Quick screening approach of shallow geothermal energy installation for heating and cooling.

Irene Manara[1], Rémi Lehu[2], Gabriele Cesari[1], Andrea Moscariello[3], Gabriele Ponzoni[1]

[1] EGEO, 88 Rue G. Carnovali , 24126 , Bergamo, Italy

[2] Geneva Earth Resources, 10 Rue Jean Jacquet 1201, Geneva, Switzerland

[3] Geo-Energy Group, University of Geneva, 13 Rue des Maraichers, 1201, Geneva, Switzerland

i.manara@egeoitalia.com

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ABSTRACT

This paper presents a quick screening approach for assessing the feasibility of installing shallow geothermal energy systems for heating and cooling applications. The method is designed to provide a rapid and reliable estimation of the key parameters necessary for decision-making, such as investment costs (CAPEX), operational costs (OPEX), levelized cost of energy (LCOE) and environmental benefits. The approach is based on fundamental input data, including the energy demand (kW) required during the peak seasons of summer and winter, the hours of peak consumption, and the cost of energy, which could be sourced from electricity or fossil fuels (diesel, gas, or coal). By applying this calculation method, potential users can quickly estimate the financial metrics of a shallow geothermal system, including the payback period. This allows stakeholders to evaluate the economic viability of transitioning to geothermal energy. In addition, the approach integrates an environmental assessment by comparing the CO2 emissions of a shallow geothermal system with those of a traditional heating and cooling system powered by conventional energy sources. This comparison highlights the reduction in greenhouse gas emissions and the overall positive environmental impact of adopting geothermal energy. The method serves as a valuable methodology for preliminary decision-making, offering a balance between speed and reliability. It facilitates early-stage evaluations, providing an economic and environmental comparison that helps guide investments in sustainable energy solutions. This screening tool is particularly useful for project developers, engineers, and policymakers seeking to explore the benefits of geothermal energy in the context of low-carbon technologies for heating and cooling applications.

1. INTRODUCTION

Ground Source Heat Pumps (GSHPs) are central to shallow geothermal energy systems, using the earth's relatively stable subsurface temperatures to provide heating and cooling. These systems circulate a heat transfer fluid through buried pipes—either in vertical boreholes or horizontal trenches—connected to a heat pump unit inside the building. In winter, heat is absorbed from the ground and transferred indoors; in summer, the process is reversed to remove heat from the building and deposit it back into the ground.

The basic working principle of a GSHP system is illustrated in Figure 1. A closed ground loop extracts low-temperature heat from the subsurface and transfers it to a working fluid in the heat pump. This fluid passes through a cycle involving an evaporator, compressor, condenser, and expansion valve. The compressor raises the temperature of the vaporized fluid, which then releases heat via the condenser into the building's distribution system—typically radiant floor heating, radiators, or forced-air systems. In cooling mode, the cycle reverses, and heat is extracted from the indoor environment and discharged into the ground (Gamage, 2014, Duque 2016, Keshav 2024).

This high-efficiency mechanism results in lower electricity consumption compared to traditional HVAC systems, especially in climates with significant seasonal temperature swings (Duque 2016). While GSHPs do require electricity to run, they produce no direct emissions on-site and have significantly lower indirect CO_2 emissions than systems relying on coal or other fossil fuels—especially when electricity is sourced from renewable or low-carbon grids.

Economically, GSHPs often involve higher upfront capital expenditure (CAPEX), mainly due to ground loop installation. However, they benefit from lower operating expenses (OPEX), reduced maintenance, and long equipment lifespans. This can result in a favourable payback period over time. The actual payback period varies based on local energy prices, building usage, and geological conditions, but the long-term savings often make GSHPs competitive or superior to traditional systems.

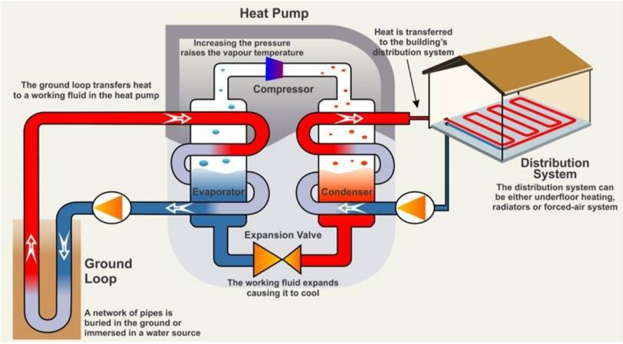

Figure 1: Basic operating principle of a ground sourced heat pump (GSHP). Source: BC Geothermal (https://www.bcgeo.ca/contact/how-geothermal-works/geothermal-heat-pumps/).

To support early-stage decision-making, we developed a easy to use screening tool that enables comparative assessment of GSHP systems against conventional energy options based on CAPEX, OPEX, CO_2 emissions, and payback period. It is particularly useful during the preliminary planning phase, helping to identify promising applications and prioritize further investigation. However, it is important to emphasize that significant uncertainties remain—particularly in geological conditions, installation costs, system performance, and energy price forecasts. While this methodology provides valuable insights at the conceptual level, detailed technical and economic studies are still essential to refine project feasibility and ensure reliable implementation.

2. ENERGY PARAMETERS, INSTALLATION AND COSTS

The performance evaluation of GSHP systems is based on a structured set of input parameters, organized and summarized in Table 1. These parameters are grouped into categories that reflect the key aspects influencing system feasibility: climatic demand, building and installation features, system performance, energy pricing and environmental impact, and financial outcomes.

Each input plays a specific role in the model, contributing to the estimation of heating and cooling loads, energy use, installation sizing, environmental impact (CO_2 emissions), and economic performance. This section provides a detailed explanation of each category and how the corresponding parameters support the screening analysis.

Climate and Thermal Demand

Climatic parameters are essential for understanding the energy needs of a building throughout the year. The monthly average outdoor temperatures allow for the calculation of seasonal energy demands by capturing typical weather variations. These values help model how much heating or cooling is required to maintain indoor comfort over different months.

Additionally, extreme outdoor temperatures for both winter and summer represent the design conditions used for system sizing. The temperature differential—between these extremes and the desired indoor set temperatures—determines the maximum thermal load the system must handle.

The heating and cooling operational hours per year reflect the time the building requires active thermal regulation. These depend on building usage and occupancy patterns and directly influence annual energy consumption and cost estimates.

Building Characteristics and Load Estimation

The total building surface area is a primary input, as it is used to scale the energy demand and the required system capacity. Along with this, the specific peak power requirement per square meter (W/m²) is used to calculate the building's total heating or cooling capacity. This parameter is highly dependent on the building's insulation quality. A well-insulated building will typically have a lower W/m² value, requiring less power to maintain indoor temperature, while poorly insulated buildings will require higher peak loads, increasing both energy use and system size. This relationship is critical in determining the technical and economic viability of the project.

System Design and Investment

From the calculated power demand, the installed system capacity is derived and used to estimate investment costs. The method applies an investment cost per kilowatt (USD/kW, Zuberi et al., 2021, Perko et al., 2011) to approximate the total capital expenditure (CAPEX) (Figure 2). This value includes the drilling, piping, equipment, and installation costs required for GSHP deployment. The cost reference is supported by investment data shown in Figure 2, which illustrates the typical cost per kilowatt as a function of system size, based on published benchmarks.

Also included is the expected energy output per geothermal well, typically expressed in kilowatt-hours per well per year (kWh/well/year). This parameter is essential for approximating the scale of the required drilling program. By dividing the total annual energy demand of the building by the estimated energy that a single well can produce, the tool provides a preliminary estimate of the number of boreholes or wells needed. This is particularly useful in the early design stages, when developers need to understand whether the required geothermal capacity is technically and spatially feasible on a given site. Although simplified, this approach enables a first-level approximation of the geothermal infrastructure, which can later be refined with site-specific geological data and provide a first criteria for site selection based on bore space availability.

Annual maintenance costs, expressed per square meter of building area, are also included. These reflect the recurring costs associated with inspections, component servicing, fluid checks, and other routine system upkeep. While GSHPs tend to have lower maintenance needs than combustion-based systems, this cost remains a necessary part of life-cycle planning.

System Efficiency Parameters

To evaluate energy performance, this framework includes several system efficiency indicators. The coefficient of performance (COP) defines the heating efficiency of the GSHP—i.e., how many units of heat are delivered per unit of electricity consumed. A higher COP reflects better performance and lower operating costs (Barotto 2022).

The energy efficiency ratio (EER) is used to assess cooling efficiency in the same way. Together, COP and EER provide a realistic picture of seasonal energy performance. For conventional systems, boiler thermal efficiency is used to estimate how effectively combustion-based equipment can convert energy into usable heat.

The thermal distribution efficiency, measured before and after GSHP installation, represents how effectively heat or cooling is transferred throughout the building. Efficiency gains in this area can significantly affect total system energy use.

Energy Source Costs and Environmental Impact

A key dimension of our screening tool is the inclusion of energy source pricing and CO_2 emission data. The cost per unit of energy is required for electricity, natural gas, and solid energy carriers such as coal. These costs are determined based on local utility rates or market prices and form the basis of annual operational cost (OPEX) calculations.

The platform also requires the energy content per unit for each source type, defined as the amount of thermal energy that can be extracted from a given quantity—such as one cubic meter or one kilowatt-hour.

These values are used to translate energy demand into quantity consumed, enabling direct comparisons across systems and energy sources.

Environmental impacts are quantified using CO_2 emission factors, which specify how much carbon dioxide is released per unit of energy used. These factors are source-specific and allow the tool to estimate the annual greenhouse gas emissions associated with each heating or cooling option. This output is particularly relevant when evaluating alignment with climate goals or regulations.

Financial Metrics: Payback and LCOE

It includes two key financial indicators: payback period and Levelized Cost of Energy (LCOE).

The payback period measures how long it takes for the cumulative savings in operational costs to match the initial investment. A shorter payback period generally indicates a more attractive investment opportunity and faster recovery of capital. It is particularly helpful in contexts where quick returns or short-term budget constraints influence project decisions.

The LCOE provides a more comprehensive economic assessment. It calculates the average cost per kilowatt-hour of thermal energy produced over the entire lifespan of the system, incorporating all capital and operating costs (Manzella et al., 2016). A low LCOE indicates that the system produces energy cost-effectively over time and is generally a sign of strong financial viability. In contrast, a high LCOE suggests that the system may have high installation or operating costs relative to its energy output, potentially making it less competitive without financial incentives or favorable energy pricing. LCOE is particularly valuable for comparing technologies or projects of different scales on a consistent economic basis.

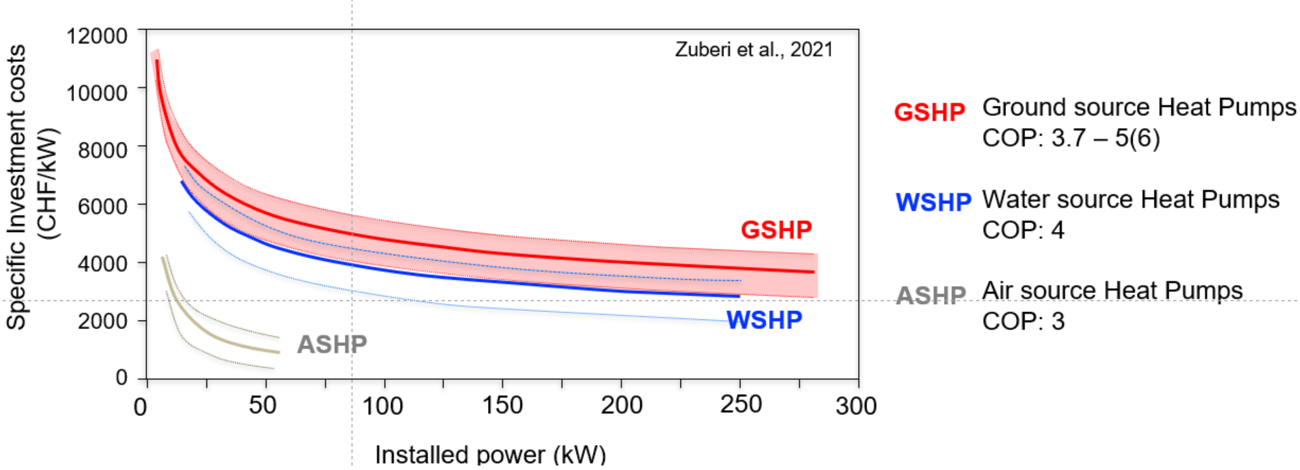

Figure 2: Investment costs as a function of installed power for Switzeland (modified from Zuberi et al.,2021). A similar graph can be generated for different countries and market areas where access to and costs of materials, technology (i.w. drilling machines etc), expertise and labour can vary greately.

Table 1: Parameters used in the for GSHP screening tool

Category	Parameter	Description
Climate & Demand	Monthly mean temperatures	Average outdoor temperature per month, used to compute seasonal loads.
	Winter extreme temperature	Coldest expected outdoor temperature for system sizing.
	Summer extreme temperature	Hottest expected outdoor temperature for cooling load sizing.
	Indoor set temperature (heating)	Desired indoor temperature during the heating season.
	Indoor set temperature (cooling)	Desired indoor temperature during the cooling season.
	Heating and cooling hours per year	Total annual hours of HVAC operation.
Building Parameters	Building surface area	Total floor area of the building in square meters.
	Specific peak load (W/m²)	Power required per square meter to meet thermal demand. Highly dependent on insulation quality.
System Design & Cost	Installed capacity	Total heating/cooling power based on building area and specific load.
	Investment cost per kW	Cost of GSHP installation per unit of installed capacity. (See **Figure 2** for cost reference).
	Energy output per well	Expected energy yield from each geothermal well.
	Maintenance cost per area	Estimated annual cost of maintenance per square meter.
	Heat pump coefficient of performance (COP)	Efficiency of the GSHP system in heating mode.
	Energy efficiency ratio (EER)	Efficiency of the GSHP system in cooling mode.
	Boiler efficiency	Efficiency of conventional combustion systems.
	Distribution system efficiency (pre & post)	Thermal delivery efficiency before and after GSHP installation.
Energy & Emissions	Electricity price	Local electricity rate used to calculate energy costs.
	Gas price	Unit cost of gas energy.
	Coal price	Unit cost of coal energy.
	Electricity CO_2 emission factor	CO_2 emitted per kWh of electricity consumed.
	Gas CO_2 emission factor	CO_2 emitted per unit of gas energy.
	Coal CO_2 emission factor	CO_2 emitted per unit of coal energy.
	Energy content per unit (gas/coal)	Heating value (kWh) of each energy source per volume or weight unit.
Financial Indicators	Payback period	Time needed for savings to offset investment.
	Levelized Cost of Energy (LCOE)	Average lifetime cost per kWh produced.

3. CASE STUDY EXAMPLE

This section applies the rapid screening method detailed earlier in this study to evaluate the feasibility of installing a GSHP system for a 3333 m² building characterized by poor insulation. The analysis systematically investigates the seasonal energy distribution, economic viability, and environmental impacts of transitioning from conventional heating and cooling methods to a GSHP-based solution. The project period spans over 30 years.

Climatic Conditions and Building Energy Profile

Figure 3 illustrates the building's local climatic conditions by displaying the mean monthly outdoor air temperatures. The temperature distribution clearly depicts significant seasonal variations, with winter months marked by colder temperatures, reaching a minimum monthly mean of approximately 3.8°C in January, and summer months peaking around 22.6°C in July. The pronounced seasonal temperature swings highlight the necessity for effective heating during winter and significant cooling requirements during summer months. Given the poor insulation of the building, these seasonal extremes notably amplify energy consumption, thus posing substantial energy management challenges and indicating strong potential benefits from installing a GSHP system capable of efficiently managing these varying energy demands.

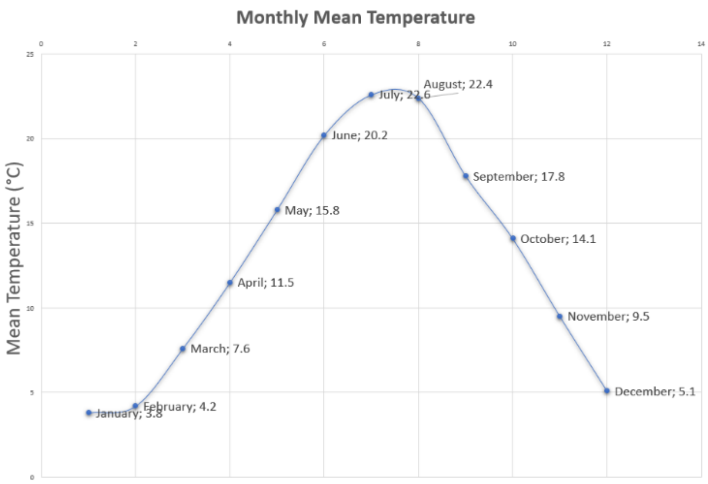

Figure 3: Example of mean temperature distribution over a year

Energy Distribution and System Performance Analysis

The seasonal distribution of energy sources used by the GSHP system throughout the year is presented in Figure 4. During the winter months (November through March), the building's heating demand is primarily met through energy extracted via geothermal boreholes, effectively utilizing the earth's stable subsurface temperatures to provide sustainable heating. The peak geothermal heat extraction notably occurs in January and December, coinciding with the periods of highest heating demand.

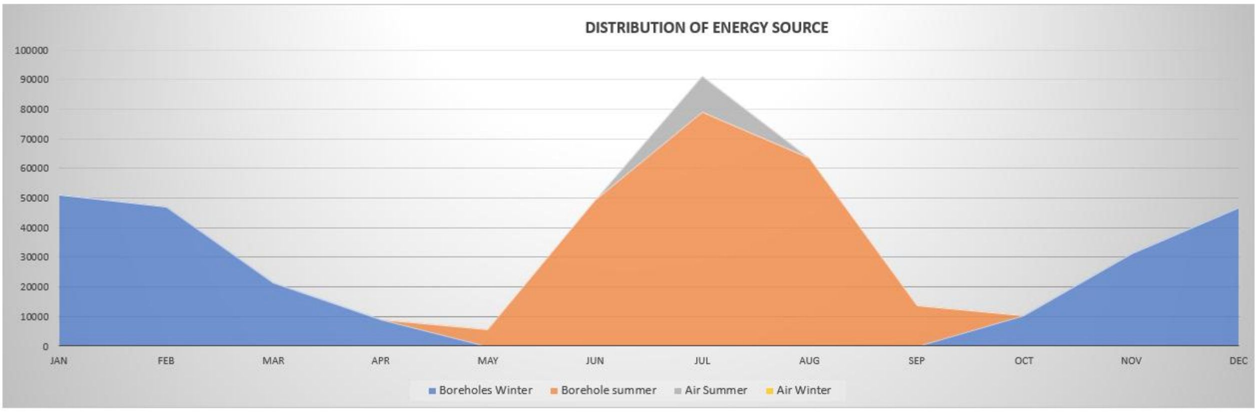

Figure 4: Seasonal distribution of energy resources

Conversely, during the summer months (June through August), geothermal cooling is employed, leveraging the same geothermal infrastructure. However, the geothermal source alone does not fully meet the building's cooling requirements due to the combination of poor insulation and high external temperatures. Consequently, additional air heat exchangers are utilized as supplemental cooling measures to cover this shortfall. This integrated system approach, using geothermal cooling supported by air-based heat exchange, effectively addresses peak cooling demands, particularly evident in July when external temperatures are highest. This hybrid approach ensures the GSHP system remains highly effective year-round, maintaining indoor comfort levels while optimizing energy efficiency.

The integration of air exchangers alongside geothermal probes represents a deliberate design choice, typically made when site constraints limit the space available for boreholes or, more commonly, to reduce capital expenditures (CAPEX). In dual-source systems (geothermal + air), the average efficiency is somewhat lower than in purely geothermal systems. Nevertheless, if well designed, the efficiency loss is minor, resulting in only a slight increase in operating expenses (OPEX), while significantly reducing CAPEX. This trade-off often makes dual-source systems a highly cost-effective and practical solution.

Comprehensive Economic and Environmental Results

The outcomes resulting from the installation of the GSHP system on the economics and impact on CO_2 emissions are shown in Figure 5 . The detailed screening analysis reveals that transitioning from a conventional heating system to GSHP dramatically reduces the building's annual heat demand by approximately 357 kWh/year. This corresponds to an 80% reduction in energy consumption, primarily due to the superior efficiency of the GSHP system compared to traditional fossil-fuel-based heating solutions. Environmentally, the adoption of GSHP technology delivers substantial benefits, notably a marked decrease in annual CO_2 emissions. The calculated reduction amounts to roughly 60 tons of CO_2 annually, representing a substantial environmental improvement of approximately 70% when compared to emissions generated by conventional heating technologies relying on fossil fuels such as natural gas or oil. Economically, despite an initial high capital expenditure (CAPEX) of approximately $500,000 for GSHP installation—including drilling, piping, and heat pump equipment—the system significantly lowers annual operational costs (OPEX). Prior to GSHP implementation, annual operational energy costs amounted to $96,530; post-installation costs reduce substantially to approximately $33,000 per year. This yields annual operational savings of approximately $63,600, corresponding to a 66% reduction compared to the previous conventional heating and cooling systems. In Figure 6 is shown the CAPEX+OPEX comparison between pre and post intervention (i.e pre and post GSHP installation) over the project period (30 years). From a financial perspective, the resulting payback period of the GSHP investment is estimated to be approximately 8 years, indicating that the initial investment can be recuperated within a relatively short timeframe. This is calculated by dividing the initial investment by the annual savings, derived from the difference between the pre- and post-intervention costs. This payback is driven primarily by reduced energy consumption and significantly lower maintenance costs compared to conventional heating systems. Furthermore, the calculated Levelized Cost of Energy (LCOE) for the GSHP system is approximately $0.27/kWh. This competitive LCOE demonstrates strong economic viability over the system's operational lifespan, reinforcing GSHP as a financially attractive long-term energy solution, particularly given its combined economic savings and substantial environmental benefits.

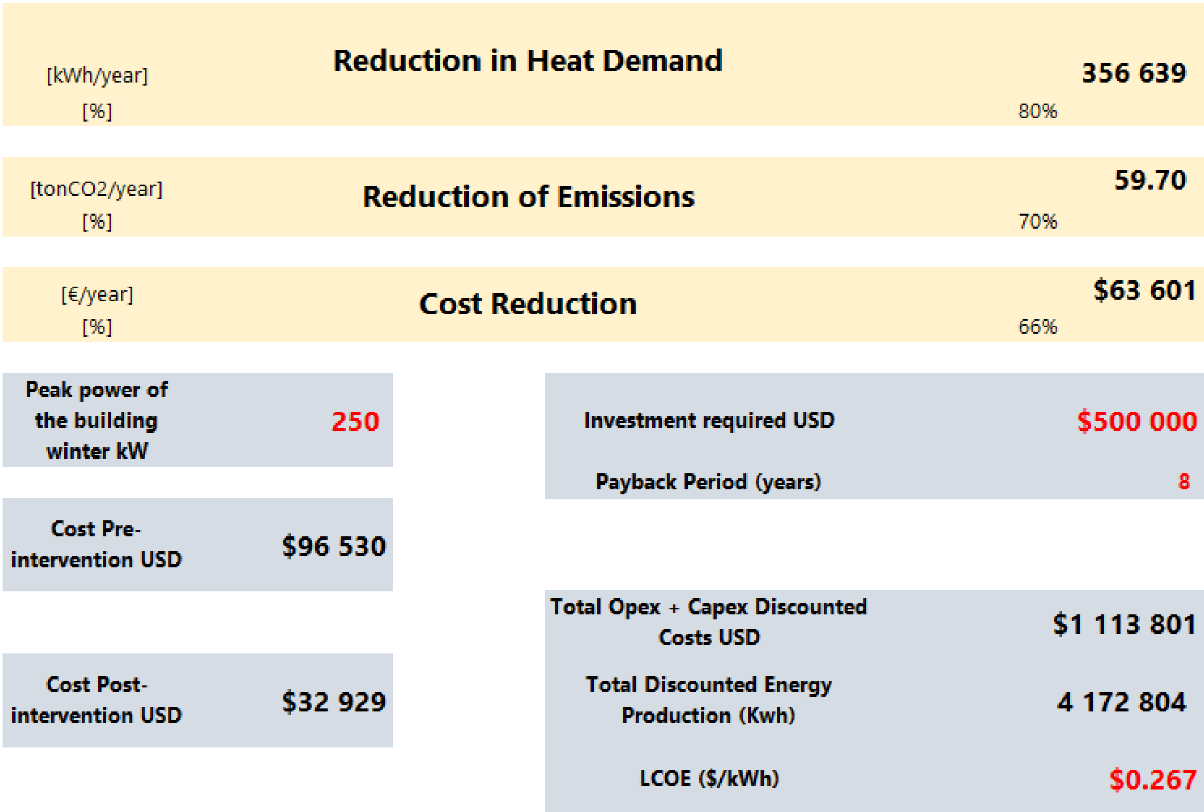

Figure 5: Environmental and economical results from the screening study for GSHP project for a 3333m2 building poorly insulated.

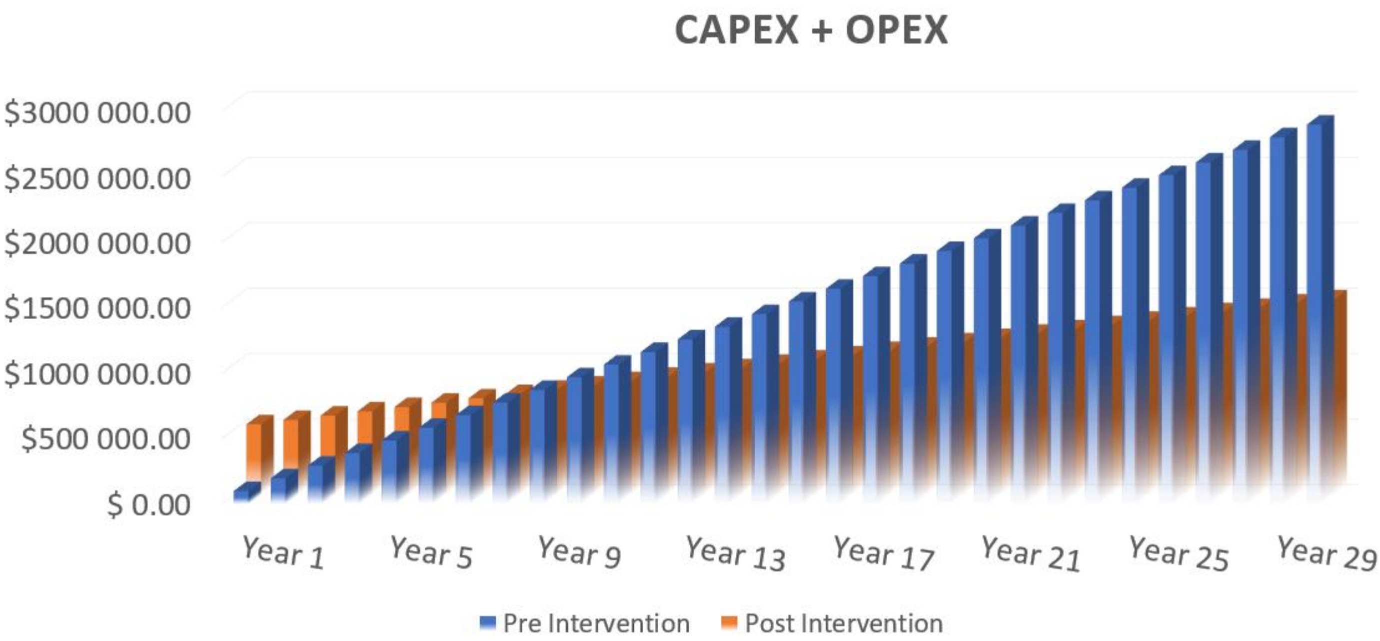

Figure 6: Capex and Opex comparison between pre and post intervention (i.e. pre and post GSHP installation).

4. DISCUSSION AND CONCLUSION

This study presents a quick and easy to use screening methodology specifically designed to facilitate early-stage assessment of Ground Source Heat Pump (GSHP) installation in buildings with poor thermal insulation and high energy demands. Through the application of this approach to a representative building case of 3300 m², significant benefits associated with GSHP systems were identified, particularly regarding energy consumption reductions, operational cost savings, and CO_2 emission mitigation. These results highlighted the substantial environmental and economic potential of transitioning from conventional heating and cooling systems toward geothermal-based solutions.

The screening tool demonstrated its utility by rapidly estimating critical decision-making parameters such as the heat demand reduction (approximately 80%), operational cost savings (66%), CO_2 emission reduction (70%), and financial viability, including an attractive payback period (approximately 8 years) and a competitive Levelized Cost of Energy (LCOE). The flexibility of the GSHP system, supported by supplementary air-based exchangers during peak cooling demands, further illustrated the technical robustness and adaptability of geothermal solutions in effectively handling seasonal variations and the heightened energy demands typical of poorly insulated buildings.

While these initial findings clearly underscore GSHP's advantages, it remains essential to acknowledge the significant uncertainties inherent to such a preliminary screening approach. Firstly, geological uncertainties pose considerable challenges, notably the variability in subsurface conditions—such as thermal conductivity, groundwater flow dynamics, and depth to suitable geological formations—that directly impact borehole sizing, system performance, and installation costs (Manzella et al., 2016). Without detailed geological surveys, these initial assumptions introduce significant variability into the feasibility predictions.

Economic uncertainties also substantially affect the reliability of the preliminary results. The cost estimations incorporated in this tool are based on benchmark data and generalized assumptions, which may differ significantly from local market realities, drilling conditions, or site-specific factors. Variability in equipment costs, labor charges, drilling complexities, and fluctuations in the energy market significantly influence the accuracy of capital and operational expense predictions. Similarly, assumptions regarding maintenance costs based on average industry standards might not accurately reflect the long-term realities encountered during the operational phase of a GSHP installation.

Additionally, uncertainties regarding future energy prices and regulatory frameworks further complicate long-term financial forecasting. Energy markets are volatile, and future fluctuations in the cost of electricity, gas, or other fossil fuels can notably alter projected operational savings, payback periods, and LCOE values. Thus, such economic and operational uncertainties require that results from the rapid screening approach be interpreted cautiously and validated by using the correct assumptions and through comprehensive follow-up analyses.

Despite these limitations, the screening methodology's strength lies precisely in its preliminary nature. It provides stakeholders with an essential early-stage decision-making tool that balances the need for rapid, accessible evaluations against acceptable reliability and detail. By clearly highlighting areas of significant savings and environmental benefit, this preliminary screening effectively guides stakeholders towards potentially favorable geothermal solutions, identifying the most promising opportunities for further detailed investigation.

In conclusion, the rapid screening tool developed and applied in this study provides a valuable, initial-level evaluation method for GSHP installations, enabling quick yet informed early-stage decision-making. While clearly highlighting significant economic and environmental benefits, it transparently acknowledges the inherent uncertainties—geological, economic, and operational—that must be addressed in subsequent comprehensive studies. Future improvements to this screening methodology could include integrating more precise geological input data, enhanced economic modeling incorporating dynamic market trends, and refined engineering assessments to further strengthen its accuracy and practical value for advancing the adoption of geothermal energy solutions.

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