scale comparative assessment of geothermal heat pumps and fuel-fired heating systems (coal-, natural-gas-, and diesel-based) across representative U.S. climate zones.
- A unified operational cost and CO₂-emissions formulation, with all parameters expressed on a common energy-equivalent basis and explicitly documented for transparency and reproducibility.
- Climate-driven comparative insights across cities, illustrating how heating demand intensity influences relative operating costs and emissions trends.
- An illustrative electricity-grid carbon-intensity sensitivity example demonstrates how grid composition affects geothermal-related emissions costs without altering the core comparative conclusions.

The rest of the paper is organized as follows. Section 2 provides the modeling and problem formulation. Section 3 presents the results and discussions, and Section 4 discusses sensitivity analysis for the cost of fuel and efficiency variation. Section 5 addresses practical feasibility, policy implications, and the limitations of the modeling approach. And finally, the concluding remarks are presented in Section 6.

2. Modeling and Problem Formulations

In this study, each heating technology is modeled using a simplified but representative configuration consistent with U.S. DOE and EIA heating-system categories. Energy sources (coal, natural gas, diesel fuel, and geothermal energy) are clearly distinguished from heating technologies; all non-geothermal systems are modeled as fuel-fired boilers or furnaces delivering thermal energy directly for space heating. The geothermal case assumes a ground-source heat pump with COP values in the 2–5 range. It should be noted that the actual COP of geothermal heat pumps varies with entering fluid temperature and seasonal operating conditions; however, a representative average value is used here to enable consistent comparison across heating technologies. The natural-gas heating system is modeled as a high-efficiency gas furnace operating solely to meet building heating demand, characterized by AFUE values consistent with current U.S. standards. Even though a natural-gas boiler is one of the major heat suppliers in building heating systems, there are still concerns regarding the environmental emissions emitted by it [14]. In addition to its environmental impacts, there are concerns about future availability since this source is not unlimited. The diesel system represents a standard No. 2 oil furnace with typical overall boiler/furnace thermal efficiency. The coal case is modeled as a generic,

building-scale coal-fired boiler/furnace delivering thermal energy solely for space heating, using fuel-to-heat conversion efficiencies and emission factors reported by the EIA. In modeling terms, this system supplies heat directly at the building scale and does not involve electricity generation, cogeneration, or district heating. Coal-fired boilers are not widely used for building heating in the United States and are included in this study solely as a reference fossil-fuel benchmark for comparative cost and emissions analysis, rather than as a representative or recommended heating option. According to EIA, coal accounts for less than 1% of residential space-heating energy use in the United States, with usage largely confined to legacy or rural applications [15]. The coal case is therefore not intended to represent a realistic or recommended residential heating option, but rather to serve as a consistent benchmark illustrating the relative cost and emissions performance of geothermal systems against a high-carbon fossil alternative within a unified analytical framework. The coal-fired boiler parameters (efficiency and emission factors) are based on representative literature values and standardized boiler performance data and are used here primarily as a counterfactual fossil-fuel benchmark for comparative analysis at the residential scale.

This study is designed as a high-level comparative assessment. The models do not incorporate dispatch optimization, hourly dynamic load profiles, or multi-unit load-sharing strategies, which are typically used in utility-scale system planning. Instead, all systems are compared under consistent seasonal heating-demand assumptions derived from the degree-day method.

Generally, coal-fired boilers, natural-gas boilers and diesel furnaces provide an uninterrupted heat supply to the building if fuel is available [16]. Like natural-gas boilers, a coal-fired boiler is a fossil fuel-based heat generator. The main concern about coal-fired boilers is that they create significant CO₂ emissions into the environment. Coal is also a limited fuel. Data from EIA shows that, in 2022, coal emitted 868 million metric tons of CO₂. This number is almost 53 percent of total emissions from the power sector [17]. While natural-gas boilers are more expensive than coal-fired boilers, their emissions impacts are less. From the modeling perspective, diesel furnaces are like a natural-gas boiler and a coal-fired boiler, as the output power will be stable if the fuel supply is available. Diesel-fired furnaces typically exhibit higher heating costs due to the relatively higher market price of heating oil compared to natural gas, as reflected in U.S. residential fuel price statistics reported by the EIA [18].

Regarding this, geothermal heat pumps can be a sustainable alternative to fossil fuels, like natural-gas boilers, coal-fired boilers and diesel furnaces, for commercial buildings. A geothermal heat pump operates on a vapor-compression refrigeration cycle that transfers heat between the building and the ground through a buried ground-loop heat exchanger. Because the ground temperature remains relatively stable compared to ambient air, the system can achieve higher and more stable performance during the heating season. One key difference between geothermal heat pumps with natural-gas boilers, coal-fired boilers and diesel furnaces is that they may not be available everywhere. In the USA, geothermal-based heat pumps are only available in a few states [3]. However, geothermal heat pumps still help reduce significant emissions and heating costs in some cases where they are available. This research discussed how geothermal heat pumps help reduce environmental emissions and energy costs while heating buildings.

It is noted that all heating technologies in this study are modeled as heat-only systems delivering thermal energy for space heating; no centralized power plants, no electricity generation, cogeneration systems, or district heating networks or dispatch strategy (thermal- or electrical-following) are considered.

For all four systems, the heat output Q_h is calculated from the degree-day heating demand, and fuel or electricity input is determined using the corresponding efficiency values (COP for geothermal, AFUE for gas and diesel, and fuel-to-heat conversion factors for coal).

In this research, a heating degree-day method is used to calculate the daily energy consumption of a building. This method relies on constant indoor building conditions during the heating period. All formulations in this section are developed specifically for heating-only applications. The heating degree-day method provides heating demand, and the energy-input equations compute the required fuel or electricity strictly for meeting this heating load. The heating demand is estimated using the degree-day method, assuming a representative residential-scale building with typical envelope performance characteristics. The analysis does not model a specific building geometry or detailed envelope parameters; rather, it applies to a standard heat-loss coefficient consistent with common residential construction.

2.1. Degree-Days Calculations

In this study, heating demand is estimated using the standard heating degree-day (HDD) method, which relates heat demand to the difference between an indoor balance temperature and the outdoor air temperature over time [19]. For a given day d , the daily heating degree days are defined as [20]

$$HDD_d = \max(0, T_{bp} - T_{ao}) \quad (1)$$

where T_{bp} represents the balance or base point temperature ($^{\circ}\text{C}$) and T_{ao} represents the average of the daily minimum and maximum outside temperatures of the building in that area. Over a month or season, the total HDD is obtained by summing over all days:

$$HDD = \sum_{d=1}^N HDD_d \quad (2)$$

where N is the number of days in the considered period. The HDD has units of $^{\circ}\text{C}\cdot\text{day}$ and provides a scalar measure of the seasonal heating requirement for a given location.

In this work, a base temperature of $T_{bp} = 18^{\circ}\text{C}$ is adopted, which is consistent with common building-energy practice and ASHRAE/DOE guidelines for residential and light-commercial buildings [21]. The resulting HDD values for each of the four selected cities (Anchorage, San Francisco, Salt Lake City, and Las Vegas) form the basis for calculating the energy consumption of each heating system in Section 2.2.

2.2. Energy Consumption (EC) Calculations

The delivered heating demand of the building is determined using the heat loss coefficient and the heating degree-day method [22]. The total thermal energy required for space heating over the considered period is calculated as

$$Q_h = HLC \times HDD \times 24 \quad (3)$$

where HLC is the building heat loss coefficient ($\text{kW}/^{\circ}\text{C}$), HDD is the total heating degree days ($^{\circ}\text{C}\cdot\text{day}$), and the factor 24 converts daily heat demand into total energy (kWh_{th}).

The required fuel or electricity input for each heating technology is computed in Section 2.3 by dividing the delivered heating demand Q_h by the corresponding system efficiency (AFUE for combustion-based systems or COP for geothermal systems). The efficiency values are discussed in Section 3.3 and moderate variations within the reported efficiency ranges do not affect the comparative nature of the analysis.

2.3. Costs of Energy (COE) Calculations

The heating-cost formulation used in this study follows the standard approach used in building-energy analysis, in which the required fuel or electricity input is determined by dividing the thermal load Q_h by the system efficiency [22–24]. For a given heating technology, the required input energy is calculated as

$$E_i = \frac{Q_h}{\eta_i} \quad (4)$$

where Q_h is the delivered thermal heating demand (kWh_{th}) obtained from the degree-day calculation, and η_i is the system efficiency. For combustion-based heating systems (coal, natural gas, and diesel), η_i corresponds to the annual fuel utilization efficiency (AFUE), while for geothermal heating systems, η_i corresponds to the coefficient of performance (COP).

The operating cost of energy is then computed as

$$\text{COE}_i = E_i \times P_{i,eq} \quad (5)$$

where $P_{i,eq}$ is the unit price of the corresponding fuel or electricity expressed on an energy-equivalent basis (USD/kWh). All fuel prices are converted to energy-equivalent prices prior to cost calculations using standard conversion factors (e.g., therm-to-kWh, gallon-to-kWh, MJ-to-kWh), which are summarized in Table 1. Conversion coefficients are applied outside the governing equations to preserve dimensional consistency.

This unified formulation is applied consistently to coal-fired boilers, natural-gas boilers, diesel (No. 2 heating oil) furnaces, and geothermal heat pump systems. Mean efficiency values adopted for each technology are discussed in Section 3.3, following EIA and U.S. Department of Energy (DOE) benchmarks [24]. Moderate variations within the reported efficiency ranges do not affect the comparative nature of the analysis. This formulation extends the simplified framework introduced in the conference version of this work [23] by providing explicit variable definitions, consistent units, and a uniform cost structure across all heating technologies.

2.4. Costs of Emissions Calculations

This study focuses on CO_2 emissions as the primary greenhouse gas associated with heating fuels. While combustion of coal-fired boiler, diesel furnace, and natural-gas boiler also generates other pollutants such as NO_x , SO_x , CO, and particulate matter, these species are not modeled here because their estimation requires detailed fuel-composition data and combustion-control assumptions. CO_2 is selected as a consistent, comparable indicator of climate-related environmental impact. The emissions model adopts a standard mass-balance formulation used in U.S. EPA and IPCC guidelines, where total emissions are computed as the product of fuel input and the respective emission factor:

$$E = F \times EF \quad (6)$$

where F is the energy input determined from the heating demand and system efficiency, and EF is the emission factor (kg CO_2 per kWh of fuel). This formulation is widely used in building-energy studies because emission factors for coal, diesel, and natural gas are well documented by the U.S. EPA and EIA. Emissions are computed solely for heating-related fuel consumption. No cooling or combined-heat-and-power behavior is considered, ensuring that emission factors are applied in a heating-only context.

The environmental emissions using a heat boiler can be determined by [23].

$$C_E = G_m^{HB} \times HV_{HB} \times G^{cin} \quad (7)$$

where G_m^{HB} is the amount of fuel for that heat boiler, G^{cin} is the carbon intensity [kg/kWh] from the fuel. For combustion-based systems, the term G^{cin} (grid or fuel carbon intensity) used in earlier formulations is equivalent to the fuel-specific emission factor EF expressed in kg CO₂ per kWh of fuel input. Thus, Equation (7) represents a specific case of the general formulation presented in (6), applied to boiler-based heating systems. For clarity and consistency, the present study adopts EF as the unified notation for all emission calculations.

The CO₂ emission price is set at \$40 per ton as a representative mid-range carbon valuation commonly adopted in comparative environmental-economic analyses [25]. This value is used for consistent cross-technology comparison and does not correspond to a specific regional compliance market (e.g., RGGI), where prices vary by jurisdiction and auction period. For better understanding and comparison, all heating costs and emissions calculations were made in terms of dollar values (results were presented in the next section). In this study, geothermal heat pump emissions are calculated indirectly based on electricity consumption multiplied by the assumed grid emission factor. No on-site combustion emissions are attributed to the geothermal system, and the upstream electricity carbon intensity is included in the analysis.

This study focuses on a first-order comparison of operational energy cost and emissions for building-scale heating systems. Capital investment costs, levelized cost metrics (e.g., LCOH), and detailed lifecycle economic analyses are intentionally excluded to maintain a consistent, first-order comparison of operational energy and emissions-related costs across locations.

All cost and emission values reported and discussed in Section 3 are calculated using the heating demand derived from the degree-day method combined with system efficiency and fuel price data. The same computational framework is applied consistently across all heating technologies to ensure a fair comparative basis.

2.5. Energy Efficiency for Heating Systems

To supply heat in a building, geothermal heating systems are highly energy-efficient technologies that transfer heat between the ground and a building. The efficiency related to geothermal-based heating systems is typically evaluated using thermodynamic performance metrics such as the coefficient of performance, generally called COP, and seasonal performance factor (SPF). These metrics help quantify how effectively the system converts electrical input into useful heating energy.

The COP can be determined using the following equation [26].

$$COP = \frac{q_H}{W} \quad (8)$$

where q_H is the heating load delivered to the building in kWh. W is the electrical work input to the system in kWh. Generally, for the entire heating season, the equation can be rewritten by SPF

$$SPF = \frac{\sum q_H}{W} \quad (9)$$

For ground-source heat pumps, COP typically ranges from 3 to 5, depending on conditions.

For combustion-based systems (natural gas, coal, and diesel), this study does not compute efficiencies from detailed thermodynamic cycle models. Instead, system performance is represented using overall boiler/furnace thermal efficiency (AFUE or equivalent), which accounts for combustion, stack, and cycling losses, rather than burner-level combustion efficiency. Typical efficiency ranges are adopted from established sources, and representative mean values are used consistently in comparative analysis.

For natural-gas boilers, the annual fuel utilization efficiency (AFUE) typically ranges between 80% and 97% for residential and light-commercial furnaces, depending on whether the unit is a standard or condensing design. For diesel-based heating, AFUE values are generally in the range of 80–90%, while coal-fired boiler efficiencies are commonly reported between 83% and 93%, depending on combustion control and boiler design. These ranges are further discussed in Section 3.3 (typical energy efficiency metrics of heating systems) and are based on Energy Star, boiler-performance guidelines, and previously published studies [27–29].

In the cost and emission calculations, we use representative mean values for each technology (e.g., η_{gas} , η_{coal} , η_{diesel}) rather than deriving efficiencies from first-principles cycle equations. This approach is consistent with the high-level, comparative scope of the present work and with the degree-day-based heating-demand model used for all systems. Specifically, we adopt $\eta_{gas} = 0.90$, $\eta_{coal} = 0.88$, and $\eta_{diesel} = 0.85$ as representative efficiencies within the reported ranges for the numerical results. The efficiency values used (COP, AFUE) refer specifically to heating modes, consistent with the heating-only scope of this study. All remaining model parameters and data sources are summarized in Table 1.

Table 1. Model parameters, assumptions, units, and data sources used in the unified heating-energy analysis.

Parameter	Symbol	Value/Range	Unit	Source
Heat Loss Coefficient	HLC	0.5	kW/°C	[22]
Heating Degree Days	HDD	City Specific	°C.day	[19–22]
Geothermal heat pump performance	COP	2–5	-	[26,30]
Carbon Intensity	G^{cin}	0.1828	kg/kWh	[23]
Carbon Price	P_{CO_2}	0.04	USD/kg	[25]
Coal Energy Content	-	0.2778	kWh/MJ	[17]
Natural Gas Energy Content	-	29.3	kWh/therm	[17]
Diesel Energy Content	-	40.3	kWh/gallon	[17,28]
Emission Factor of Natural Gas	EF_{gas}	~0.180	kg CO ₂ per kWh	[31]
Emission Factor of Coal	EF_{coal}	~0.335	kg CO ₂ per kWh	[31]
Emission Factor of Diesel	EF_{diesel}	~0.253	kg CO ₂ per kWh	[31]
Unit Price of Heating Oil	P_{diesel}	~\$0.092	(USD/kWh)	[24]

Note: Fuel energy-content conversion factors are applied outside the governing equations to express fuel prices and emission factors on a consistent energy-equivalent basis (kWh), ensuring dimensional consistency across all model formulations.

3. Results and Discussions

In this research, four different cities, Anchorage (AK), San Francisco (CA), Salt Lake City (UT), and Las Vegas (NV) were selected as case studies. The cities are selected in a way to make a better comparison and analysis of the energy costs and emissions. For these purposes, two of them were selected from the major winter states, and two were selected from the warmer states in the USA. Since this research was analyzed to heat the building, only data from the peak winter months (December, January, and February) were considered, and their average values were taken to get the results and analysis. To ensure a consistent comparison across all cities, this research analyzes the same three peak winter months for each location. This approach allows for a uniform basis of comparison, recognizing that individual cities may have different heating needs outside this peak period.

The present study is intended as a first-order comparative assessment rather than a predictive or site-specific model. Due to variability in building characteristics, heating system configurations, and local cost structures, directly comparable real-world case studies across all four cities are not readily available in the literature. Instead, internal consistency checks were performed to ensure that the assumed efficiency values, heating demand magnitudes, and resulting operational costs are physically plausible and consistent with established engineering expectations. The results should therefore be interpreted as comparative trends under a unified set of assumptions, rather than as calibrated predictions for specific installations. All systems were evaluated using the same delivered-heat demand and consistent unit conversions, ensuring that relative comparisons are internally consistent across technologies and locations.

This research considers buildings heated in the winter season and the energy capacities needed for that using a coal-fired boiler, natural-gas boiler, diesel furnace, and geothermal heat pump. Data and results are presented and analyzed in different figures and tables, listed in this and the following section.

Figure 1 shows the number of degree days in four selected cities: Anchorage (AK), San Francisco (CA), Salt Lake City (UT), and Las Vegas (NV). The degree days were presented in the months of December, January, and February, and their corresponding average was taken for calculation and shown in this figure. It is evident/obvious from Figure 1 that January has the highest number of degree days among the three months for all the cities, as is expected because of the colder months compared to others. Anchorage (AK) and Salt Lake City (UT) have more degree days than the other two cities, as these two cities typically face colder weather than the other two. For example, an HDD value near 1600 compared to about 400 indicates roughly four times greater cumulative heating demand, implying longer heating system operation and higher seasonal energy requirements in colder regions.

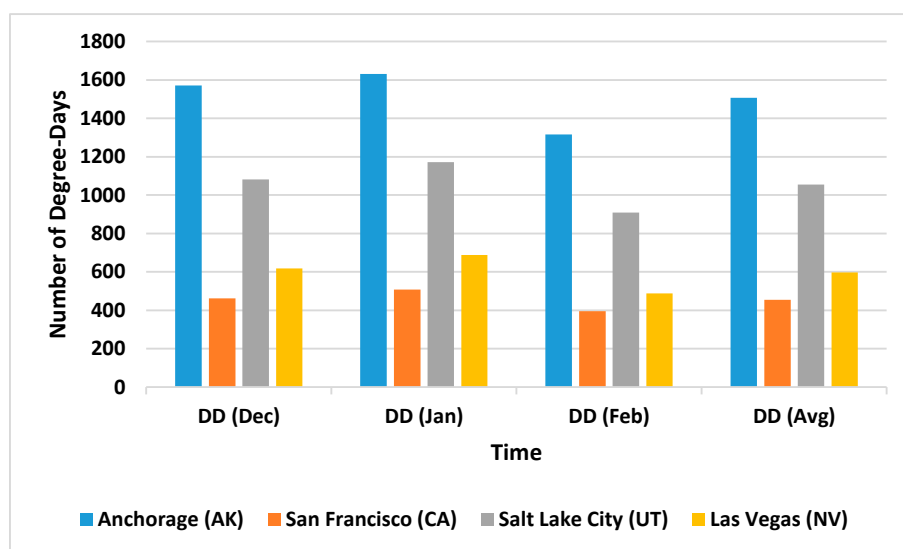


Figure 1. Degree-Days in Dec-Feb for Selected Cities in the USA.

3.1. Energy Consumption and Cost of Energy

Table 2 represents the energy consumption data for fossil fuel boilers and geothermal heat pumps to heat the buildings in the four selected cities. Energy consumption for coal-fired boilers, natural-gas boilers, diesel furnaces, and geothermal heat pumps is calculated in a consistent unit, kWh. The process of calculating the kWh for a fossil fuel boiler and a geothermal heat pump is discussed in Section 2.

Table 2. Energy Consumption using Fossil Fuel-based Boiler and Geothermal Heat Pump in Selected Cities in the USA.

City Name	Delivered Heat Q_h (kWh)	Coal Input (kWh eq)	Gas Input (kWh eq)	Diesel Input (kWh eq)	Geo Electric Input (kWh)
Anchorage (AK)	18,021.40	20,536.36	20,075.19	23,367.96	6007.13
San Francisco (CA)	5444.71	6204.54	6065.10	7060.56	1814.90
Salt Lake City (UT)	12,620.48	14,386.36	14,058.73	16,369.86	4206.83
Las Vegas (NV)	7143.94	8140.90	7958.17	9263.36	2381.31

For combustion-based systems (coal-fired boiler, natural-gas boiler, diesel furnace), input energy values represent fuel energy input prior to conversion losses and are converted to kWh equivalents using standard EIA conversion factors (1 MJ = 0.2778 kWh; 1 therm = 29.3 kWh; 1 gallon diesel = 40.3 kWh). An effective electricity price of \$0.02/kWh is assumed for geothermal systems, representing a policy-optimized electricity rate that may occur under favorable tariffs, renewable-energy incentives, or off-peak electricity pricing programs [32]. For comparison, the average U.S. residential retail electricity price is approximately \$0.12/kWh; higher electricity prices would increase the operational cost of geothermal systems and reduce their cost advantage relative to fossil-fuel heating options, while the emissions comparison remains unchanged. The delivered heating demand Q_h is identical for all systems within a given city; differences in input energy arise solely from technology-specific efficiencies (AFUE for combustion systems and COP for geothermal systems). The electricity price used for the geothermal system represents an assumed effective rate for scenario analysis and does not necessarily reflect the average U.S. residential retail electricity price.

It is seen from Table 2 that Anchorage shows the highest values in each category, with 20,536.36 kWh of coal-fired boiler, 20,075.19 kWh of natural-gas boiler, 23,367.96 kWh of diesel furnace, and 6007.13 kWh of geothermal heat pump input. Salt Lake City also reports relatively high usage, particularly in coal-fired boilers (14,386.36 kWh) and natural-gas boilers (14,058.73 kWh). Las Vegas and San Francisco show lower overall values in all categories, with San Francisco reporting the smallest amounts of coal-fired boiler (6204.54 kWh), natural-gas boiler (6065.10 kWh), diesel furnace (7060.56 kWh) and geothermal heat pump (1814.90 kWh). These values illustrate how heating demand differences across climates influence the required input energy for each technology. Similarly, Table 3 shows the cost of heating energy data for fossil fuel-based boilers and geothermal heat pumps to heat the buildings in the four selected cities.

Table 3. Cost of Energy using Fossil Fuel-based Boiler and Geothermal Heat Pump in Selected Cities.

City Name	COE, Coal (\$)	COE, Gas (\$)	COE, Diesel (\$)	COE, Geo (\$)
Anchorage (AK)	554.48	763.04	3299.00	360.43
San Francisco (CA)	167.52	230.53	996.78	108.90
Salt Lake City (UT)	388.43	534.36	2781.62	252.41
Las Vegas (NV)	219.80	302.48	1307.77	142.88

It is seen from Table 3 that Anchorage records the highest costs in every category, including \$554.48 for a coal-fired boiler, \$763.04 for a natural-gas boiler, and \$3299.00 for a diesel furnace, reflecting its higher energy use and pricing conditions. Salt Lake City also shows relatively elevated costs, such as \$534.36 for a natural-gas boiler and \$2781.62 for

a diesel furnace. In contrast, San Francisco reports the lowest overall costs, with coal at \$167.52 and geothermal at \$108.90. Las Vegas falls in the lower-to-mid range, with diesel costing \$1307.77 and geothermal at \$142.88. These values provide a general view of how energy expenses differ by location and energy type to heat a building. The COE for a diesel furnace is usually higher than that of other heating systems because of the high fuel costs.

It is also seen from Tables 2 and 3 that the cost of energy using a geothermal heat pump, in USD, is generally lower than that of a coal-fired boiler, a natural-gas boiler, and a diesel furnace. Diesel furnaces are the most expensive heating source among coal-fired boilers, natural-gas boilers, and geothermal heat pumps, primarily due to their higher fuel price. This results in significantly greater energy costs across all cities, making diesel the least economical option for producing heat to supply the building.

3.2. Emissions

Table 4 summarizes the results for the costs of emissions using a coal-fired boiler, natural gas boiler, diesel furnace, and geothermal heat pump. All the emissions costs were also converted into USD, like energy generation costs.

Table 4. Emissions Costs using Coal-fired Boiler, Natural-gas boiler, Diesel Furnace and Geothermal Heat Pump in Selected Cities in the USA.

City Name	Emission Costs, Coal-Fired Boiler (\$)	Emission Costs, Natural-Gas Boiler (\$)	Emission Costs, Diesel Furnace (\$)	Emission Costs, Geothermal Heat Pump (\$)
Anchorage (AK)	92.00	49.00	76.65	10.16
San Francisco (CA)	27.80	14.80	23.16	2.29
Salt Lake City (UT)	64.45	34.31	53.69	7.91
Las Vegas (NV)	36.35	19.42	30.38	4.02

Table 4 shows that coal-fired boilers have the highest emission costs in all cities, with the peak value observed in Anchorage (AK) at \$92.00, followed by Salt Lake City (UT) at \$64.45. Diesel furnaces also result in substantial emission costs, such as \$76.65 in Anchorage (AK) and \$53.69 in Salt Lake City (UT), making them the second most emission-intensive source in the dataset. Natural-gas boiler shows moderately lower emission costs, ranging from \$14.80 in San Francisco (CA) to \$49.00 in Anchorage (AK). Geothermal heat pump, by contrast, consistently incurs the lowest emission costs, with values as low as \$2.29 in San Francisco (CA) and a maximum of just \$10.16 in Anchorage (AK). Even though coal-fired boilers are better in terms of COE than natural-gas boilers, they naturally emit more emissions than natural-gas-fired boilers.

From Table 4, it is obvious that the environmental and economic burden is associated with fossil fuel-based heat boilers, particularly coal-fired boilers and diesel furnaces. In comparison, geothermal heat pumps emerge as the cleanest and most cost-effective option in terms of emission costs, reinforcing their potential as a sustainable energy alternative to heat the building.

Figure 2 presents a comparison of the cost of energy and total cost (TC) for four heating energy sources—coal-fired boiler, natural-gas boiler, diesel furnace, and geothermal heat pump—across the selected four U.S. cities. In this study, total cost (TC) represents the sum of operational energy cost and associated CO₂ emission cost. Capital investment, maintenance expenses, and life-cycle economic metrics such as levelized cost of heat (LCOH) are not included in this definition. Thus, TC is computed as the sum of COE and the associated CO₂ emission cost calculated using the above formulation showed in Section 2. It can be seen from Figure 2 that the cost of energy and total cost (combining both the cost of energy

and emission costs) vary across various cities and energy sources, and geothermal heat pump generally remains the most affordable overall.

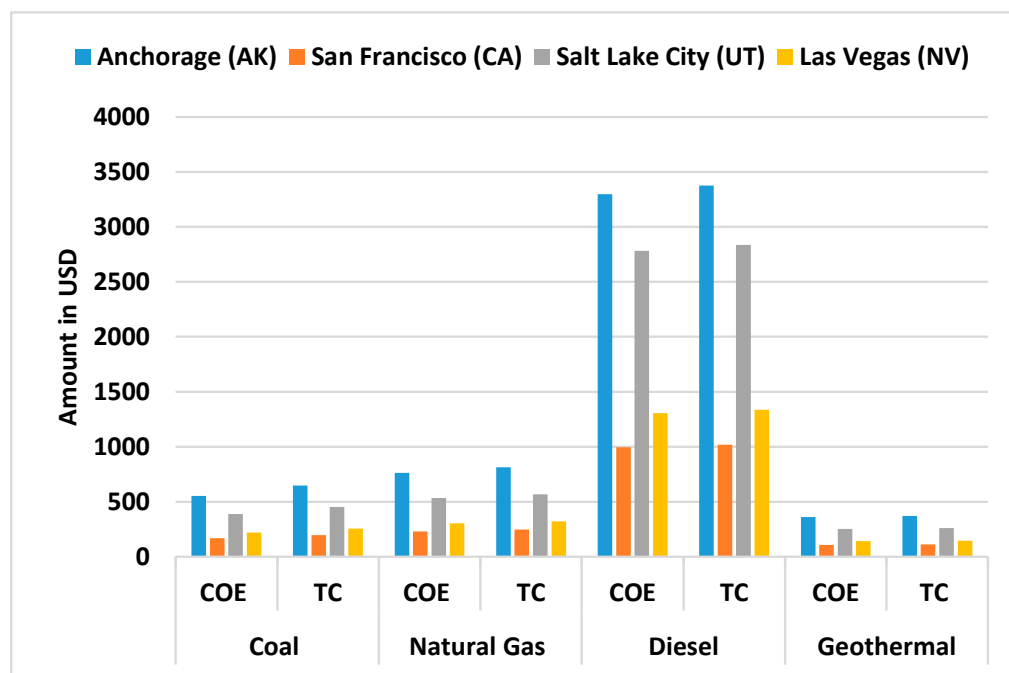


Figure 2. Total cost (TC) comparison of heating technologies across selected U.S. cities. TC is defined as the sum of the cost of energy (COE) and the associated CO₂ emissions cost, calculated consistently for coal-fired boiler, natural-gas boiler, diesel furnace, and geothermal heating systems.

The cost differences observed among the heating technologies can be explained by their underlying fuel prices and system efficiencies. Diesel-based heating systems show the highest operational cost primarily due to the relatively high market price of heating oil and its lower overall combustion efficiency compared with natural gas systems. In contrast, geothermal heat pumps maintain a cost advantage because they deliver multiple units of heat per unit of electricity consumed (COP > 1). This efficiency advantage becomes particularly important in colder climates such as Anchorage, where higher heating demand increases the benefits of high-efficiency heat pump operation. In Anchorage (AK), geothermal has the lowest cost of energy at \$360.43 compared to a coal-fired boiler at \$554.48. Geothermal's total cost of \$370.59 is also cheaper than coal's \$646.48, making it a more economical option. This represents approximately a 34% lower cost of energy and about 43% lower total cost compared to coal in Anchorage, highlighting the significant economic advantage of geothermal in colder climates. In San Francisco (CA), geothermal is also the cheapest option in both measures, with a cost of energy of \$108.90 and a total cost of \$111.19, while diesel is the most expensive at \$996.78 and \$1019.94 for the cost of energy and the total cost, respectively. This is because the cost of diesel fuel is generally high.

In Salt Lake City (UT), geothermal has a total cost of \$260.32, which is lower than coal \$452.88, natural gas \$568.67, and diesel \$2835.31, respectively. Lastly, in Las Vegas (NV), geothermal remains the least costly, with a total cost of \$146.90, compared to coal at \$256.15, natural gas at \$321.90, and diesel at \$1338.15. In this case, the geothermal total cost is roughly 43% lower than coal and more than 85% lower than diesel, further confirming its strong cost competitiveness across different regions. Overall, Figure 2 shows that geothermal consistently results in lower total costs, i.e., across all cities.

From the analysis of this figure, it is obvious that coal is a traditional but high-emission heating source that can appear cheaper initially compared to gas and diesel, but often leads

to higher operational and emissions-related costs over the analyzed period. Natural gas offers cleaner combustion than coal, but it is sensitive to market prices. Diesel is reliable yet extremely expensive due to fuel costs. The advantage of geothermal—combining relatively low electricity costs with moderate grid carbon intensity—naturally results in lower emissions. This double benefit reflects the inherent characteristics of geothermal generation and its interaction with the electricity grid. In addition, geothermal energy is renewable and stable, making it a practical and environmentally friendly alternative for long-term energy use, but it may not be available everywhere.

3.3. Energy Efficiency

Table 5 summarizes the typical energy efficiency metrics for the four (geothermal, gas, coal, and diesel) heating systems considered in this research.

Table 5. Typical Energy Efficiency Metrics of Heating Systems.

Heating System	Efficiency Metric	Typical Range	Selected Value	Description	Refs.
Geothermal	COP/SPF	2.0–5.0	3.0	Uses electricity to extract heat from the ground, offering high efficiency through heat pump technology.	[26,30]
Natural Gas	AFUE	80–97%	88.5	Burns natural gas to produce heat, with efficiency depending on whether it is a standard or condensing unit.	[27,28]
Coal	η_{coal}	83–93%	88.0	Generates heat by burning solid coal, with performance influenced by combustion control and fuel quality.	[21,29]
Diesel	AFUE	80–90%	85.0	Uses oil-based fuel to produce heat, with efficiency affected by burner design and heat exchanger effectiveness.	[27,28]

Table 5 presents the range and selected efficiency values used in this research. It also shows that the performance of the four heating systems—geothermal heat pumps, natural-gas boiler, coal-fired boiler, and diesel furnace varies significantly depending on the technology and fuel type. Geothermal heat pumps demonstrate the highest efficiency, with a COP ranging from 2.0 to 5.0. It should be noted that a coefficient of performance (COP) greater than one does not imply an efficiency exceeding 100%; rather, it reflects the ability of a heat pump to transfer thermal energy from the ground using electrical input, consistent with the first and second laws of thermodynamics. In this case, it means they deliver 2 to 5 units of heat for every unit of electricity consumed. COP is defined as the ratio of useful heat delivered to electrical energy consumed; therefore, values greater than one are expected for heat pump systems and do not indicate a violation of thermodynamic efficiency limits. In comparison, gas systems typically offer AFUE values between 80% and 97%, with modern condensing units achieving high performance levels. However, it should be noted that the coefficient of performance (COP) of geothermal heat pumps is not directly equivalent to combustion efficiency metrics such as AFUE. Coal-fired boilers operate at a thermal efficiency of 83% to 93%, generally outperforming standard gas and diesel systems but falling short of high-efficiency natural-gas boilers and geothermal systems. Diesel furnaces, with AFUE values between 80% and 90%, offer reliable performance where gas is unavailable, but they tend to be less efficient than coal and high-end gas systems. Overall, geothermal stands out as the most efficient and sustainable option, while among combustion-based systems, coal and condensing gas offer the highest efficiencies.

The general overview of results analysis is presented graphically in Figure 3.

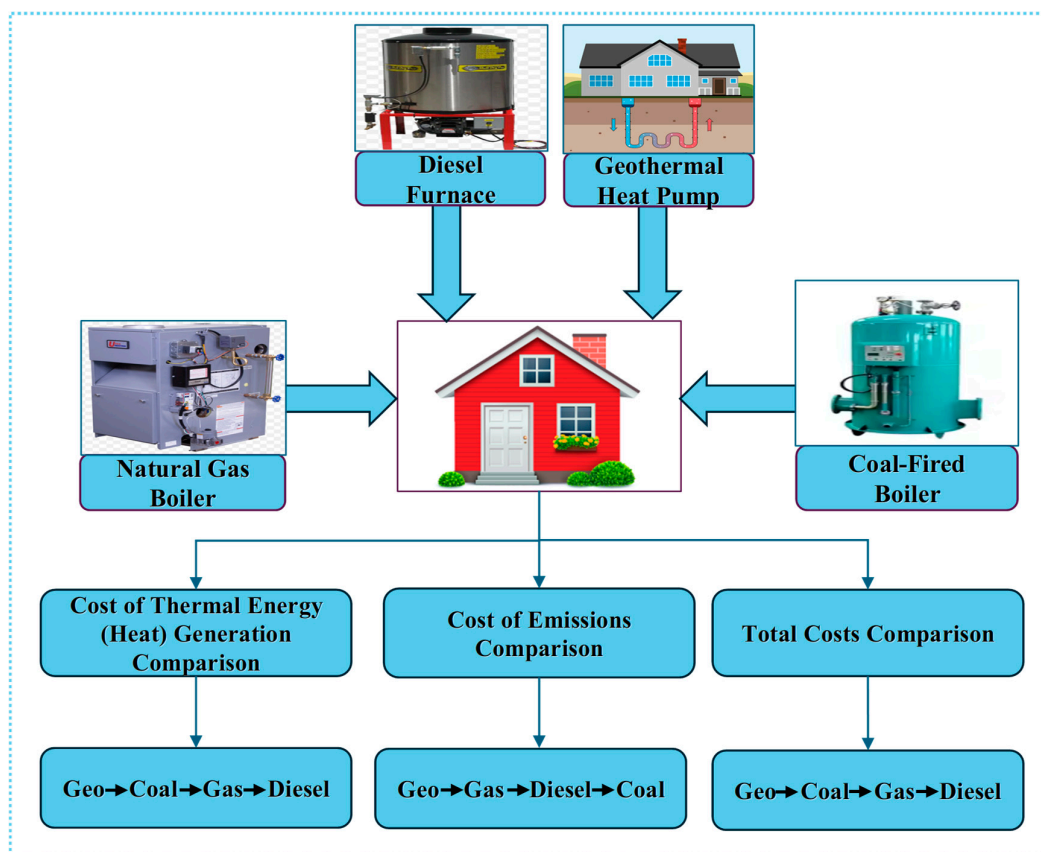


Figure 3. Comparison of operational energy cost, emissions cost, and total cost for decentralized, building-scale heating systems, including geothermal heat pumps, coal-fired boilers, natural-gas boilers, and diesel furnaces.

As illustrated in Figure 3, geothermal energy is the most economically sustainable option for generating heat in buildings. Coal remains the least expensive option after geothermal in terms of initial energy cost; natural gas and diesel heating systems incur higher operating expenses. Nevertheless, coal produces the greatest CO₂ emissions, followed by gas and diesel, whereas geothermal energy results in minimal environmental impact.

4. Sensitivity Analysis

This section presents a sensitivity analysis of the COE for coal-fired boiler, natural-gas boiler, diesel furnace, and geothermal heat pump across selected U.S. cities. This analysis considers variations in efficiency, $\pm 10\%$, between minimum and maximum range, showing how minimum and maximum performance levels affect COE, as well as the impact of fuel and maintenance cost increases ($+10\%$). The $\pm 10\%$ variation is selected to represent a moderate and realistic uncertainty range commonly adopted in sensitivity studies of heating system performance. In addition, this section also analyses grid-carbon-intensity sensitivity for geothermal heating. Basically, inside this section, Section 4.1 considered the minimum and maximum efficiency and Section 4.2 considered fuel and maintenance costs variation for each energy source to calculate the costs of energy in different cities using formulas described in Section 2. Section 4.3 tabulates results for carbon-intensity sensitivity for geothermal heating. These results are presented in Figures 4 and 5 and Table 6. These variation results are compared with the results presented in Section 3 and plotted here for better comparison.

4.1. Cost of Energy with Efficiency Variation

Figure 4 presents the energy costs using coal-fired boiler, natural-gas boiler, diesel furnace, and geothermal heat pump at existing, minimum-efficiency, and maximum-efficiency conditions at the selected four cities. It shows current energy costs and how they vary between minimum and maximum system efficiency. For example, in Anchorage, costs range from 524.54 to 587.75 for coal, 707.98 to 858.42 for gas, 3114.26 to 3496.94 for diesel, and 327.6 to 400.48 for geothermal. Similar results show for the rest of the cities as well. Across all cities, the maximum-to-minimum cost variation is relatively small for geothermal (about 18–22%) compared to diesel (around 12–15% but at a significantly higher absolute cost), indicating that geothermal remains economically stable even with efficiency fluctuations. The data show that geothermal provides the lowest and most stable cost, while diesel is the most expensive and most sensitive to efficiency changes. Overall, improving system efficiency significantly reduces heating costs across all energy sources.

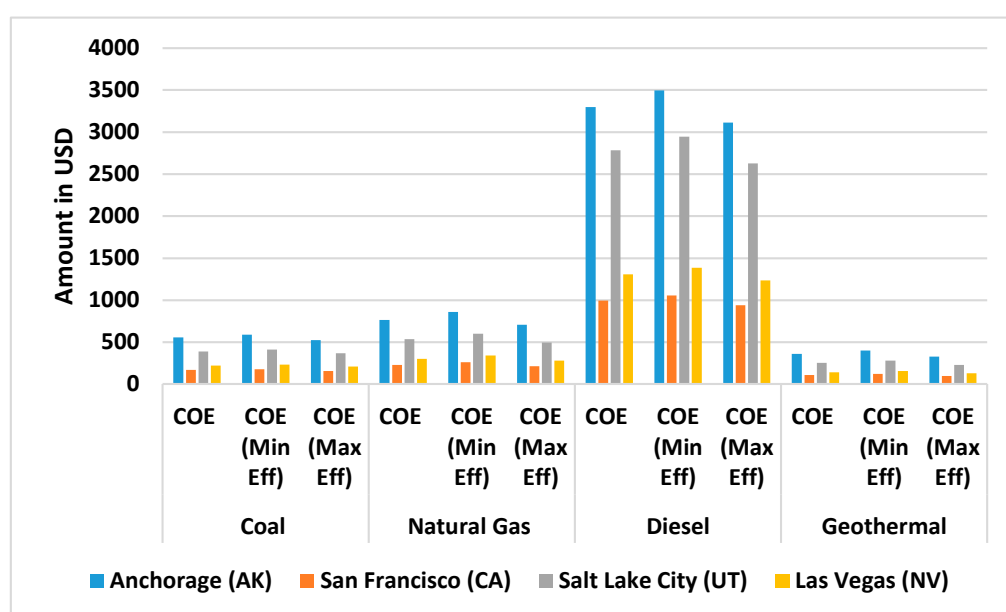


Figure 4. Cost of Energy with Minimum and Maximum Efficiency Ranges for the Sources in Selected Cities in the USA.

4.2. Cost of Energy with Fuel and Maintenance Costs Variation

The values shown in Figure 5 are obtained using the same baseline cost model described in Section 2, with additional fuel and maintenance cost escalation factors applied to evaluate sensitivity effects. Figure 5 presents the sensitivity analysis of the percentage increase in fuel and maintenance costs (F & M) for coal, gas, diesel, and geothermal. In general, coal, natural gas, and diesel are more affected by increases in fuel prices, with only minimal increases in maintenance costs. In contrast, a geothermal heat pump is primarily impacted by changes in maintenance costs rather than fuel costs. For this reason, in this research, for sensitivity analysis, coal, natural gas, and diesel are considered for fuel price increases, and geothermal is considered for maintenance costs increases.

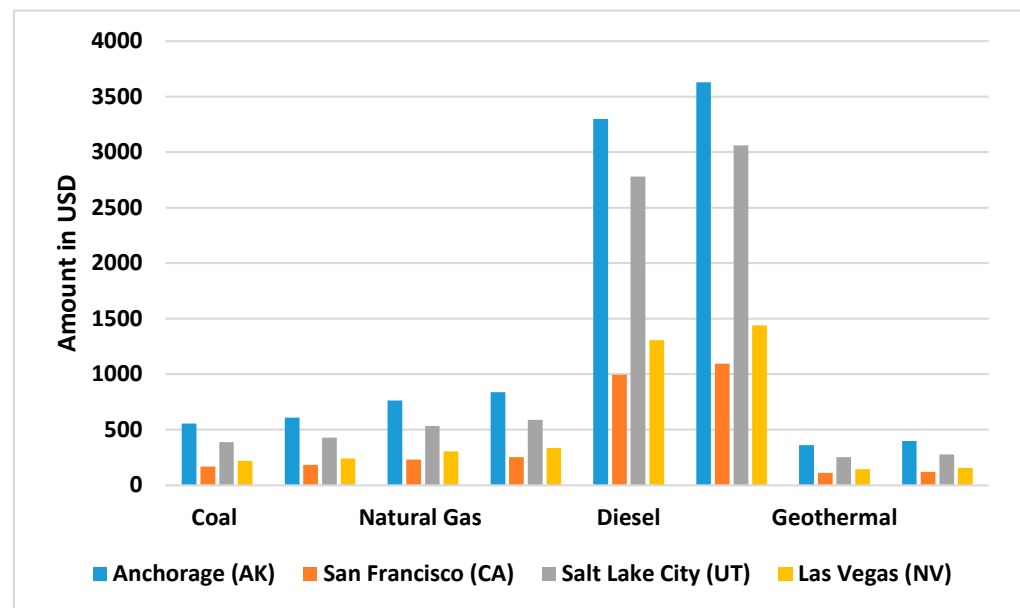


Figure 5. Cost of Energy with Fuel and Maintenance (F & M) Increases for the Sources in Selected Cities in the USA.

Figure 5 shows the COE for coal-fired boiler, natural-gas boiler, diesel furnace, and geothermal heat pump across four U.S. cities, along with COE adjustments for F & M cost increases (maintenance only for geothermal). For example, in San Francisco, coal rises from \$167.52 to \$184.27, natural gas from \$230.53 to \$253.58, and diesel from \$996.78 to \$1096.46, while geothermal increases from \$108.90 to \$119.79. This corresponds to an approximate 10% increase for all systems, but geothermal maintains the lowest absolute COE, demonstrating that even with maintenance cost escalation, it remains more cost-effective than fossil-fuel-based alternatives. It is noticeable that the geothermal price increase ($\approx \$11$) is lower than that of the other sources. This is because, in general, maintenance cost increases do not necessarily follow the same pattern as fuel price increases. Across cities, Anchorage (AK) exhibits the highest COE for fossil fuels (e.g., \$3628.9 for diesel), and fossil fuels generally show larger increases than geothermal.

4.3. Grid-Carbon-Intensity Sensitivity for Geothermal Heating

Because geothermal heat pumps operate using electricity, the associated CO₂ emissions cost depends on the carbon intensity of the electricity supply. When electricity is generated primarily from low-carbon sources (e.g., wind, solar, or hydropower), the resulting emissions attributable to geothermal operation are minimal, whereas electricity supplied from more carbon-intensive grids leads to higher associated emissions. Although emissions costs are implicitly reflected in retail electricity prices paid by system owners, a separate emissions-cost calculation is introduced here solely to illustrate sensitivity to grid composition. To this end, the geothermal-related emissions-cost term is recomputed using state-average electricity CO₂ emission rates from the U.S. EPA eGRID database (2022) [33]. The geothermal emissions cost per kWh of electricity consumption is calculated as:

$$E_{C, geo} = EF_{geo} \times P_{CO_2} \quad (10)$$

where EF_{geo} is the grid CO₂ emission factor (kg CO₂/kWh), and P_{CO_2} is the carbon price (USD/kg CO₂).

Table 6 summarizes the state-average electricity CO₂ emission rates for Alaska (AK), California (CA), Utah (UT), and Nevada (NV), along with the resulting geothermal emis-

sions cost per kWh. The results indicate that geothermal emissions costs are lowest in lower-carbon grids (e.g., CA) and higher in more carbon-intensive grids (e.g., UT), while the relative cost trends and policy-relevant insights remain consistent across locations. In addition to the state averages, two near extreme grid cases, Oregon and Hawaii, which have geothermal systems, are included to represent low-carbon and high-carbon electricity mixes, respectively. These illustrative cases further highlight the importance of ongoing grid decarbonization in maximizing the environmental benefits of geothermal heating systems.

Table 6. Sensitivity of geothermal emissions cost to state-average grid CO₂ intensity.

City/State	eGRID CO ₂ Emission Rate (kg/MWh)	Converted EF _{geo} (kg CO ₂ /kWh)	E _{C,geo} (USD/kWh)
Anchorage (AK)	421.2	0.41	0.0164
San Francisco (CA)	206.98	0.21	0.0084
Salt Lake City (UT)	687.50	0.69	0.0276
Las Vegas (NV)	307.36	0.31	0.0124
Idaho (low-carbon example)	112.55	0.1135	0.0045
Hawaii (near high-carbon example)	659.75	0.66	0.0266

5. Practical Feasibility, Limitations, and Policy Context

The feasibility of geothermal heating systems in the United States depends strongly on geological suitability, installation cost, regional energy prices, and policy incentives. While geothermal heat pumps offer one of the cleanest and most efficient heating options available, their high initial installation cost—primarily due to drilling and ground-loop construction—remains a barrier in areas lacking specialized contractors or incentive programs [34]. By contrast, natural-gas boilers and diesel furnaces are well established, with mature distribution infrastructure and lower upfront costs [35].

To evaluate how external factors influence system competitiveness, a sensitivity analysis was performed by varying fuel and electricity prices (+10%) and system efficiencies (about ±10%, between minimum and maximum range) relative to baseline conditions. The results confirm that the geothermal heat pump remains the least emission-intensive option under all tested scenarios. A 10% rise in electricity price increases the total heating cost of geothermal systems by only 4–5%, whereas diesel and natural-gas systems experience cost escalations exceeding 13%. Coal and diesel options remain highly sensitive to both fuel price volatility and emission charges, eroding any initial cost benefit.

From an energy-efficiency perspective, geothermal heat pumps exhibit a COP between 2 and 5, equivalent to heating efficiencies of 200–500%, over a 20-year service life. Fossil-based systems, while inexpensive to install, incur higher operational and emissions-related costs due to fuel price variability and tightening emission regulations [36]. In particular, coal use in the United States has steadily declined in recent years as market competitiveness decreases and environmental regulations become more restrictive [37].

Government incentives substantially improve the economic feasibility of geothermal heating. Federal and state programs, such as the Inflation Reduction Act (2022) and the Database of State Incentives for Renewables and Efficiency (DSIRE), provide tax credits, grants, and rebates that can offset 25–40% of installation expenses, thereby improving financial feasibility in colder regions. Table 7 summarizes representative U.S. incentive mechanisms relevant to geothermal heating adoption. A detailed quantitative evaluation

of individual policy incentives is left for future work, as the present study focuses primarily on comparative operational and emissions-related costs.

In regions with high heating degree-days, such as Anchorage (AK) and Salt Lake City (UT), these incentives improve cost recovery prospects of geothermal installations, even without explicit carbon pricing. In milder climates, state-level rebates and low-interest financing are critical for economic parity.

Table 7. Selected U.S. policy incentives and credits supporting geothermal heating systems (as of 2025).

Program/Policy	Type of Incentive	Typical Value/Range	Coverage and Notes	Source
Federal Clean Energy Investment Tax Credit (IRA 2022)	Tax credit	30% of installed cost (residential/commercial)	Applies to geothermal heat pumps placed in service 2022–2032	U.S. DOE/IRS
DSIRE State-Level Programs	Rebates/Grants	\$1000–\$5000 per unit	Varies by state (CA, NV, UT offer the highest rebates)	DSIRE Database [38]
Low-Interest Energy-Efficiency Loans (DOE Weatherization Assistance)	Financing support	0–3% interest	Available for low-income households	DOE WAP 2024
Carbon Credit/CO ₂ Emission Trading (Regional Greenhouse Gas Initiative)	Carbon-cost offset	≈\$12–\$15/ton CO ₂	Applies to fossil-fuel systems in participating states	RGGI 2024
Utility Demand-Side Rebate Programs	Bill credit	\$200–\$800 per ton of heat-pump capacity	Offered by local utilities	NREL 2023

Overall, the sensitivity and feasibility analyses demonstrate that a geothermal heat pump provides a technically resilient and environmentally superior pathway for building heating. Although high capital costs and limited drilling expertise still restrict large-scale deployment, continuing workforce development, improved heat-pump technology, and expanding incentive programs are expected to enhance adoption. As emission regulations tighten and carbon-pricing mechanisms mature, geothermal systems will increasingly emerge as the most reliable and cost-effective option for sustainable building heating across U.S. climatic regions. The analytical framework used in this study is designed for a high-level comparative assessment of heating technologies across different climatic regions. The degree-day approach provides a consistent seasonal measure of heating demand, while recognizing that base-temperature selection and the exclusion of factors such as solar gains, internal loads, humidity, and occupant behavior mean that the results represent comparative trends rather than precise hourly predictions. The cost model focuses on operational energy use and does not include capital expenditures, drilling constraints, or site-specific geological factors associated with geothermal installation. Similarly, the environmental analysis emphasizes CO₂ emissions, with other pollutants such as NO_x and SO_x offering opportunities for future expansion. The comparison of COP-based geothermal systems and AFUE-based combustion systems is conducted on a delivered-heat basis, with upstream electricity impacts addressed through grid-carbon intensity. Elements such as dynamic dispatch behavior, load-sharing strategies, and hourly demand modeling fall within detailed system-planning studies and can be integrated into future extensions of this framework. Incorporating lifecycle economic metrics such as operational cost, along with dynamic energy-system models, represents a natural continuation of this work.

6. Conclusions

This research analyzes the use of geothermal energy to heat a building in various locations in the United States, focusing on the costs of energy and emissions. The results were compared with the traditional fossil-based coal-fired boiler, natural-gas boiler, and diesel furnace used for the same purposes. Using the degree-day approach, the study also examined system efficiency and total operational cost, defined as the sum of energy and emissions costs across four representative cities, Anchorage (AK), San Francisco (CA), Salt Lake City (UT), and Las Vegas (NV).

The analysis reveals that geothermal heating presents a promising alternative with lower emissions compared to coal-fired boilers, natural-gas boilers, and diesel furnaces. Although geothermal systems are often associated with higher initial investment costs in the literature, the present study focuses exclusively on operational energy and emissions-related costs and does not explicitly quantify capital investment. Overall, geothermal heating systems demonstrate the cleanest and most energy-efficient performance among the technologies considered.

The sensitivity analysis conducted in this study showed that geothermal systems remain cost-stable with 10% changes in fuel and electricity prices and $\pm 10\%$ variations in system efficiency. In contrast, coal and diesel options exhibit high sensitivity to fuel price volatility and carbon-cost penalties, which rapidly diminish their economic advantage. It should be noted that the present analysis primarily considers operating and emission-related costs; therefore, the observed economic resilience of geothermal systems is conditional on these assumptions and does not explicitly account for capital cost variations. Within this defined scope, the sensitivity results consistently indicate that geothermal systems maintain lower operational and emissions-related costs across the scenarios examined.

This study also recognizes that while geothermal systems are effective, they are not always easy to install. In some areas, the cost is high, and it is hard to find trained professionals. Natural gas systems, on the other hand, are more common and easier to set up. Diesel is expensive, but it can be a good alternative for urgent needs, as fuel is available. However, the feasibility of geothermal systems improves substantially under current incentive frameworks. Federal tax credits under the Inflation Reduction Act (2022) and state-level programs, summarized in Table 7, can offset 25–40% of installation costs and enhance economic attractiveness in colder regions such as Anchorage and Salt Lake City. These incentives, combined with ongoing advances in drilling technology and heat-pump efficiency, strengthen the case for geothermal adoption nationwide. The analysis from this research will further help policymakers, utilities, and the government consider renewable energy resources, including geothermal energy, wherever available, to reduce dependency on fossil fuel-based energy resources and mitigate the environmental impact.

As a future research direction, the work can be expanded by including certain real-life factors—like local energy prices, how long the equipment lasts, or how much it costs to keep running overtime. Future studies will also incorporate life-cycle cost and exergy analyses, hybrid geothermal–solar configurations, and machine-learning-based performance forecasting using region-specific data to support optimized, location-dependent design and policy decisions.

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