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Review

A Critical Review on the Use of Shallow Geothermal Energy Systems for Heating and Cooling Purposes

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Abstract: The reduction of CO_2 emissions has become a global concern. In this regard, the EU intends to cut CO_2 emissions by 55% by 2030 compared to those of 1990. The utilization of shallow geothermal energy (SGE) in EU countries is considered the most effective measure for decarbonizing heating and cooling. SGE systems utilize heat energy collected from the earth's crust to provide secure, clean, and ubiquitous energy. This paper provides a literature review on the use of SGE for heating and cooling purposes. The latest advances in materials, new innovative structures, and techno-economic optimization approaches have been discussed in detail. Shallow geothermal energy's potential is first introduced, and the innovative borehole structures to improve performance and reduce installation cost is outlined. This is followed by an extensive survey of different types of conventional and thermally enhanced collectors and grouts. Attention is mainly given to the techno-economic analysis and optimization approaches. In published case studies, the least economic break-even point against fossil fuel-based heating systems occurs within 2.5 to 17 years, depending on the local geological conditions, installation efficiency, energy prices, and subsidy. Ground source heat pumps' cost-effectiveness could be improved through market maturity, increased efficiency, cheap electricity, and good subsidy programs.

Keywords: shallow geothermal energy; borehole heat exchanger; collector; grout; geoenergetics; techno-economic analysis; optimization

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1. Introduction

The reduction of greenhouse gas (GHG) emissions has become a global concern, often cited as a necessary step to successfully overcome climate change and the damage it causes. Nearly all countries have joined the Paris Agreement on Climate Change (2015), which calls for keeping the global temperature rise at 1.5 °C above pre-industrial levels [1]. However, increasing energy consumption driven by an increasing population, accelerated industrial growth, and technological development leads to high GHG emissions. An increasing energy demand for heating and cooling in the residential and industrial sectors significantly contributes to carbon dioxide emissions. International Energy Agency (IEA) data (2019) indicated that heating accounts for 40% of the global CO_2 emissions [2]. In Europe, 50% of final energy consumption is directly related to heating and cooling [3]. According to Eurostat data, in 2019, 63% of Europe's heating and cooling was powered by fossil fuels, mostly gas (38%), coal (22%), and oil (3%) as shown in Figure 1a, whereas renewable's share was only 30% of heating and cooling. It is essential that the EU substitutes high GHG emission fossil fuels, that are used for heating and cooling, with lower carbon sources to meet the energy transition target. In this direction, the European Commission has set targets of 55% reduction in GHGs by 2030, at least a 32% increase in renewable energy consumption, and 32.5% improvement in energy efficiency across the EU. On the other hand, biomass represents the main renewable energy used for heating and cooling in the EU with a 70.9% share (Figure 1b), while only 1.9% weas generated from geothermal energy. Despite the continuous attention towards phasing out the use of coal and replacing it with renewables, coal still represents 22% of gross derived heat production (Figure 1a). The use of coal is mostly concentrated in Germany, Poland, and the Czech Republic, which together account for nearly 57% of coal consumption and 87% of coal-mining jobs in the EU [4].

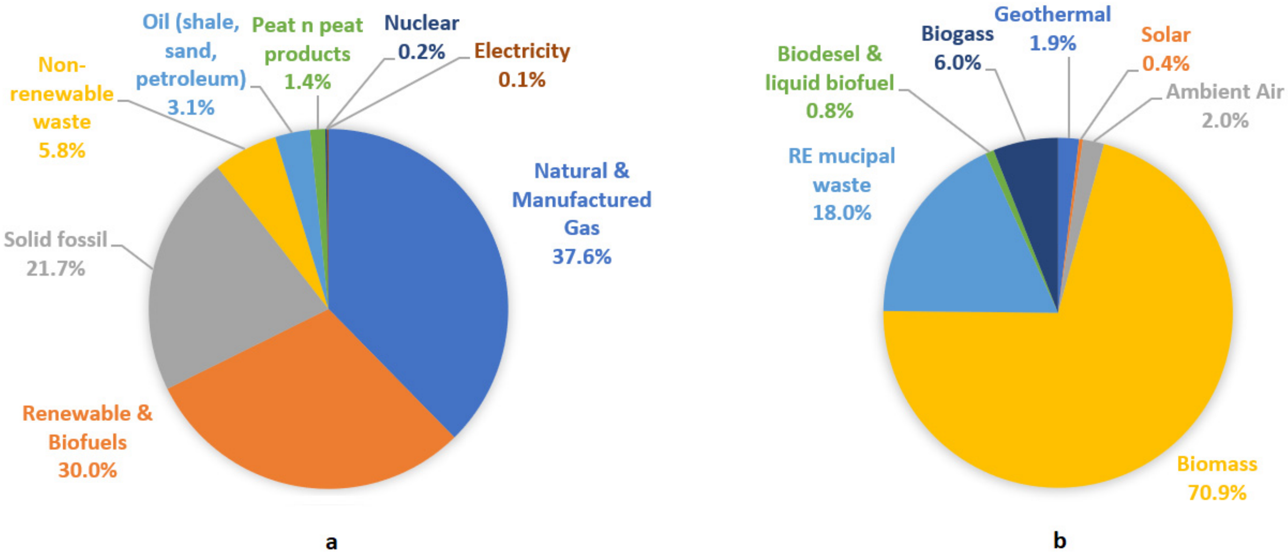

Figure 1. (**a**) Heating and cooling fuels, breakdown in EU@ Eurostat, 2019. (**b**) Renewable Heating and cooling, fuels breakdown in EU@ Eurostat, 2019.

In 2018, Poland's final energy consumption (FEC) for heating and cooling amounted to 37.7 Mtoe (50.3% of total FEC) which was predominantly generated by hard coal [5]. Although district heating plants are covering most of the heating demand for Poland's residential blocks, 74% of that demand is met by CO_2-intensive coal-fired cogeneration [6]. Hence, the heating and cooling sector plays an important role in achieving Poland's climate and energy goals. Poland's policy objectives suggest that the use of natural gas is an important alternative to coal. Changing from coal to gas has provided some climate benefits towards lowering CO_2 emissions and air pollutants [2]. However, net-zero targets require the phasing-out of gas heat systems within a couple of decades. In addition, the volatility of natural gas market prices and the risks of methane leakage need to be well considered. Supporting and incentivizing the usage of zero-compatible technologies will prove to be beneficial. A broad adaptation of renewables such as geothermal heat pumps, solar thermal energy, and ambient heat for the heating and cooling sector would reduce dependency on fossil fuels and benefit from saving on carbon prices in the future.

Geothermal energy, energy derived from the Earth's interior, offers incredible potential for heating and cooling production almost everywhere. It has been recognized as one of the major clean and reliable energies. Combining geothermal energy with heat pumps can significantly contribute to decarbonizing the heating and cooling sectors. The GSHP is an efficient heating/cooling system with a coefficient of performance (COP) higher than one, specifically, between three to five [7]. This means an efficiency of 300–500% in terms of the heat provided for the electricity used compared to traditional combustion-based heaters or electric heaters, where efficiency never exceeds 100%. However, GSHPs suffer from higher upfront drilling and installation costs than other competing heating technologies. Therefore, the optimization of expenditures is essential for owning and operating these systems [8]. There is another heat pump setup that uses ambient air (as well as waste heat, etc.) and achieves higher efficiencies than 100%. However, they are noisy, and their efficiency drops as the outdoor temperature drops. GSHP produces more heat for less electricity in cold climates compared to air source heat pumps. In addition, GSHP has the advantage of being able to be used as a heating or cooling system depending on the weather [9]. During the winter, GSHP systems transfer heat stored in the ground to buildings (heating systems). As the weather warms in the summer, GSHPs remove heat from buildings and send it to the earth (cooling systems). A GSHP system consists of three main components, namely, ground loops or a borehole heat exchanger (BHE), a heat pump system, and a heat distribution system in the conditioned space [10]. Extracting the geothermal heat with the BHEs has various advantages, including no high risks associated with exploration drilling, high durability, and a lesser environmental impact [11]. The BHE consists of a borehole and tubing where heat-carrying fluid flows through. The geothermal borehole is filled with water (the Scandinavian practice) or backfilled with grout (the mainland Europe, Canada, US, and Japan practices). Figure 2 illustrates a schematic flow diagram of GSHP systems. Ground heat is transferred first from the rock body to the borehole wall and then to a circulating thermal fluid. Secondly, the circulating thermal fluid, in turn, transfers the extracted ground energy to the heat pump at the surface. Finally, the heat pump uses electricity to upgrade and move thermal energy from the ground loop to the water-based recirculating heating system that conditions spaces.

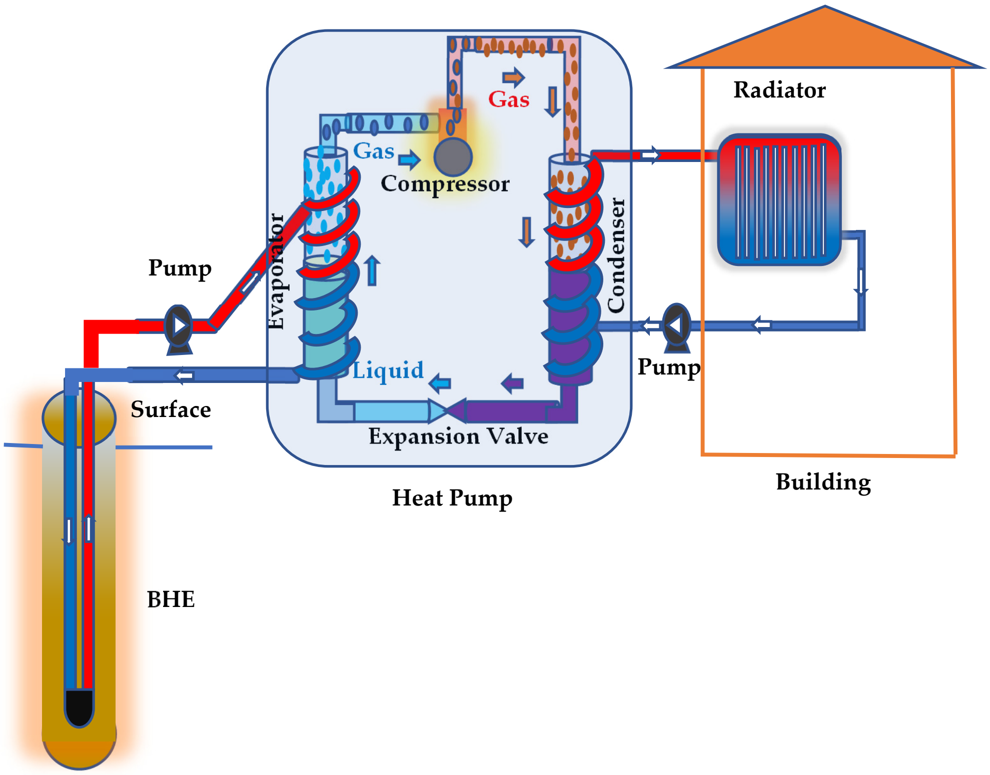

Figure 2. Schematic flow diagram of GSHP systems for heating model (cooling mode with reversed flow).

The thermal efficiency of BHE is characterized by the thermal resistance between the circulating fluid and the borehole wall [12]. Two methods can be used to estimate the BHE's thermal resistance: either thermal response tests (TRT) [13,14] or numerical calculations [15]. The thermal resistance of BHE depends on the properties of the circulating thermal fluid, flow rates, borehole diameters, collector-pipe geometry, collector-pipe material, and grout [12]. The lower the BHE thermal resistance is, the better the thermal performance behavior. The lower BHE thermal resistance can be achieved by using thermally enhanced pipes and grout, increasing the surface area of the loop, and locating the legs proximal to the borehole [16].

Globally, GSHPs represent 71.6% of all direct-use geothermal installations and 59.2% of direct-use geothermal energy consumption per year [17]. For the heating mode alone, the total installed capacity and energy produced by GSHPs worldwide are 77,547 MWt, 599,981 TJ/yr, respectively. The intermediate target for district heating and cooling (DHC) is to reach 30% of Europe's heating and cooling demand by 2030, where more than 10% (of the 30%) should come from geothermal energy [18]. Currently, DHC's share is only 12% and the contribution of geothermal energy is less than 1% [19]. This indicates that greater efforts and swifter actions are needed in geothermal development to achieve the aforementioned goal. The efforts can be seen in the rapid yearly growth rate of the geothermal heat pump market. A report by the IEA (2021) shows that the global stock of heat pumps has grown approximately 10% per year for the last five years. That growth resulted in over 2.1 million geothermal heat pumps being installed in Europe as of June 2020 [20]. The new promoted heat pump incentive and target of installing 600,000 heat pumps each year in the UK will contribute to the rapid growth of this number in the coming years [21]. Dalla Longa et al. project that the geothermal energy heat production would reach around 100–210 TWh/y by 2050 [22].

2. State of the Art and Technological Advancements

2.1. Rock Thermal Conductivity

The thermal conductivity of the rock surrounding the BHE is one of the most significant influencing factors that affects heat the extraction rate and performance of GSHP [23,24]. The thermal conductivity of rocks is a measure of their ability to transfer heat. The heat exchangeability of the surrounding rocks is determined by specific heat extraction (W/m), which is the product of the temperature gradient and the rock's thermal conductivity divided by the BHE's length. Therefore, thermal conductivity is essential for the optimal design of the BHE since it determines the specific heat extraction of the borehole, which is directly related to the length of the buried pipe and the cost of installation [25]. This means that the ground thermal parameters should be determined accurately to optimize the total length, the spacing, and the layout of BHEs [24]. A traditional thermal response test (TRT) and a distributed thermal response test (DTRT) can be used to determine the in situ effective thermal conductivity and other thermal properties of a BHE. The rock's thermal conductivity depends strongly on the rock type, stratigraphy, and hydrogeology [24]. Dry rock and saturated rock can affect the value of thermal conductivity. The dry rock will have a lower thermal conductivity than the saturated one [26]. Typical values for the rock's thermal conductivity values for sandstone are in the range of 2.50 to 4.20 $Wm^{-1}K^{-1}$, for Sand 0.3 to 2.95 $Wm^{-1}K^{-1}$, for gravel 0.3 to 0.5 $Wm^{-1}K^{-1}$, for shale 1.05 to 1.45 $Wm^{-1}K^{-1}$, for claystone and siltstone from 0.80 to1.25 $Wm^{-1}K^{-1}$, and for granite from 1.9 to 3.35 $Wm^{-1}K^{-1}$ [22,27].

2.2. Innovative Borehole Heat Exchanger Structures

There are two primary techniques used for shallow geothermal systems to heat buildings, namely, the closed-loop and open-loop systems. In the first type, the heat carrier fluid is forcefully circulated through a buried or submerged ground heat exchanger. This type is the most prevalent shallow geothermal system in Europe. Some practical examples of closed-loop systems are vertical loops, horizontal loops, energy piles, and groundwater coil. For a large available space, the horizontal loop (0.2 to 2 m depth) is a more cost-effective option, while vertical loops (<300–500 m) are mostly used in urban areas with smaller land occupancy to reach a higher thermal gradient. The vertical BHE consists of a hole drilled in the ground and completed with different pipe geometries such as single/double or triple U-shaped tubes, co-axial, and multi-pipe configurations. Recent developments in ground BHEs have focused on the design of new innovative structures [28–32] and the use of thermally enhanced materials [33–41]. Figure 3 illustrates a variety of common and innovative BHE configurations.

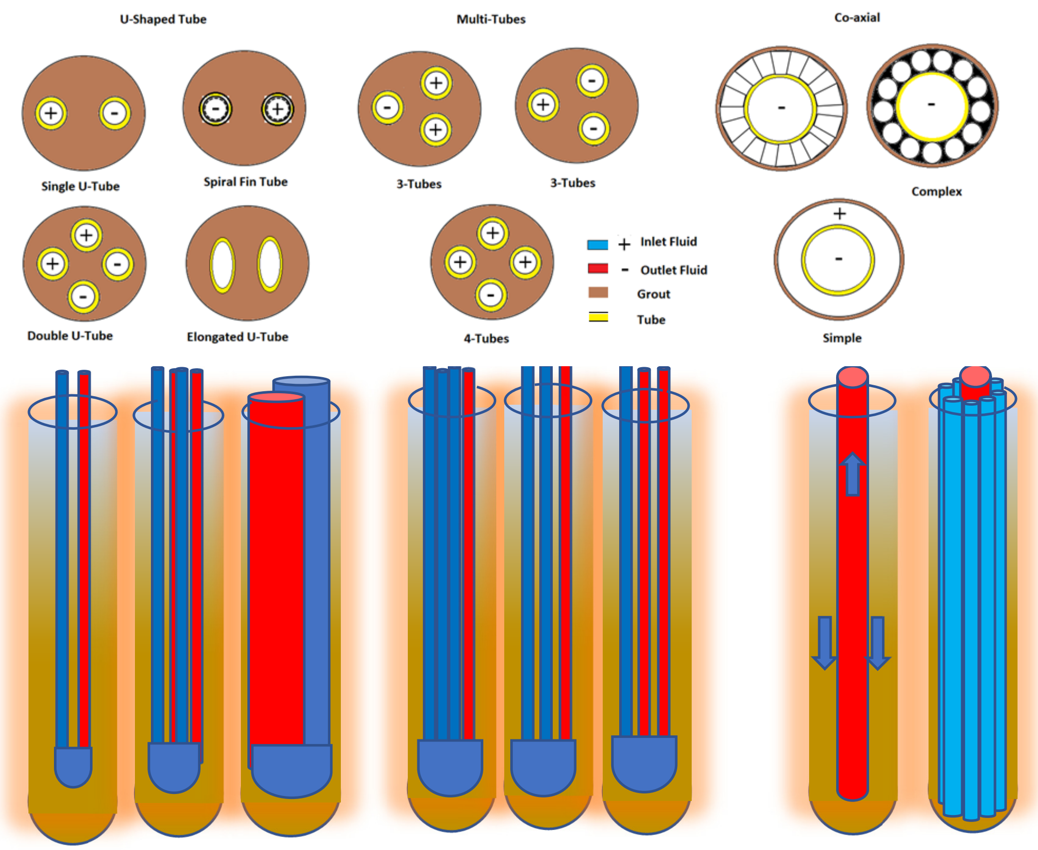

Figure 3. The cross-sections of various configurations of BHE.

Jalaluddin and Miyara (2014) have compared the performances of BHEs installed with a U-shaped tube, 3-tubes, and 4-tubes in a steel pile [28]. The results showed that multi-inlet tubes increased the contact surface area and then increased the BHE performance compared to a single U-shaped tube, by 9.1% and 13.6–20.1% for the 3-tube and 4-tube, respectively. Experimental measurements and modeling have been carried out to investigate the performance of a single U-shaped tube, double U-shaped tubes, and the new 4-tube structure (3 inlet tubes and 1 outlet tube). The thermal resistance of the 4-tube structure was 15.8 and 31.1% lower than that of the single U-shaped tube and double U-shaped tubes, respectively [29]. Chang and Kim (2016) reported that the thermal resistance of BHEs reduced with an increasing heat transfer area either by using a larger diameter of tube or the insertion of more tubes [31]. Raymond et al. (2015) have performed analytical design calculations for single and double U-shaped tubes as well as coaxial pipe structures [30]. To maintain low pumping power at the higher flow rate needed to generate turbulence, only pure water was used as the heat transport fluid by the author. The results indicated that the thermal resistance of the coaxial BHE was reduced by up to 55% compared to that of single U-pipe BHEs when the outer pipe thermal conductivity and standard dimensional ratio (SDR) were raised. That led to a 23% shorter borehole length than the single U-shaped tube for a synthetic building load profile dominated by cooling. Using co-axial BHEs enables deeper drilling and access to higher geothermal gradients than conventional U-shaped pipe BHEs. However, it is important to have sufficiently thick outer pipes (low SDR) to withstand the high external load caused by grout and formation water as the borehole is drilled deeper. For deeper depths, it is also necessary to use insulated inner tubing in the co-axial configuration to create an efficient BHE. Three high-thickness pipes are expensive and have an adverse effect on BHE thermal resistance. The coaxial BHE's thermal efficiency can be improved by developing a new composite coaxial pipe system with thin walls, high strength, and a high conductivity outer pipe [30].

2.3. Grouting Materials

Grouts, also known as backfill materials, are used as a sealant agent to block fluid flow from the formation or surface into the borehole or vice versa. In addition, it holds heat carrier pipes in place and creates a heat transfer link between the pipe and the earth. Figure 4 shows a schematic diagram of a borehole annulus filled with water and grout.

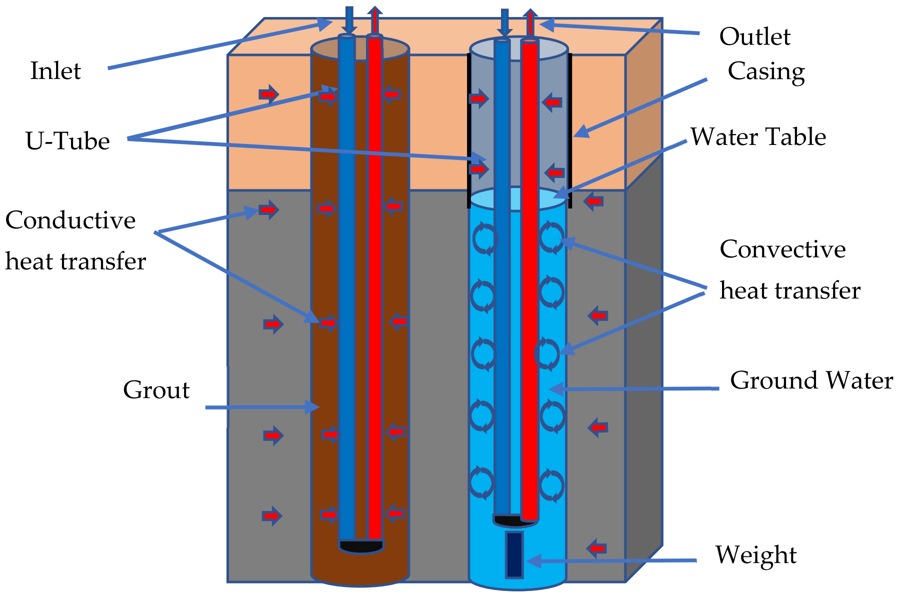

Figure 4. A water-filled borehole exchanger—Sweden practice (**right**), a BHE backfilled with grout—western practice (**left**).

The thermal conductivity of grout has a significant impact on the borehole's thermal resistance [31,42]. Dehkordi and Schincariol indicated a more than 10% increase in heat extraction when grout conductivity was enhanced from 1 $Wm^{-1}K^{-1}$ to 3 $Wm^{-1}K^{-1}$ [34]. Lee et al. clearly detailed that an increase in the thermal conductivity of grouts has a substantial impact on the reduction in the total required borehole depth [35]. Badenes, B. et al. (2020) have carried out a parameter sensitivity analysis on the effect of theoretical grout thermal conductivity from 0.5 to 8.0 $Wm^{-1}K^{-1}$ on borehole thermal resistance using HDPE (0.42 $Wm^{-1}K^{-1}$) [33]. The results show that a significant enhancement in thermal resistance can be seen until a grout conductivity of 4.0 $Wm^{-1}K^{-1}$; further increase of the conductivity has little effect on the thermal resistance. Sliwa and Rosen (2017) investigated the effect of varying grout thermal conductivity on the performance of coaxial, single, and double U-shaped BHEs [43]. According to the authors, increasing the thermal conductivity of grout from 1 to 2.5 $Wm^{-1}K^{-1}$ reduces BHE's resistance by 13.7%, 8.3%, and 7.6% for coaxial, single, and double U-shaped BHEs, respectively. Traditionally, bentonite and cement materials have been used for borehole grouting. Both materials have the disadvantage of low thermal conductivity: 0.7 $Wm^{-1}K^{-1}$ and 0.8–1.0 $Wm^{-1}K^{-1}$ for bentonite and cement, respectively. Recently, more attention has been paid to enhancing the thermal conductivity of conventional grouts. The results from various works have shown a remarkable increase in conventional grout's thermal conductivity when mixed with thermal enhancement additives. A few additives, such as silica, graphite, and dolomite, have been investigated to increase grout's thermal conductivity [36]. At a sand content of 50%, cement's thermal conductivity increased to 1.5 $Wm^{-1}K^{-1}$ [37]. The study of Jobmann and Buntebar (2009), showed that, when using a grout composed of bentonite and 50% quartz, the thermal conductivity is increased by a factor of 1.5 [38]. Graphite has a significant impact on the thermal conductivity of grouts. Berktas, et al. (2020) indicated that a mixture of cement and 5% hybrid additive (silica and graphite) increased the thermal conductivity to a value of 2.656 $Wm^{-1}K^{-1}$ [39]. A grout conductivity of 5 $Wm^{-1}K^{-1}$ was achieved when 5% graphite was added to bentonite [40]. In addition, an enhanced conductivity of 3 $Wm^{-1}K^{-1}$ for a mixture of bentonite with graphite (percentage not mentioned) was reported by Hellström et.al, 1998 [44]. Graphite and graphene have also been found to increase cement's thermal conductivity by more than 11% when added to cement slurry in an energy pile construction [45]. A 68% increase in cement slurry's thermal conductivity (from 0.69 to 1.17 $Wm^{-1}K^{-1}$) was achieved by adding 45% magnesium powder [46]. Thermally enhanced grouts are commercially available with thermal conductivities up to 2.8 $Wm^{-1}K^{-1}$ [47].

2.4. Bore Heat Exchanger Collector

The most common types of carrier fluid pipe used to complete a geothermal well are plastic-based materials. Although metallic-based pipes have been used for a very long time, corrosion issues and a high associated cost have limited their applications. In contrast, plastic-based pipes have become a better choice in Europe due to their lower cost, corrosion resistance, easy handling, welding, and longevity. Similar to the grout effect, pipe thermal conductivity has a great influence on borehole thermal resistance. Various plastic-based pipes are used in BHEs such as polyethylene (PE), polyvinyl chloride (PVC), Polypropylene (PP), polyurethane (PU), and polybutylene (PB). However, polyethylene (PE) is the most commonly used pipe material for BHE's installations. Historically, PE pipes were classified based on their density, i.e., high-density polyethylene (HDPE) or low-density polyethylene (LDPE). The ISO 9080 standard reclassifies polyethylene pipes for pressure applications according to their minimum required strength (MRS) [48]. The MRS used most commonly for BHE is PE pipe's grade of 8 MPa (PE-80) and 10 MPa (PE-100). Table 1 presents typical pipe materials and the thermal conductivity use with BHE. According to Badenes et al. (2020), increasing pipes' thermal conductivity from 0.2 to 1 $Wm^{-1}K^{-1}$ results in a substantial reduction in borehole resistance. However, with a further increase of the thermal conductivity of the pipe (>1 $Wm^{-1}K^{-1}$), only a minor reduction was observed [33]. Further improvement of pipe materials is needed as the technical optimum pipe thermal conductivity is higher than the commercially available ones (0.7 $Wm^{-1}K^{-1}$). Boreholes completed with HDPE-nano type and the spiral finned type have shown decreased thermal resistance compared to PE-100 by 1.02% and 1.13%, respectively [41]. The configuration with a spiral fin tube or an inner tube with helical ribs provides a better heat transfer coefficient than a smooth tube due to the former's ability to induce turbulence even at low flow rates [49]. In a study by Bassiouny et al. (2016), it was suggested that the thermal conductivity of PE pipe could be improved by fabricating a composite material of HDPE reinforced with aluminum wires [48]. The aluminum wires were evenly distributed circumferentially throughout the pipe's thickness. The thermal conductivity of the composite was increased by 150% by using computational analysis, as determined by the authors. Kalantar et al. (2019) studied the influence of talc on thermal oxidation, morphology, dynamic mechanical behavior, and strain hardening by using them as fillers in high-density polyethylene (PE-100). The authors observed an increase in thermal stability of PE100 and in the stiffness with the addition of talc nanoparticles [50,51]. The thermal conductivity of PE-100 was significantly increased by 70% when a 35% talc filler was used [52]. Compared to pure HDPE, the talc filler had no effect on melt viscosity, but it reduced the flexibility of the polymer system [53].

2.5. Heat Carrier Fluids

Heat carrier fluid, also referred to as heat transfer fluid or secondary fluid in the literature, is circulated in BHE pipes between the ground and the heat pump to extract or reject heat energy. A variety of heat carrier fluids have been used in BHEs, including pure water, water mixed with antifreeze, and nanofluids. Since water has a relatively high thermal conductivity and a low viscosity, it is an ideal fluid for BHE systems. Pure water, however, is impossible to use in some countries where temperatures fall below 0 °C in winter, such as in Central and Northern Europe [54]. For this reason, anti-freeze additives such as ethyl alcohol, ethylene glycol, propylene glycol, and calcium chloride are used [55]. The thermophysical properties of the commonly used heat-carriers are shown in Table 2. Mixing the water medium with anti-freezing additives not only prevents freezing but it can allow for a large temperature difference between the heat-carrier fluid and the undisturbed ground temperature [56]. By increasing the ratio of the antifreeze agent to water, the freezing point can be dropped further below 0 °C (see Table 2), thereby driving a greater heat transfer between the BHE and the ground and reducing the depth of the BHE [54]. However, the high viscosity of water mixed with anti-freeze leads to a high pressure drop and thus increases the circulating pump cost [57]. Toxicity is another issue to be considered when selecting the anti- freeze agent. Propylene glycol solution is preferred over ethylene glycol and ethyl alcohol solutions since it is less toxic (20 g/kg) compared to ethylene glycol (only 4.7 g/kg) and ethyl alcohol (only 7.06 g/kg), as can be seen in Table 2. However, the high viscosity of propylene glycol solution is an unpreferable property. In some cases, ethylene glycol and ethyl alcohol solutions are preferable due to their more desirable physical properties, especially at lower temperatures and with fewer environmental considerations. In addition, both water and water mixed with anti-freeze have limitation of relatively low thermal conductivity when compared to thermal conductivity of the grout and the ground. Calcium chloride or brine has a better heat transfer coefficient, but it is highly corrosive if it is not maintained properly [58].

Table 1. Pipe Material Properties [33,47].

Pipe Materials	Thermal Conductivity, $Wm^{-1}K^{-1}$	Temperature for Continued Operation, °C
HDPE-Nano	0.55	NA
HDPE-Talc	0.72	
PE100/ PE100-RC	0.42	40
PE-RT	0.42	70
PE-X	0.41	70
PA	0.24	40
PB	0.22	70
PU	0.29	40
PVC	0.12–0.25	27
PP	0.1–0.22	63
Steel	45	399
Copper	395	205

Table 2. Heat-carrier fluid Properties [55,59–66].

Heat-Carrier Fluids	Thermal Conductivity, $Wm^{-1}K^{-1}$	Freezing Point, C	Viscosity, cP	Toxicity, LD50 g/kg
Water	0.598	0	1	
$CaCl_2$ 20%	0.572	−17.2	4.8	1.94
$CaCl_2$ 12%	0.588	−7.2	2.4	
Ethyl alcohol 20 wt.%	0.46	−11	1.4	7.06
Ethyl alcohol 30 wt.%	0.41	−20	1.6	
Propylene glycol 25 wt.%	0.48	−10	3.7	20
Propylene glycol 33 wt.%	0.44	−17	6.8	
Ethylene glycol 25 wt.%	0.49	−12.2	1.4	4.7
Ethylene glycol 33 wt.%	0.4	−18	2.84	

The recent development of heat-carriers focuses on improving their heat transfer efficiency and ecology [67–71]. Nanoparticles have been proved to improve heat transfer efficiency by increasing the thermal conductivity of the working fluid. The thermal conductivity of carrier fluid was apparently improved by using metal or metal oxides such as CuO, SiO_2, Al_2O_3, and graphite nanoparticles. CuO/water nanofluid as a working fluid has an enhanced heat exchange rate by up to 39.84% compared with pure water in a double U-tube horizontal ground heat exchanger [72]. However, pumping power consumption increased by 16.75% due to a higher pressure drop. In another study conducted on a coaxial BHE, nanofluid was used as heat carrier fluid instead of pure water [69]. The results showed an increase of 11.24% in heat extraction compared to pure water. Despite the potential benefits of nanofluids for increasing heat extraction, particle dispersion stability, increased pressure drop, and the possibility for erosion are still the main challenges.

2.6. Underground Thermal Energy Storages (UTES)

Thermal energy storage is basically divided into three types, sensible, latent heat, and thermochemical storage [73]. Underground thermal energy storage (UTES) systems store thermal energy in natural underground formations. Generally, a UTES uses aquifers (ATES) or boreholes (BTES) to store sensible heat by lowering or raising the temperature of water [74]. Some new UTES systems incorporate latent heat storage, where the phase of the heat storage medium changes from solid to liquid. This has been demonstrated as a viable heating and cooling system for residential, commercial, and institutional buildings throughout Europe and North America [75]. BTESs could make an important contribution in areas where seasonal demands vary substantially [76]. In addition, renewable energy sources such as solar and wind energy are intermittent sources—that is, the energy produced is fluctuating on a daily, weekly, or seasonal basis [77,78]. This causes an imbalance in energy demand and supply. UTESs can store surplus solar and waste thermal energy collected in the summer which can be used in the winter [79]. Figure 5 illustrates the ATES system, which recycles surplus heat and cooling from buildings. Each well in the ATES system is capable of injecting or producing water, and at the same time the water flow is reversible.

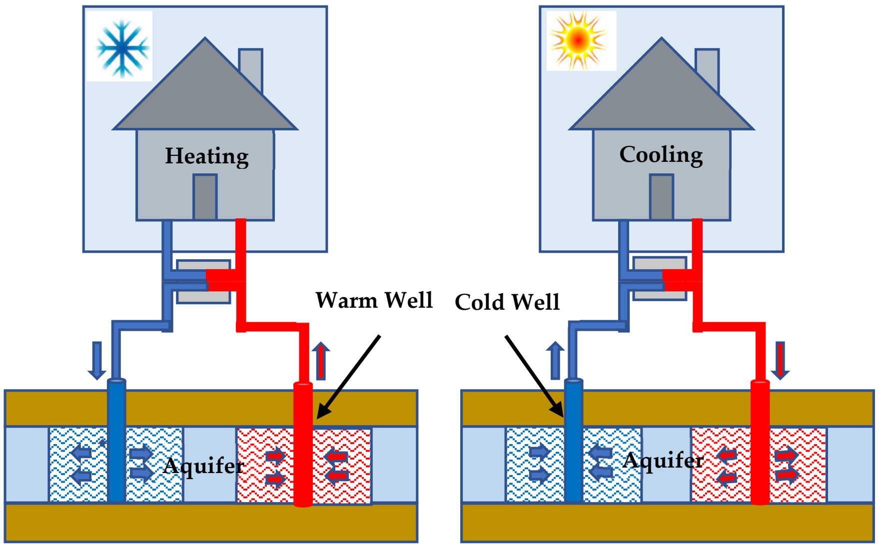

Figure 5. Schematic of an Aquifer Thermal Energy Storage (ATES).

The first BTES system established in the world was in Sweden, in 1983, after the energy shortage crisis [80]. As of today, many BTES projects have been completed globally, mostly for storing solar energy in the summer for usage later in the winter [81–85]. BTESs employ vertical boreholes that are piped in series to create concentric thermal zones (Figure 6) or piped in parallel as a normal closed-loop BHE (Figure 7). The former has the advantages of creating cold and warm zones as well as the possibility to switch to a reverse flow. In the BTES charging process, hot water flows into an inner header of the BTES and then flows into a decreasingly hotter two or up to six parallel thermal zones. The cold water returns to the building from an outer circumferential header around the perimeter of the borehole field. This process could be reversed during the BTES discharging period.

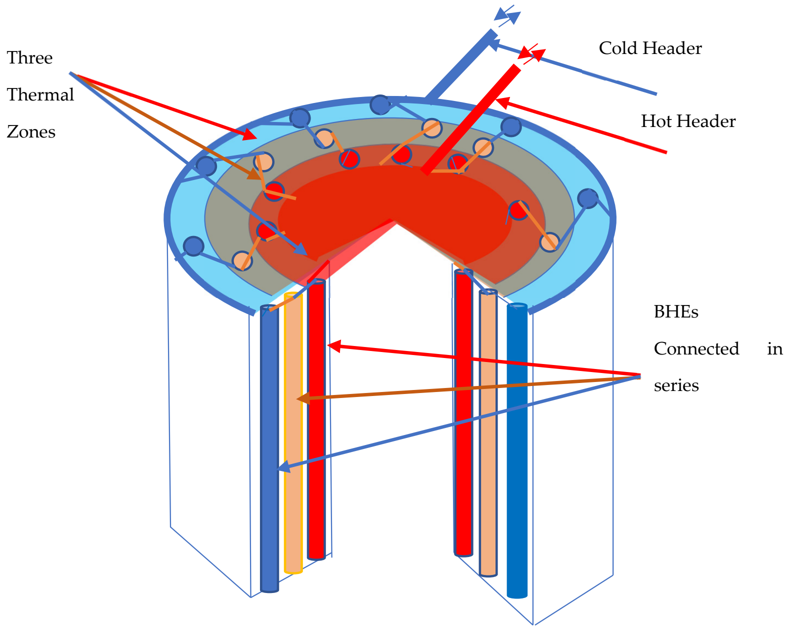

Figure 6. Schematic of Borehole Thermal Energy Storage (BTES and BHEs are connected in series).

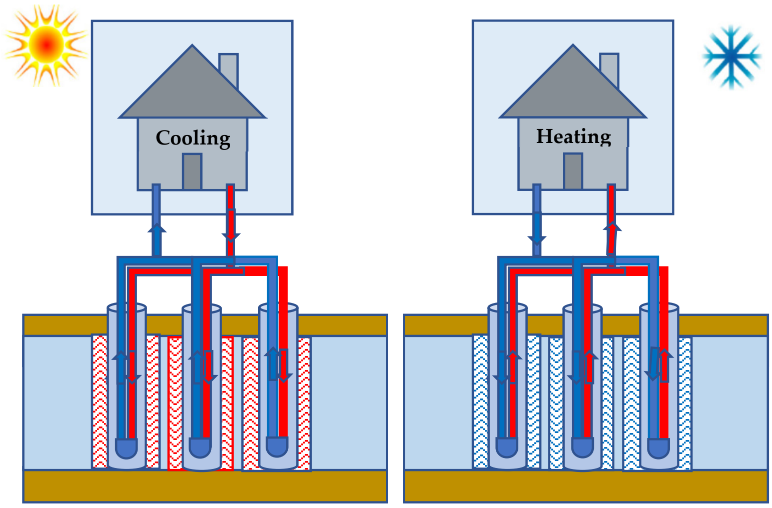

Figure 7. Schematic of Borehole Thermal Energy Storage (BTES), BHEs are connected in parallel.

3. Techno-Economic Analysis

The techno-economic analysis (TEA) method has become popular for evaluating renewable energy by both academic and industrial communities. It enables engineers or researchers to simultaneously analyze the technical and financial feasibility of new technologies [86]. In general, TEA models include the analysis aspects of cost, profitability, and uncertainty [87]. Despite the high efficiency of GSHPs in extracting geothermal energy, high initial costs are arguably the single biggest impediment to their widespread use [88,89]. Thus, TEA modelling of the GSHP system is critical not just for cost reductions but also for guiding decisions on incentive design. Such an evaluation process provides costs and performance boundaries that assist in designing and evaluating the efficiency of GSHPs. For the sustainable design of new technologies, further assessment of the potential environmental impacts is required [90]. However, the literature review reveals a lack of environmental effect assessments and the implementation of a CO_2 emission credit to the TEA model. A standard TEA approach to studying GSHP is to combine building energy, BHE, and heat pump thermodynamic models with economic models. Heat demand and heat transfer calculations are used to simulate the technological potential of GSHPs. The TEA approach and methodology is outlined in Figure 8.

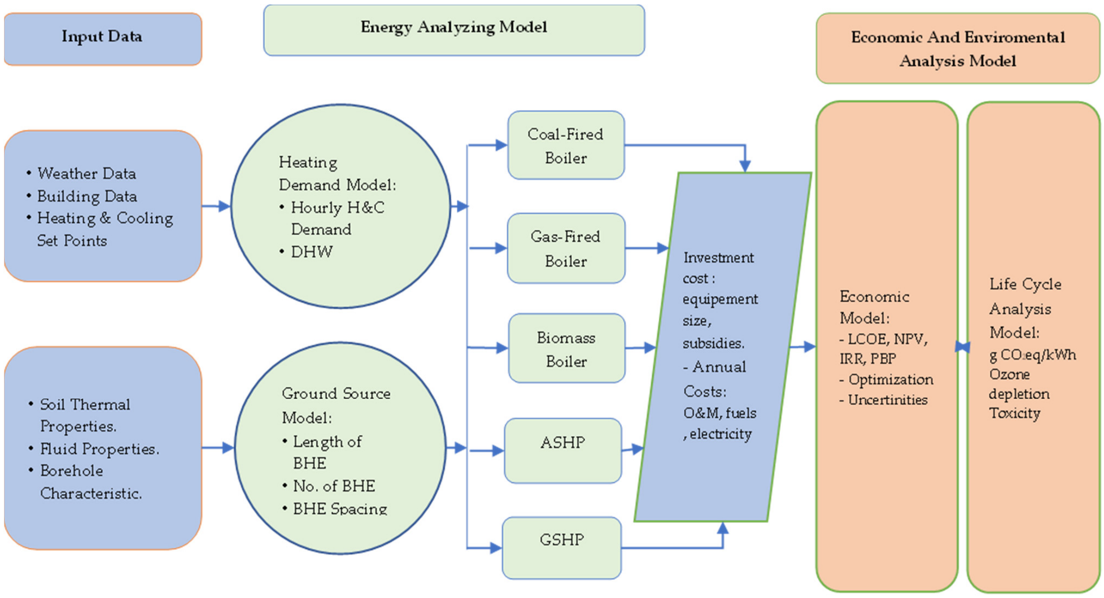

Figure 8. The proposed methodology for techno-economic modelling.

To forecast heat demand, software services such as EnergyPlus, Design Builder, and TRNSYS have been widely used [91–93]. Additionally, a standalone mathematical code for calculating the heat demand has also been reported [92]. In the heat transfer mode, analytical models, numerical models, and empirical equations are utilized to compute borehole heat exchanger efficiency and the required borehole depth. To establish financial viability, a traditional cost-benefit analysis (CBA) or a levelized cost of energy (LCOE) could be considered. CBA captures all the benefits and total costs invested during the installation and operation stages and displays them as flows over the GSHPs' lifetime (cash flow). Costs and benefits can then be directly compared between various scenarios and with reasonable alternatives to the proposed project. Mostly, a project is regarded as feasible if the sum of the expected incremental benefits exceeds the sum of all costs incurred in the project's implementation. This can be assessed using profitability (decision-making) metrics such as net present value (NPV), internal rate of return (IRR), benefit-cost ratio (B/C), and the payback period (PBP). These metrics measure the attractiveness of an investment by comparing present money values to future money values, considering the time value of money (discount rate) and the investment returns. LCOEs, on the other hand, are extensively used metrics for comparing heat and power generation technologies. The LCOE is a ratio that compares the total lifetime cost of an investment to the total energy yielded by that investment [94]. Either using CBA or LCOE metrics, GSHP's techno-economic analyses have been reported by many scholars in the last 10 years. Important insights into shallow geothermal energy and the required performances from an economic point of view have been published [12,95]. However, a few works have focused on optimizing the GSHP's design parameters to reduce costs or improve efficiency. New approaches for mapping a techno-economic geothermal potential of a shallow system have been proposed [96,97]. Surface temperature, ground temperature, and ground thermal characteristics, for example, can be measured at various sites and then dispersed on maps. These spatial dataset maps are converted into heating demand and geothermal potential for each site. Mapping techno-economic geothermal potential could help understand GSHP's performance for locations with different climatic conditions and under various financial scenarios. Table 3 summarizes the important literature on the application of a techno-economic analysis and ground source heat pump optimization.

Table 3. Overview of the major TEA studies.

Source	Description	Economic Indicators	Remarks
Neves et al., 2020 (USA) [98]	Analyzed the energy savings by replacing an old electric air conditioning/gas furnace system by vertical BHE.	Simple and discounted payback period $SPP = Cost_{ca}/AS,\ Cost_{ca} = (Cost_{cb}) + \sum in_i$ $Cost_n = AS/[(1+j)/(1+i)]^n$	The operation and maintenance costs cannot be assumed due to a neutral component for the payback period calculation that may cause a deviation from the real value. CO_2 emissions credits should be considered. Uncertainty analysis should be considered to minimize risks.
Hakkaki-Fard et al., 2015 [99]	Studied efficiency and life cycle cost analysis (LCC) for initial & 10-year operating costs and relative payback period of ASHP (air-source heat pump) and DX-GSHP (direct expansion ground-source heat pump).	$LCC = IC + PV_{electricity}$ $PV_{electricity} = \frac{COST_{annual}}{(1+ESC)^{years}}.(1+DISC)^{year}$ IC: initial cost, $PV_{ectricity}$: energy consumed	CO_2 emission credits should be considered. The results show that energy consumption of the DX-GSHP system could be reduced by 50%.
Perkovi'c et al., 2021 (Croatia) [100]	Investigated the integration of a carbon-free photovoltaic electricity source and a shallow geothermal reservoir as a heat source and heat sink during the heating and cooling season.	Levelized cost of energy $(LCOE)$ $LCOE = \frac{C_d}{\sum_{i=1}^{Ny} \frac{e_{dem}}{(1+d)^j}}$ C_d is total capital and operating cost	Reduction in CO_2 emission has been estimated but it was not considered in financial analysis. The payback period calculation should be considered to identify system feasibility.
Schreurs et al., 2021 (Austria) [101]	Identified the critical economic parameters on profitability and make policy recommendations.	NPV, BCR and IRR $NPV = \sum_{j=1}^{n} \frac{B_j - C_j}{(1+i)^j} - C_0,\ \ BCR = \frac{\sum_{j=1}^{n} \frac{B_j - C_j}{(1+i)^j}}{C_0}$ $NPV = \sum_{j=1}^{n} \frac{B_j - C_j}{(1+IRR)^j} - C_0 = 0$	Reduction in CO_2 emissions has been estimated but was not included in financial analysis. Only used for 'what-if scenario' and comparison. Optimization for selected system should be considered. ASHP and GSHP combined with PV were profitable under current subsidy schemes.
Durga et al., 2021(USA) [102]	Investigated the technical and economic feasibility of BTES.	NPV, IRR, PBP and LCOH	Annual emission saving was estimated but not considered in financial analysis.
Perego et al., 2019 (Switzerland) [96]	Developed techno-economic maps for potential of shallow and closed-loop geothermal system.	Payback Period for BHE when replacing oil and natural gas heating systems.	More accurate mathematical modelling should be considered to minimize the error (23%) for generating m/kW map and to improve PBP. Emission savings against fossils fuel have been estimated but not considered in financial analysis.

4. Optimization and Modeling

The optimization of the GSHP's design is required to improve its performance and economic competitiveness [103]. The optimal decisions for GSHP's design parameters and operating conditions have been investigated in terms of thermodynamic performance and economics. A single or multi-objective function is typically used for such system optimization. A single-objective optimization uses either thermodynamics or economics metrics as objective functions, while multi-objective optimization combines both. The goal of thermodynamic optimization is to maximize the total energy efficiency of the GHSP system or to minimize entropy generation and exergy destruction [8,92,104,105], whereas economic optimization aims to minimize the total cost or maximize NPV of the GHSP system [103,105,106]. Several articles indicate that GSHPs' coefficient of performance and total cycle costs are not in harmony. Therefore, the optimal decision requires accounting for the trade-offs between COP and total costs. This can only be achieved through multi-objective optimization (also known as Pareto optimization). Ma et al. (2020) have reviewed the recent research progress of GSHP systems optimization, focusing on their optimal design (single and multi-objective function) and optimal control [107]. Pu et al. (2017) suggested combining a multi-objective genetic algorithm (MOGA) with a response surface method to optimize the design parameters of the borehole heat exchanger (BHE) [104]. The study looked at the impact of five design parameters (velocity, inlet flow temperature, U-tube diameter, borehole diameter, and pipe spacing) on the entropy generation number and the integrated evaluation factor. According to the findings, the BHE's thermal performance was improved, and its annual energy consumption was reduced. Sayyaadi et al. (2009) have presented three levels of optimization for a vertical loop GSHP system: single objective (thermodynamic), single objective (thermo-economic), and multi-objective (thermodynamic and thermo-economic) [8]. It was shown that multi-objective optimization can reduce levelized cost and exergy destruction. For the single objective (thermo-economic), the optimized total capital cost was found to be 15% cheaper than the base case, whereas for the single objective (thermodynamic) and the multi-objective, it was 37.9% and 14.4% higher, respectively. The higher value of the multi-objective optimization could be justified by optimizing the thermodynamic and thermo-economic options simultaneously. Zhou et al. (2020) utilized COMSOL Multiphysics 5.4 software to create a 3D numerical BHE model that is coupled with a heat pump and an economic model [88]. The impact of five parameters on the thermal and economic performance of a GSHP was designed and evaluated using the Taguchi method. Based on the variance analyzed, the relative importance of velocity, borehole depth, and pipe material largely depends on the drilling costs, pipe prices, and the interest rate. Zhao et al. (2021) demonstrated a new reliability-based design optimization (RBDO) strategy for dealing with the GSHP system's reliability issue [103]. Two random variables (groundwater velocity and soil thermal conductivity) and three decision variables (depth, pipe radius, and velocity) were incorporated into the design. Uncertainties in the selected variables had a strong effect on the system reliability and total cost estimation. The impact of uncertainty on borehole depth and groundwater velocity was found to be colossal, while ground thermal conductivity had less of an influence on the GSHP's total cost.

In Figure 9, a GSHP optimization methodology is outlined, with a summary of its basic steps and approaches, including multi-objective and single-objective optimization. The optimization methods, objective functions, and decision variables reported in the literature are outlined in Table 4.

Table 4. Summary of the GSHP optimization (objective function, decision variables, and modelling approach.

Source	Objective Function	Decision Variables	Tools Used	Remarks
Pu et al., 2017 [104]	Objective Function: Multi-objective. (1) Min entropy generation number. (2) Max integrated evaluation Factor.	▪ Inlet velocity and temperature ▪ U-tube and borehole diameter ▪ Pipe spacing	ANYSIS, Central composite design, Kriging and multi-objective genetic algorithm (MOGA).	Cost-based optimization was not included in the study. CO_2 emissions credits should be considered.
Farzanehkhameneh et al., (2020) [92]	Objective Function: Single objective. (1) Thermodynamic irreversibility.	▪ External and internal pipe's radius	TRNSYS software and Genetic Algorithm.	Cost-based optimization was not included. CO_2 emissions credits should be considered.
Wang et al., (2020) [89]	Objective Function: Single objective. (1) Minimize the energy consumption.	▪ Water supply temperature ▪ Part load ratio	Data driven optimization used ANN, Detailed and DOE-2 techniques, which relates variables, energy consumption, and heating demand.	Cost-based optimization was not included. ANN and DOE-2 were in good agreement with the data.
Sivasakthi–vel et al., 2014 [105]	Objective Function: Multi-objective. (1) COP for heating mode. (2) COP for cooling mode.	▪ Condenser inlet temperature ▪ Condenser outlet temperature ▪ Dryness fraction ▪ Evaporator outlet temperature	Taguchi optimization analysis and utility concept.	Utility concept combined with Taguchi are useful to predict COPs with high confidence level (95%).
Zhao et al., 2021 (USA) [103]	Objective **Function**: Single objective. (1) Total cost of GSHP system over a 20-year life span.	▪ BHE's depth and pipe radius ▪ Mass flow rate ▪ Groundwater velocity and ground thermal conductivity	An analytical borehole and probabilistic uncertainties using reliability-based design optimization (RBDO).	CO_2 emissions credits should be considered.
GAMAGE et al., 2014 [108]	Objective Function: Number of boreholes.	▪ BHE length and number ▪ Spacing between boreholes ▪ Contribution of the GSHP	EnergyPlus, cylindrical heat source solution and Monte Carlo simulation.	CO_2 emissions credits should be considered.
Ma and Xia (2017) [109]	Objective Function: Single objective. (1) Minimize the system power consumption.	▪ BHE outlet temperature ▪ Flow rate ▪ Pump operating speed	EnergyPlus and G-function was used for BHE.	Cost-based optimization was not included in the study.

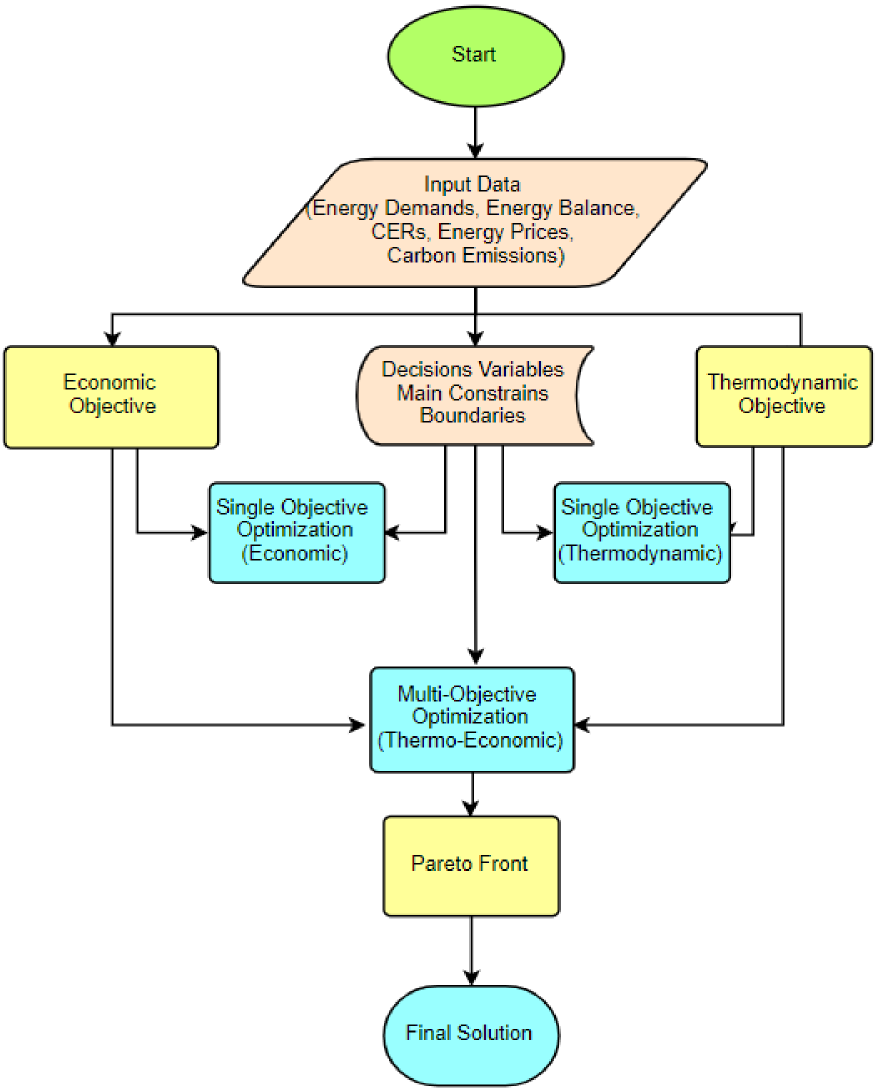

Figure 9. The proposed optimization methodology.

5. Life Cycle Assessment

Life cycle analysis (LCA) is a method for studying the environmental impacts and environmental aspects of a product or system during its life cycle [110]. LCA is required for assessing GSHPs' potential environmental issues and sustainability over its lifetime. There are four components of the LCA process according to ISO standards 14040 and ISO14044: goal definition and scoping, inventory analysis, impact assessment, and interpretation (see Figure 10). LCA is necessary to make informed decisions about alternative fuels and technologies. For a consistent comparison between the alternatives, a common unit is used to express the results for the same output. This common unit is the functional unit (CO_2 eq/kWh). To accurately estimate the environmental impact, the LCA should consider the manufacturing of equipment, materials, transportation, execution, use, and disposal [111,112]. Astu and Pratiwi (2021) conducted LCA for shallow and medium depth geothermal systems [113]. The results indicated that shallower systems with connected heat pumps have better environmental performances than systems with district heating. This depends on the fuels and grid used in the study's district heating system. In addition, the environmental impacts of the geothermal systems were lower than those of fossil fuels, except for mineral resource scarcity, especially with decentralized heat pumps and free cooling.

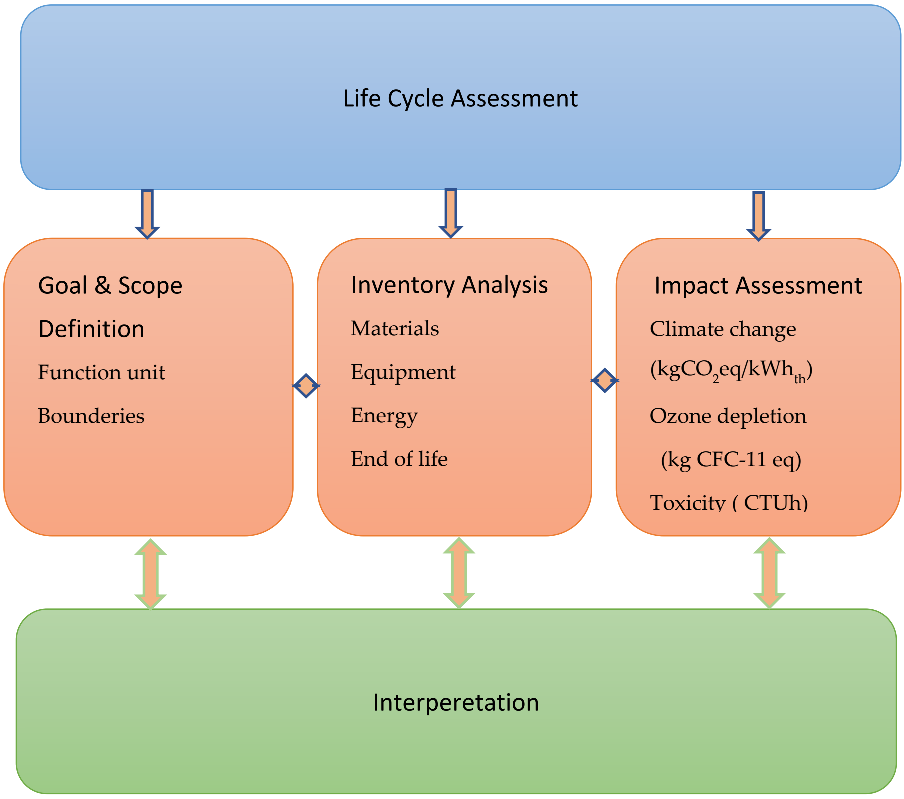

Figure 10. Stages of life cycle assessment.

6. Conclusions

The ground-source heat pump (GSHP) is a promising technology with great potential towards decarbonizing the heating and cooling sector in Europe. The wider adoption of GSHP systems could lead to energy efficacy improvement, energy-saving, and carbon emissions reduction. In this work, an overview of the use of SGE for heating and cooling purposes was presented. The latest developments of GSHP were discussed in terms of materials and BHE configuration, while emphasizing the most up-to-date literature regarding techno-economic optimization approaches. Detailed conclusions are given below.

(1) GSHP has one of the highest efficiencies among the other renewable energy systems with efficiency in ranges of 300–500%. By increasing the value of heat transfer in BHE, the efficiency of the GSHP system is increased. GSHPs have been shown to be both profitable and capable of reducing CO_2 emissions by numerous researchers, who demonstrated that 26–50% energy reduction and 65–85% emission reduction is achievable when using GSHPs compared to combustion-based fossil fuel systems. In addition, GSHPs have the advantage of being used as a heating or cooling system, depending on the weather, with lower yearly operation and maintenance (O&M) costs compared to other traditional heating systems.

(2) The thermal conductivity of the grout and collector has a significant impact on the borehole thermal resistance. Adding thermally enhanced materials such as graphite to grout or pipe materials improves their thermal properties and thus reduces the borehole thermal resistance. Laboratory investigations have shown the great potential for graphite, sand, and magnesium powder additives to increase the cement and bentonite conductivity to 1.5 to 5 $Wm^{-1}K^{-1}$. Despite the development of increasing the thermal conductivity of the grout and collector materials used in borehole completion, there is still a gap between the theoretical optimum and the commercially available products. Modeling has shown a continuous reduction in BHE's thermal resistance, with the collector's thermal conductivities up to 4–5 $Wm^{-1}K^{-1}$, while commercial collectors have thermal conductivities less than 1 $Wm^{-1}K^{-1}$. This is also the case

for grout materials, which have a commercial product with a maximum thermal conductivity of 2.8 $Wm^{-1}K^{-1}$. Many researchers have shown the significant effect of using enhanced materials to reduce the borehole thermal resistance and increase the thermal exchange rate. However, investigations of BHEs' design length have reduced and the economic benefits of using enhanced materials remain scarce.

(3) BTES is the ideal alternative for seasonal cooling and heat energy storage due to the high thermal capacity of the ground. BTES can store surplus solar, and waste the thermal energy collected in the summer that can be used in the winter. BTES is a dispatchable renewable energy source, available everywhere, that can reduce the undesired effects of the intermittency of the other renewable energy sources. BTES should be designed so that its internal volume and external surface areas are maximized. Therefore, equidimensional cylindrical or cubic arrays of the BTES will perform best. For BTES systems, geological conditions are not crucial, unlike ATES systems, which depend heavily on the geology of the subsurface layers and the type of aquifer.

(4) The high upfront cost of shallow geothermal energy systems creates financing obstacles for households. GSHPs without subsidy are more expensive heating solutions compared to fuel-based heating systems. To make GSHP compete with gas, it is necessary to create balanced taxation levels between electricity and gas. Increased prices or carbon taxation on fossil fuels will likely have a direct impact on GSHPs' ability to compete against gas boilers. The cost-effectiveness of GSHP could be improved in the future through several driving factors, including market maturity, increased efficiency, access to cheap electricity, and subsidy programs.

(5) Increasing the thermal properties of materials (grout, collector, and heat-carrier fluid) and implementing innovative configurations could improve BHE performance. The extra costs associated with using such materials must be justified by their reasonable effect on BHE efficiency. The optimal decision should therefore consider efficiency alongside the total costs.

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Nomenclature

Abbreviation	**Full Title**
ATES	Aquifer Thermal Energy Storage
BHE	Borehole Heat Exchanger
BTES	Boreholes Thermal Energy Storage
Capex	Capital Expenditure
CBA	Cost Benefits Analysis
COP	Coefficient of Performance
DHW	Domestic Hot Water
GHG	Greenhouse Gas

GSHP	Ground Source Heat Pump
IEA	International Energy Agency
IRR	Internal Rate of Return
LCOE	Levelized Cost of Energy
LCOH	Levelized Cost of Heat
MOGA	Multi-Objective Genetic Algorithm
MRE	Mean Relative Error
NPV	Net Present Value
Opex	Operating Expenditure
O&M	Operation And Maintenance
PBP	Payback Period
PE	Polyethylene
PP	Polypropylene
PU	Polyurethane
PVC	Polyvinylchloride
UTES	Under Ground Thermal Energy Storage
RBDO	Reliability-Based Design Optimization
RMSE	Root Mean Squared Error
TRT	Thermal Response Test

References

1. Secretariat, United Nations Framework Convention on Climate Change. *Report of the Conference of the Parties on Its Twenty-First*; United Nations Framework Convention on Climate Change: Bonn, Germany, 2015.
2. International Energy Agency. Renewables. 2019. Available online: www.iea.org/renewables2019 (accessed on 8 January 2022).
3. European Union. *An EU Strategy on Heating and Cooling*; European Union: Brussels, Belgium, 2016.
4. Osička, J.; Kemmerzell, J.; Zoll, M.; Lehotský, L.; Černoch, F.; Knodt, M. What's next for the European coal heartland? Exploring the future of coal as presented in German, Polish and Czech press. *Energy Res. Soc. Sci.* **2020**, *61*, 101316. [CrossRef]
5. Toleikyte, A.; Carlsson, J.; European Commission. Joint Research Centre. In *Assessment of Heating and Cooling Related Chapters of the National Energy and Climate Plans (NECPs)*; Publications Office of the European Union: Luxembourg, 2021.
6. Institute for Renewable Energy. *Implementation of Renewable Energy Sources in District Heating Systems in Poland*; Institute for Renewable Energy: Bozen, Italy, 2018.
7. Hakkaki-Fard, A.; Aidoun, Z.; Ouzzane, M. Applying refrigerant mixtures with thermal glide in cold climate air-source heat pumps. *Appl. Therm. Eng.* **2014**, *62*, 714–722. [CrossRef]
8. Sayyaadi, H.; Amlashi, E.H.; Amidpour, M. Multi-objective optimization of a vertical ground source heat pump using evolutionary algorithm. *Energy Convers. Manag.* **2009**, *50*, 2035–2046. [CrossRef]
9. Javadi, H.; Ajarostaghi, S.S.M.; Rosen, M.A.; Pourfallah, M. Performance of ground heat exchangers: A comprehensive review of recent advances. *Energy* **2019**, *178*, 207–233. [CrossRef]
10. Gamage, K.J. Numerical Methodology for Feasibility Analysis of Ground Source Heat Pumps. Master's Thesis, Middle East Technical University, Ankara, Türkiye, 2014. Available online: https://www.researchgate.net/publication/265250440 (accessed on 8 January 2022).
11. Sliwa, T.; Sapińska-Śliwa, A.; Gonet, A.; Kowalski, T.; Sojczyńska, A. Geothermal Boreholes in Poland—Overview of the Current State of Knowledge. *Energies* **2021**, *14*, 3251. [CrossRef]
12. Badenes, B.; Pla, M.M.; Magraner, T.; Soriano, J.; Urchueguía, J.F. Theoretical and Experimental Cost–Benefit Assessment of Borehole Heat Exchangers (BHEs) According to Working Fluid Flow Rate. *Energies* **2020**, *13*, 4925. [CrossRef]
13. Sliwa, T.; Leśniak, P.; Sapińska-Śliwa, A.; Rosen, M.A. Effective Thermal Conductivity and Borehole Thermal Resistance in Selected Borehole Heat Exchangers for the Same Geology. *Energies* **2022**, *15*, 1152. [CrossRef]
14. Sapińska-Sliwa, A.; Rosen, M.A.; Gonet, A.; Kowalczyk, J.; Sliwa, T. A New Method Based on Thermal Response Tests for Determining Effective Thermal Conductivity and Borehole Resistivity for Borehole Heat Exchangers. *Energies* **2019**, *12*, 1072. [CrossRef]
15. Sliwa, T.; Gołas, A.; Wołoszyn, J.; Gonet, A. Numerical model of borehole heat exchanger in ansys CFX software. *Arch. Min. Sci.* **2012**, *57*, 375–390. [CrossRef]
16. Koenig, A. Thermal resistance of borehole heat exchangers composed of multiple loops and custom shapes. *Geotherm. Energy* **2015**, *3*, 933. [CrossRef]
17. Lund, J.W.; Toth, A.N. Direct utilization of geothermal energy 2020 worldwide review. *Geothermics* **2021**, *90*, 101915. [CrossRef]
18. García, L.S.; Paardekooper, S.; Thellufsen, J.Z.; Djørup, S.R. *Towards a Decarbonised Heating and Cooling Sector in Europe Unlocking the Potential of Energy Efficiency and District Energy*; Aalborg Universitet: Aalborg, Denmark, 2019.

19. Galindo Fernández, M.; Bacquet, A.; Bensadi, S.; Morisot, P.; Oger, A.; European Commission; Joint Research Centre. *Integrating Renewable and Waste Heat and Cold Sources into District Heating and Cooling Systems: Case Studies Analysis, Replicable Key Success Factors and Potential Policy Implications*; Institute for Renewable Energy: Bozen, Italy, 2021.
20. Garabetian, T. *EGEC Geothermal Market Report*; European Geothermal Energy Council: Bruxelles, Belgium, 2021.
21. Meek, C. Heat pumps and UK's decarbonisation: Lessons from an Ofgem dataset of more than 2000 domestic installations. In *Context-Methodology-Analysis-Discussion-Recommendations*; Spring 2021; RECC: London, UK, 2021.
22. Longa, F.D.; Nogueira, L.P.; Limberger, J.; van Wees, J.-D.; van der Zwaan, B. Scenarios for geothermal energy deployment in Europe. *Energy* **2020**, *206*, 118060. [CrossRef]
23. Zhang, Y.; Hao, S.; Yu, Z.; Fang, J.; Zhang, J.; Yu, X. Comparison of test methods for shallow layered rock thermal conductivity between in situ distributed thermal response tests and laboratory test based on drilling in northeast China. *Energy Build.* **2018**, *173*, 634–648. [CrossRef]
24. Santa, G.D.; Galgaro, A.; Sassi, R.; Cultrera, M.; Scotton, P.; Mueller, J.; Bertermann, D.; Mendrinos, D.; Pasquali, R.; Perego, R.; et al. An updated ground thermal properties database for GSHP applications. *Geothermics* **2020**, *85*, 101758. [CrossRef]
25. Fujii, H.; Okubo, H.; Nishi, K.; Itoi, R.; Ohyama, K.; Shibata, K. An improved thermal response test for U-tube ground heat exchanger based on optical fiber thermometers. *Geothermics* **2009**, *38*, 399–406. [CrossRef]
26. Jia, G.; Tao, Z.; Meng, X.; Ma, C.; Chai, J.; Jin, L. Review of effective thermal conductivity models of rock-soil for geothermal energy applications. *Geothermics* **2019**, *77*, 1–11. [CrossRef]
27. Horai, K.-I.; Simmons, G. Thermal conductivity of rock-forming minerals. *Earth Planet. Sci. Lett.* **1969**, *6*, 359–368. [CrossRef]
28. Null, J. Performance Investigation of Multiple-Tube Ground Heat Exchangers for Ground-Source Heat Pump. *Am. J. Energy Eng.* **2014**, *2*, 103. [CrossRef]
29. Liu, X.; Xiao, Y.; Inthavong, K.; Tu, J. Experimental and numerical investigation on a new type of heat exchanger in ground source heat pump system. *Energy Effic.* **2015**, *8*, 845–857. [CrossRef]
30. Raymond, J.; Mercier, S.; Nguyen, L. Designing coaxial ground heat exchangers with a thermally enhanced outer pipe. *Geotherm. Energy* **2015**, *3*, 7. [CrossRef]
31. Chang, K.S.; Kim, M.J. Thermal performance evaluation of vertical U-loop ground heat exchanger using in-situ thermal response test. *Renew. Energy* **2016**, *87*, 585–591. [CrossRef]
32. Jahanbin, A. Thermal performance of the vertical ground heat exchanger with a novel elliptical single U-tube. *Geothermics* **2020**, *86*, 101804. [CrossRef]
33. Badenes, B.; Sanner, B.; Pla, M.M.; Cuevas, J.M.; Bartoli, F.; Ciardelli, F.; González, R.M.; Ghafar, A.N.; Fontana, P.; Zuñiga, L.L.; et al. Development of advanced materials guided by numerical simulations to improve performance and cost-efficiency of borehole heat exchangers (BHEs). *Energy* **2020**, *201*, 117628. [CrossRef]
34. Dehkordi, S.E.; Schincariol, R.A. Effect of thermal-hydrogeological and borehole heat exchanger properties on performance and impact of vertical closed-loop geothermal heat pump systems. *Appl. Hydrogeol.* **2014**, *22*, 189–203. [CrossRef]
35. Lee, C.; Lee, K.; Choi, H.; Choi, H.-P. Characteristics of thermally-enhanced bentonite grouts for geothermal heat exchanger in South Korea. *Sci. China Technol. Sci.* **2010**, *53*, 123–128. [CrossRef]
36. Mahmoud, M.; Ramadan, M.; Pullen, K.; Abdelkareem, M.A.; Wilberforce, T.; Olabi, A.-G.; Naher, S. A review of grout materials in geothermal energy applications. *Int. J. Thermofluids* **2021**, *10*, 100070. [CrossRef]
37. Kim, D.; Oh, S. Relationship between the thermal properties and degree of saturation of cementitious grouts used in vertical borehole heat exchangers. *Energy Build.* **2019**, *201*, 1–9. [CrossRef]
38. Jobmann, M.; Buntebarth, G. Influence of graphite and quartz addition on the thermo–physical properties of bentonite for sealing heat-generating radioactive waste. *Appl. Clay Sci.* **2009**, *44*, 206–210. [CrossRef]
39. Berktaş, İ. Facile Synthesis of Graphite-and Graphene-Based Hybrid Additives by Silanization and Effects of These Additives on the Thermal Conductivity of Cementitious Grouts Used in Shallow Geothermal Systems. Ph.D. Thesis, Sabanci University, Tuzla, Türkiye, 2020.
40. Delaleux, F.; Py, X.; Olives, R.; Dominguez, A. Enhancement of geothermal borehole heat exchangers performances by improvement of bentonite grouts conductivity. *Appl. Therm. Eng.* **2012**, *33*, 92–99. [CrossRef]
41. Bae, S.; Nam, Y.; Choi, J.; Lee, K.; Choi, J. Analysis on Thermal Performance of Ground Heat Exchanger According to Design Type Based on Thermal Response Test. *Energies* **2019**, *12*, 651. [CrossRef]
42. Zeng, H.; Diao, N.; Fang, Z. Heat transfer analysis of boreholes in vertical ground heat exchangers. *Int. J. Heat Mass Transf.* **2003**, *46*, 4467–4481. [CrossRef]
43. Śliwa, T.; Rosen, M. Efficiency analysis of borehole heat exchangers as grout varies via thermal response test simulations. *Geothermics* **2017**, *69*, 132–138. [CrossRef]
44. Hellström, G. THERMAL Performance of Borehole Heat Exchangers. In Proceedings of the Stockton International Geothermal Conference, Stockton, NJ, USA, 16–17 March 1998.
45. Sliwa, T.; Sapińska-Śliwa, A.; Wysogląd, T.; Kowalski, T.; Konopka, I. Strength Tests of Hardened Cement Slurries for Energy Piles, with the Addition of Graphite and Graphene, in Terms of Increasing the Heat Transfer Efficiency. *Energies* **2021**, *14*, 1190. [CrossRef]
46. Sliwa, T.; Kowalski, T.; Cekus, D.; Sapińska-Śliwa, A. Research on Fresh and Hardened Sealing Slurries with the Addition of Magnesium Regarding Thermal Conductivity for Energy Piles and Borehole Heat Exchangers. *Energies* **2021**, *14*, 5119. [CrossRef]

47. Liu, X.; Spitler, J.D.; Qu, M.; Shi, L. Recent Developments in the Design of Vertical Borehole Ground Heat Exchangers for Cost Reduction and Thermal Energy Storage. *J. Energy Resour. Technol.* **2021**, *143*, 100803. [CrossRef]
48. Mehrjerdi, A.K.; Naudin, S.; Skrifvars, M. *Development of Polyolefin Compound and Post-Polymerization Treatments for Ground Heat Exchangers*; SHAREOK: Norman, OK, USA, 2017.
49. Kurevija, T.; Kalantar, A.; Macenić, M.; Hranić, J. Investigation of Steady-State Heat Extraction Rates for Different Borehole Heat Exchanger Configurations from the Aspect of Implementation of New TurboCollector™ Pipe System Design. *Energies* **2019**, *12*, 1504. [CrossRef]
50. Mehrjerdi, A.K.; Åkesson, D.; Skrifvars, M. Influence of talc fillers on bimodal polyethylene composites for ground heat exchangers. *J. Appl. Polym. Sci.* **2020**, *137*, 49220. [CrossRef]
51. Mehrjerdi, A.K.; Adl-Zarrabi, B.; Cho, S.-W.; Skrifvars, M. Mechanical and thermo-physical properties of high-density polyethylene modified with talc. *J. Appl. Polym. Sci.* **2013**, *129*, 2128–2138. [CrossRef]
52. Mehrjerdi, A.K. Thesis for the Degree of Doctor of Philosophy Thermally Conductive High-Density Polyethylene Composites for Ground Heat Exchangers. 2020. Available online: http://urn.kb.se/resolve?urn=urn:nbn:se:hb:diva-23698 (accessed on 8 January 2022).
53. Mehrjerdi, A.K.; Bashir, T.; Skrifvars, M. Melt rheology and extrudate swell properties of talc filled polyethylene compounds. *Heliyon* **2020**, *6*, e04060. [CrossRef]
54. Emmi, G.; Zarrella, A.; De Carli, M.; Donà, M.; Galgaro, A. Energy performance and cost analysis of some borehole heat exchanger configurations with different heat-carrier fluids in mild climates. *Geothermics* **2017**, *65*, 158–169. [CrossRef]
55. Melinder, Å. Thermophysical Properties of Aqueous Solutions Used as Secondary Working Fluids. Ph.D. Thesis, KTH Royal Institute of Technology, Stockholm, Sweden, 2007.
56. Klotzbücher, T.; Kappler, A.; Straub, K.L.; Haderlein, S.B. Biodegradability and groundwater pollutant potential of organic anti-freeze liquids used in borehole heat exchangers. *Geothermics* **2007**, *36*, 348–361. [CrossRef]
57. Casasso, A.; Sethi, R. Efficiency of closed loop geothermal heat pumps: A sensitivity analysis. *Renew. Energy* **2014**, *62*, 737–746. [CrossRef]
58. Kavanaugh, S.P.; Rafferty, K.D.; Kavanaugh, S.P. *Geothermal Heating and Cooling: Design of Ground-Source Heat Pump Systems*; ASHRAE: Peachtree Corners, GA, USA, 2014.
59. Patel, D.M. Brines–A Large Scale Cooling Solution | Cooling India Monthly Business Magazine on the HVACR Business | Green HVAC Industry | Heating, Ventilation, Air conditioning and Refrigeration News Magazine Updates, Articles, Publications on HVACR Business Industry | HVACR Business Magazine. *Cooling India*, 15 February 2016.
60. Sundar, L.S.; Ramana, E.V.; Singh, M.K.; Sousa, A. Thermal conductivity and viscosity of stabilized ethylene glycol and water mixture Al2O3 nanofluids for heat transfer applications: An experimental study. *Int. Commun. Heat Mass Transf.* **2014**, *56*, 86–95. [CrossRef]
61. Wei, X.; Li, N.; Peng, J.; Cheng, J.; Su, L.; Hu, J. Analysis of the Effect of the CaCl2 Mass Fraction on the Efficiency of a Heat Pump Integrated Heat-Source Tower Using an Artificial Neural Network Model. *Sustainability* **2016**, *8*, 410. [CrossRef]
62. Herri, J.M.; Darbouret, M.; Herr, J.-M. Rheological Study of Two-Phase Secondary Fluids for Refrigeration and Air Conditioning. Mines Saint-Etienne. 2013. Available online: https://hal.archives-ouvertes.fr/hal-00841701 (accessed on 8 January 2022).
63. Song, S.; Peng, C. Viscosities of Binary and Ternary Mixtures of Water, Alcohol, Acetone, and Hexane. *J. Dispers. Sci. Technol.* **2008**, *29*, 1367–1372. [CrossRef]
64. Conde, M. *Thermophysical Properties of Brines Models*; Conde Engineering: Zurich, Switzerland, 2011.
65. Available online: https://www.vapcocompany.com/glycol-calculator/ (accessed on 20 March 2022).
66. Available online: https://sciencelab.com/ (accessed on 20 March 2022).
67. Tarodiya, R.; Verma, V.; Thangavel, S. A study on utilization of ground source energy for space heating using a nanofluid as a heat carrier. *Heat Transf.* **2021**, *50*, 3842–3860. [CrossRef]
68. Pérez-Tavernier, J.; Vallejo, J.; Cabaleiro, D.; Fernández-Seara, J.; Lugo, L. Heat transfer performance of a nano-enhanced propylene glycol:water mixture. *Int. J. Therm. Sci.* **2019**, *139*, 413–423. [CrossRef]
69. Sui, D.; Langåker, V.H.; Yu, Z. Investigation of Thermophysical Properties of Nanofluids for Application in Geothermal Energy. *Energy Procedia* **2017**, *105*, 5055–5060. [CrossRef]
70. Sun, X.-H.; Yan, H.; Massoudi, M.; Chen, Z.-H.; Wu, W.-T. Numerical Simulation of Nanofluid Suspensions in a Geothermal Heat Exchanger. *Energies* **2018**, *11*, 919. [CrossRef]
71. Du, R.; Jiang, D.; Wang, Y. Numerical Investigation of the Effect of Nanoparticle Diameter and Sphericity on the Thermal Performance of Geothermal Heat Exchanger Using Nanofluid as Heat Transfer Fluid. *Energies* **2020**, *13*, 1653. [CrossRef]
72. Du, R.; Jiang, D.; Wang, Y.; Shah, K.W. An experimental investigation of CuO/water nanofluid heat transfer in geothermal heat exchanger. *Energy Build.* **2020**, *227*, 110402. [CrossRef]
73. Doerte, L.; Wolf-Dieter, S.; Rainer, T. Advances in thermal energy storage development at the German Aerospace Center DLR). *Energy Storage Sci. Technol.* **2012**, *1*, 13.
74. Skarphagen, H.; Banks, D.; Frengstad, B.S.; Gether, H. Design Considerations for Borehole Thermal Energy Storage (BTES): A Review with Emphasis on Convective Heat Transfer. *Geofluids* **2019**, *2019*, 1–26. [CrossRef]

75. Hendriks, M.; Snijders, A.; Boid, N. Underground thermal energy storage for efficient heating and cooling of buildings. In Proceedings of the 1st International Conference on Industrialised, Integrated, Intelligent Construction, Loughborough, UK, 14–16 May 2008; p. 358.
76. Guo, F.; Zhu, X.; Zhang, J.; Yang, X. Large-scale living laboratory of seasonal borehole thermal energy storage system for urban district heating. *Appl. Energy* **2020**, *264*, 114763. [CrossRef]
77. Dahash, A.; Ochs, F.; Janetti, M.B.; Streicher, W. Advances in seasonal thermal energy storage for solar district heating applications: A critical review on large-scale hot-water tank and pit thermal energy storage systems. *Appl. Energy* **2019**, *239*, 296–315. [CrossRef]
78. Sovacool, B. The intermittency of wind, solar, and renewable electricity generators: Technical barrier or rhetorical excuse? *Util. Policy* **2009**, *17*, 288–296. [CrossRef]
79. Schmidt, T.; Pauschinger, T.; Sørensen, P.A.; Snijders, A.; Djebbar, R.; Boulter, R.; Thornton, J. Design Aspects for Large-scale Pit and Aquifer Thermal Energy Storage for District Heating and Cooling. *Energy Procedia* **2018**, *149*, 585–594. [CrossRef]
80. Nordell, B. *A Borehole Heat Store in Rock at the University of Luleaa*; ETDEWeb: Oak Ridge, TN, USA, 1989.
81. Chuard, P.; Hadorn, J.C. *Central Solar Heating Plants with Seasonal Storage Heat Storage Systems Concepts Engineering Data and Compilation of Projects*; ETDEWeb: Oak Ridge, TN, USA, 1983.
82. Seiwald, H.; Hahne, E.; Reus, M. Underground seasonal heat storage for a solar heating system in Neckarsulm, Germany. *Bull. Hydrogeol.* **1999**, *17*, 349–357.
83. Xu, L.; Torrens, J.I.; Guo, F.; Yang, X.; Hensen, J. Application of large underground seasonal thermal energy storage in district heating system: A model-based energy performance assessment of a pilot system in Chifeng, China. *Appl. Therm. Eng.* **2018**, *137*, 319–328. [CrossRef]
84. Midttømme, K.; Hauge, A.; Grini, R.S.; Stene, J.; Skarphagen, H. Underground Thermal Energy Storage (UTES) with Heat Pumps in Norway. 2009. Available online: https://www.researchgate.net/publication/264846817 (accessed on 20 March 2022).
85. Hammock, C.W.; Sullens, J.S. *Coupling Geothermal Heat Pumps with Underground Seasonal Thermal Energy Storage*; Andrews, Hammock and Powell, Inc.: Macon, GA, USA, 2017.
86. Burk, C. Techno-Economic Modeling for New Technology Development. *Chem. Eng. Prog.* **2017**, *114*, 43–52.
87. Giacomella, L. Techno-Economic Assessment (TEA) and Life Cycle Costing Analysis (LCCA): Discussing methodological steps and integrability. *Insights Reg. Dev.* **2021**, *3*, 176–197. [CrossRef]
88. Zhou, K.; Mao, J.; Li, Y.; Zhang, H. Performance assessment and techno-economic optimization of ground source heat pump for residential heating and cooling: A case study of Nanjing, China. *Sustain. Energy Technol. Assess.* **2020**, *40*, 100782. [CrossRef]
89. Wang, G.; Wang, H.; Kang, Z.; Feng, G. Data-Driven Optimization for Capacity Control of Multiple Ground Source Heat Pump System in Heating Mode. *Energies* **2020**, *13*, 3595. [CrossRef]
90. Mahmud, R.; Moni, S.M.; High, K.; Carbajales-Dale, M. Integration of techno-economic analysis and life cycle assessment for sustainable process design—A review. *J. Clean. Prod.* **2021**, *317*, 128247. [CrossRef]
91. Turhan, C.; Kazanasmaz, T.; Uygun, I.E.; Ekmen, K.E.; Akkurt, G.G. Comparative study of a building energy performance software (KEP-IYTE-ESS) and ANN-based building heat load estimation. *Energy Build.* **2014**, *85*, 115–125. [CrossRef]
92. Farzanehkhameneh, P.; Soltani, M.; Kashkooli, F.M.; Ziabasharhagh, M. Optimization and energy-economic assessment of a geothermal heat pump system. *Renew. Sustain. Energy Rev.* **2020**, *133*, 110282. [CrossRef]
93. Ilisei, G.; Catalina, T.; Gavriliuc, R. Sensitivity analysis using simulations for a ground source heat pump—Implementation on a solar passive house. *E3S Web Conf.* **2019**, *111*, 01070. [CrossRef]
94. Pawel, I. The Cost of Storage—How to Calculate the Levelized Cost of Stored Energy (LCOE) and Applications to Renewable Energy Generation. *Energy Procedia* **2014**, *46*, 68–77. [CrossRef]
95. Habibi, M.; Aligolzadeh, F.; Hakkaki-Fard, A. A techno-economic analysis of geothermal ejector cooling system. *Energy* **2020**, *193*, 116760. [CrossRef]
96. Perego, R.; Pera, S.; Galgaro, A. Techno-Economic Mapping for the Improvement of Shallow Geothermal Management in Southern Switzerland. *Energies* **2019**, *12*, 279. [CrossRef]
97. Wang, Y.; He, W. Temporospatial techno-economic analysis of heat pumps for decarbonising heating in Great Britain. *Energy Build.* **2021**, *250*, 111198. [CrossRef]
98. Neves, R.; Cho, H.; Zhang, J. Techno-economic analysis of geothermal system in residential building in Memphis, Tennessee. *J. Build. Eng.* **2020**, *27*, 100993. [CrossRef]
99. Hakkaki-Fard, A.; Eslami-Nejad, P.; Aidoun, Z.; Ouzzane, M. A techno-economic comparison of a direct expansion ground-source and an air-source heat pump system in Canadian cold climates. *Energy* **2015**, *87*, 49–59. [CrossRef]
100. Perković, L.; Leko, D.; Brettschneider, A.; Mikulčić, H.; Varbanov, P. Integration of Photovoltaic Electricity with Shallow Geothermal Systems for Residential Microgrids: Proof of Concept and Techno-Economic Analysis with RES2GEO Model. *Energies* **2021**, *14*, 1923. [CrossRef]
101. Schreurs, T.; Madani, H.; Zottl, A.; Sommerfeldt, N.; Zucker, G. Techno-economic analysis of combined heat pump and solar PV system for multi-family houses: An Austrian case study. *Energy Strategy Rev.* **2021**, *36*, 100666. [CrossRef]
102. Durga, S.; Beckers, K.F.; Taam, M.; Horowitz, F.; Cathles, L.M.; Tester, J.W. Techno-economic analysis of decarbonizing building heating in Upstate New York using seasonal borehole thermal energy storage. *Energy Build.* **2021**, *241*, 110890. [CrossRef]
103. Zhao, Z.; Xu, Y.; Lin, Y.-F.; Wang, X.; Wang, P. Probabilistic modeling and reliability-based design optimization of a ground source heat pump system. *Appl. Therm. Eng.* **2021**, *197*, 117341. [CrossRef]

104. Pu, L.; Qi, D.; Xu, L.; Li, Y. Optimization on the performance of ground heat exchangers for GSHP using Kriging model based on MOGA. *Appl. Therm. Eng.* **2017**, *118*, 480–489. [CrossRef]
105. Sivasakthivel, T.; Murugesan, K.; Thomas, H. Optimization of operating parameters of ground source heat pump system for space heating and cooling by Taguchi method and utility concept. *Appl. Energy* **2014**, *116*, 76–85. [CrossRef]
106. Xia, L.; Ma, Z.; McLauchlan, C.; Wang, S. Experimental investigation and control optimization of a ground source heat pump system. *Appl. Therm. Eng.* **2017**, *127*, 70–80. [CrossRef]
107. Ma, Z.; Xia, L.; Gong, X.; Kokogiannakis, G.; Wang, S.; Zhou, X. Recent advances and development in optimal design and control of ground source heat pump systems. *Renew. Sustain. Energy Rev.* **2020**, *131*, 11001. [CrossRef]
108. Gamage, K.; Yousefzadeh, M.; Merzifonluoglu, Y.; Uzgören, E.; Uzgören, Y.M. Optimization of a ground source heat pump system using Monte-Carlo simulation Organic Rankine cycles View project Concentrated solar power View project Optimization of a Ground Source Heat Pump System Using Monte-Carlo Simulation. In Proceedings of the 7th International Ege Energy Symposium & Exhibition, Usak, Turkey, 18–20 June 2014. [CrossRef]
109. Ma, Z.; Xia, L. Model-based Optimization of Ground Source Heat Pump Systems. *Energy Procedia* **2017**, *111*, 12–20. [CrossRef]
110. Soleimani, T.; Gilbert, H. An approach to achieve overall farm feed efficiency in pig production: Environmental evaluation through individual life cycle assessment. *Int. J. Life Cycle Assess.* **2021**, *26*, 455–469. [CrossRef]
111. Sutman, M.; Speranza, G.; Ferrari, A.; Larrey-Lassalle, P.; Laloui, L. Long-term performance and life cycle assessment of energy piles in three different climatic conditions. *Renew. Energy* **2020**, *146*, 1177–1191. [CrossRef]
112. Saner, D.; Juraske, R.; Kübert, M.; Blum, P.; Hellweg, S.; Bayer, P. Is it only CO2 that matters? A life cycle perspective on shallow geothermal systems. *Renew. Sustain. Energy Rev.* **2010**, *14*, 1798–1813. [CrossRef]
113. Pratiwi, A.S.; Trutnevyte, E. Life cycle assessment of shallow to medium-depth geothermal heating and cooling networks in the State of Geneva. *Geothermics* **2021**, *90*, 101988. [CrossRef]