J Ther Eng, Vol. 9, No. 5, pp. 1386–1417, September, 2023

Journal of Thermal Engineering
Web page info: https://jten.yildiz.edu.tr
DOI: 10.18186/thermal.1377257

Review Article

Fossil energy reduction for heating and cooling of buildings using shallow geothermal integrated energy systems – a comprehensive review

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ARTICLE INFO

Article history
Received: 13 March 2022
Accepted: 26 April 2022

Keywords:
Ground Source Heat Pump (GSHP); Shallow Geothermal Energy (SGE); GSHP Simulation; GSHP Feasibility; Refrigerant; Compressor

ABSTRACT

Ground source heat pumps (GSHP) are a very efficient system for space heating and cooling, and it was established in 1904. GSHPs can minimize the environmental effect of buildings by using the ground as a renewable energy source. The ground will act as a heat sink or heat source. The research collection aims at finding the various possible opportunities for the effective integration of shallow geothermal energy (SGE) to decrease the fossil energy in the built environment and to reduce emission associated with it. The direct utilization of SGE using a ground source heat pump (GSHP) has been reviewed in detail for global north and global south countries, with a primary focus on heating application. The punctual information of results of various authors have been extensively summarized. This review discusses the GSHP installation status, SGE availability, GSHP system simulation, feasibilities, and performance. Worldwide more than one million GSHP systems have been installed, and the system is prevalent in Europe, the Americas, and Asia. Most of the systems are installed for heating-dominated buildings in the global north. This paper also contains the research details pertaining to the last two decades about refrigerants and compressors for the development of GSHP. Finally, the feasibility study and the performance of the GSHP unit for different climatic conditions are reviewed and it is found that the technique is more feasible for cold and dry climatic conditions. This paper highlights the recent research findings and a potential gap in the above components for further research and development.

Cite this article as: Kumar B. Fossil energy reduction for heating and cooling of buildings using shallow geothermal integrated energy systems – a comprehensive review. J Ther Eng 2023;9(5):1386–1417.

INTRODUCTION

Space heating is the major energy end-use sector compared to other appliances and half of the demand in the built environment occurs due to space heating systems [1]. The growth of heating appliances leads to severe environmental and energy security challenges. The energy, economic and environmental analysis of different heating systems such as solar/biomass boiler, biomass boiler, coal-fired boiler, Air Source Heat Pump system (ASHP), and solar/electrical

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This paper was recommended for publication in revised form by Regional Editor Omid Mahian

Published by Yıldız Technical University Press, İstanbul, Turkey

heating have been done. The biomass-based system achieves the best in the result with first and second position, while the coal-fired and electrical heating systems are the worst rural houses space heating [2]. The primary energy consumption for heating the building area of 4852.26 m^2 has been analyzed using different heating techniques such as ASHP, WGH, DEH, RCH, LCH, and CHP [3]. The initial investment cost, Primary Energy Consumption (PEC), and CO_2 emission of the above heating systems are shown in Table 1, From Table 1, it is concluded that the ASHP system has excellent potential for heating application compared to RCH, LCH, and DEH systems. However, the CO_2 emissions from WGH and CHP are lower than ASHP because it is powered by natural gas. Intrinsic challenges for transitioning from carbon-based heating to electrically-based heating include efficient electrically-based systems such as air or ground source heat pumps (GSHP) is the need of the hour.

Geothermal energy is one of the easily accessible and 24x7 available renewable energy sources, and it can be used for space heating and cooling application in the built environment [4]. The integrated ASHP system with SGE is called a GSHP, which consumes very little energy because of the stable ground temperature [5]. GSHP system can be classified as a surface water heat pump (SWHP) and Ground Heat Exchanger (GHE) heat pump based on the geothermal energy utilization. The pool, river, channel, and lagoon water act as a heat sink in the SWHP technique [6]. The dynamic growth of fouling characteristics due to the surface water in the heat exchanger is a significant drawback of the system [7]. Techno-economic analysis reveals that the GHE heat pump system has good effectiveness related to the SWHP because of a more stable temperature in the ground [8]. The ground temperature is higher than the atmospheric temperature during winter and vice versa in summer. The SGE can be used for the energy-efficient operation of the ASHP, and thereby the fossil energy in the built environment can be reduced [9]. A survey conducted in Greece mainly focuses to understand the knowledge about the GSHP system. The authors have concluded that the following four factors are the reasons for the market barrier, a) installation cost b) insufficient subsidies c) lack of awareness on the technology and its advantage d) economic recession [10]. The investment advantage of GSHP is forecasted from 2019 to 2040 considering both investment and operational benefits [11]. The authors suggest various policies timeline including carbon trading mechanism (CTM), subsidy, and preferential taxation for the development of SGE.

The experimental result shows that the GSHP system has better COP and seasonal performance factors (SPF) compared to a conventional ASHP [12–14]. The average SPF for GSHP and ASHP is 2.39 and 1.83, respectively, and it is estimated from the sample size of 49 for GSHP and 22 for ASHP systems [15]. Similarly, a comparative analysis has been done for ten different states in India, and the result shows that for heating and cooling applications, GSHP saves 13 to 48% power compared to ASHP [16]. The performance and financial details of the conventional heating system, such as electric resistance, gas-fired, oil, and liquid fired, are compared with GSHP. They inferred that the GSHP system is highly beneficial compared to the above conventional system in terms of energy and economics [17]. The unit energy cost of GSHP is relatively meager compared to the other conventional systems (Figure 1) [18]. Further, the performance enhancement of the GSHP by integrating solar thermal [19,20], natural gas-fired water heater [21] system plays a vital role in diminishing the peak demand, PEC and emission in the built environment.

A study conducted to replace natural gas heating with GSHP heating in European Union, concluded that in 2050, 60% of the PEC and 90% of the CO_2 emission could be saved [22]. According to another study, the GSHP system saves PEC by 43% for heating and 37 % for cooling, in European cities [23]. Similarly, a comparative analysis between ASHP and GSHP system has been experimentally investigated in Greece and the results confirmed that the GSHP system saves 25.7% of PEC compared to ASHP. Also, it reduces NOx and CO_2 pollution by 99.6% and 22.7%, respectively. On the other hand, it increases the SO_2 emission by 18.4% [24]. A feasibility study of the GSHP system has been carried out in Sweden to replace conventional district heating to save energy and the environment [25]. Due to space constrain for boreholes and market entry barriers, it is quite hard to retrofit in urban areas. Whereas it is a good competitor when there is a space.

Table 1. Energy consumption, CO_2 emission and total investment cost for the various heating system [3].

Type of system	PEC (kilogram of coal equivalent/m²)	CO_2 emission ($kgCO_2$ /m²)	Initial investment (USD/ m²)	Heating cost (USD/m²)
Air Source Heat Pump (ASHP)	7.4	18.3	41.91	2.07
Wall hanging gas boiler (WGH)	8.1	11.7	11.18	2.07
Direct electric heating (DEH)	22.9	57	8.38	5.12
Regional coal-fired boiler (RCH)	14.1	35	15.37	2.87
Large coal-fired heating (LCH)	12.1	30.1	18.16	2.87
Local fired cogeneration (CHP)	5.9	14.8	36.32	3.47

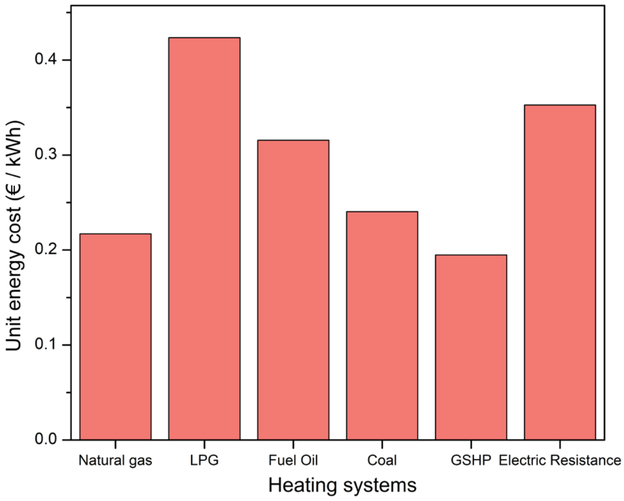


Figure 1. Energy consumption costs for the different heating system [18].

Table 2 shows a different heating system (OB, GB, LTGB, DEH, GSHP, and HGSHP) energy efficiency and CO_2 emission [26]. Heating efficiency for heat pumps is indicated by the heating season performance factor (HSPF). The HSPF tells the ratio of the seasonal heating output divided by the seasonal power consumption in Watt-hours. From Table 2, it is concluded that the GSHP and HSHP have higher primary energy efficiency and lower CO_2 emission. GSHP system avoids 45%, 33%, and 15% to 77% of CO_2 emissions compared with OB, GB, and fossil fuel heating, respectively [27,28]. A building with an average heating demand of 0.55 kWh has been analyzed to replace the GB and OB using GSHP for ten years and the CO_2 saving achieved 36.34 tons and 51.9 tons, respectively [29,30].

The CO_2 saving potential of 0.88 million installed units for heating applications with an average size of 12 kW in European countries has been analyzed and found that 3.7 million tons of CO_2 emission are protected per year using the GSHP system [31]. In another study, an 11 kW GSHP system for the heating application installed in Germany could save 1800 kg of CO_2 per year [27]. The CO_2 savings potential of the GSHP unit has been calculated for ten states in India, and the annual CO_2 savings varied from 1248 to 14281 million kg [16,32]. The yearly CO_2 savings ranged from 24 to 54 % compared to ASHP. The above studies reveal that the practice of GSHP reduces the PEC and CO_2 emission related to the ASHP, oil-fired, and gas-fired systems, and this system can be used for the space heating and cooling application in the built environment. The review aims at finding the various possible opportunities for the effective integration of shallow geothermal energy (SGE) to decrease the fossil energy in the built environment and to reduce emission associated with it. This is the first review addresses the development of ground source heat pumps (GSHP) in the global north and global south countries. Also, the punctual information of the results of various authors has been extensively summarized.

Literature Details

The data collected from Engineering Village shows that GSHP research has a total of 5913 documents as of 26 June 2020 as shown in Figure 2. The share of journal articles, conference articles, conference proceedings, and book chapters are 70, 26.5, 1.2, and 1.16, respectively. China and the USA have published more research articles with a contribution of 38% and 10.3%, respectively, as shown in Figure 3. The number of research articles published has significantly increased in recent years, as shown in Figure 4. This comprehensive review highlights more than 230 research articles that have been published in the last two decades to reduce the energy demand in the built environment.

GSHP Background and Installation Status

The GSHP system was introduced in 1904 in Italy, and in recent years, it is gaining attention due to its energy and environmental benefits. The direct utilization of SGE has been extensively reported based on the documents available in the World Geothermal Congress (WGC) [33,34]. Direct utilization includes various applications such as space heating and cooling, greenhouse heating, agricultural drying ([35,36]), etc. At the global level, the total installed capacity as of 2014 was 70885 MWt, and the average annual growth rate is 7.9% since 2010. In which, the GSHP system capacity alone contributes to 50,258 MWt. The annual installation of GSHP systems has been varying from 5 to 20% based on the incentives and government policies [37]. Worldwide more than one million GSHP systems have been installed,

Table 2. Comparison of efficiency and emissions of different heating systems [26]

Type of system	Primary energy efficiency (%)	CO_2 emission (kgCO_2/kWh heat)
Oil-fired boiler (OB)	60-65	0.45-0.48
Gas-fired boiler (GB)	70-80	0.26-0.31
Low temperature system + gas boiler (LTGB)	100	0.21
Direct electrical heating (DEH)	36	0.9
Conventional electricity + GSHP (GSHP)	120-160	0.20-0.27
Green electricity + GSHP (HGSHP)	300-400	0

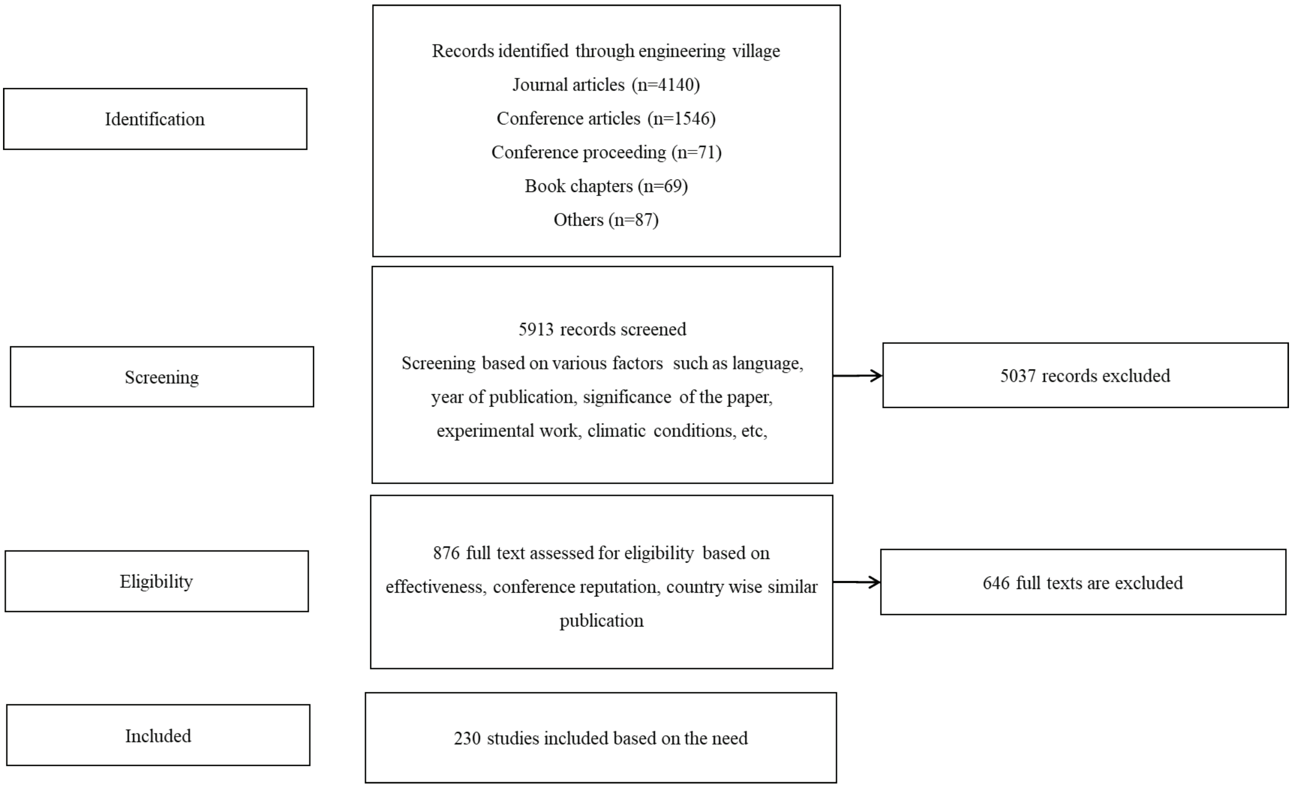


Figure 2. Preferred Reporting Items for Systematic Review (PRISMA).

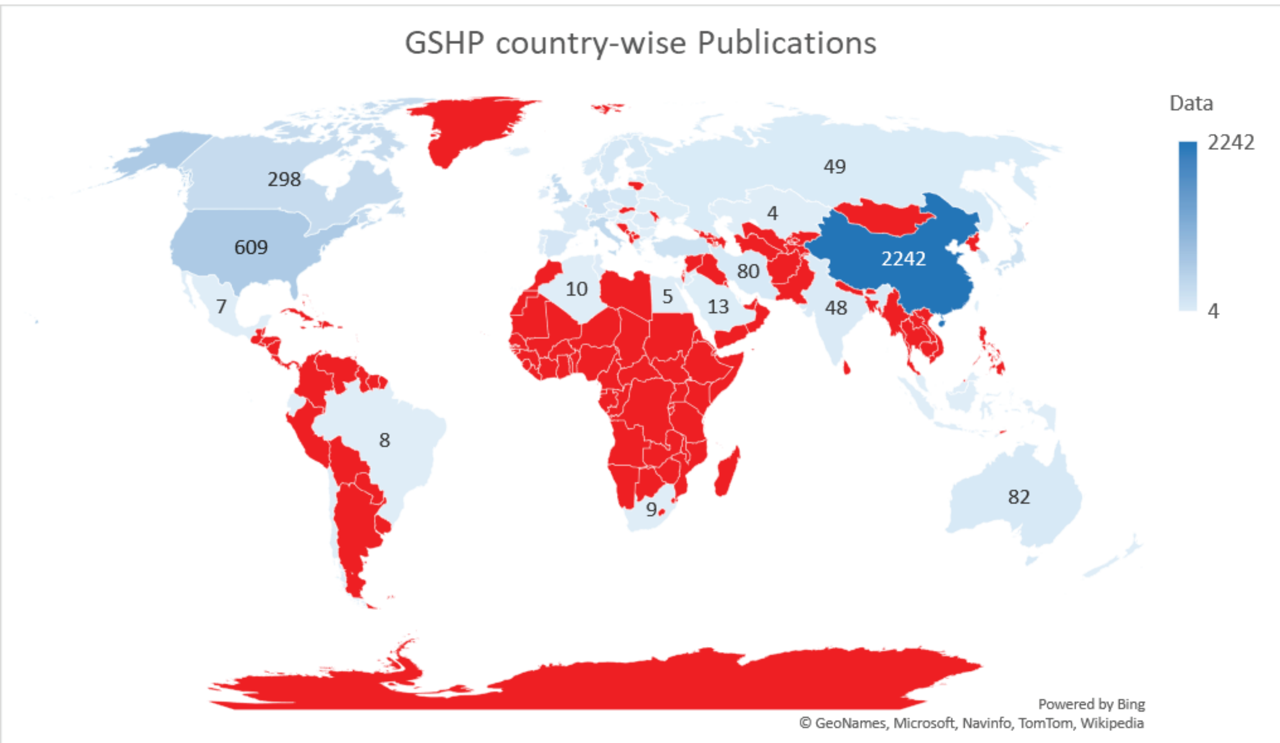


Figure 3. Country-wise number of publication.

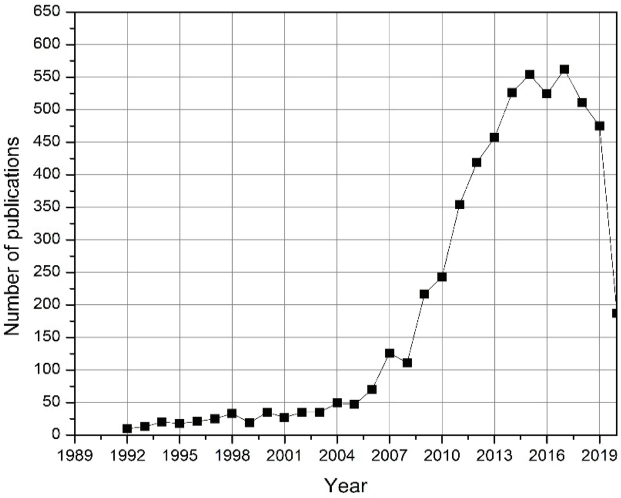


Figure 4. Year-wise publication list.

and the system is prevalent in Europe, the Americas, and Asia (Table 3) [38,39]. The comprehensive data of research articles country-wise has been presented in Table 4.

The percentage of installed systems (direct utilization) in the top five countries such as China, the USA, Sweden, Turkey, and Germany are 25.2, 24.5, 7.9, 4.14, and 4.0%, respectively, and it accounts for 65.8% of the world installed capacity (Figure 5). In the Americas, outstanding work is done in North America, especially in the USA and Canada. The USA and Canada contribute 88.8% and 7.4% in the total installed capacity in the sixteen countries of the Americas. In the USA, 90% of the installed systems are closed-loop systems. In which vertical loop and horizontal closed-loop account for 30% and 70%, respectively, for residential application. In USA, the installed power of heat sources is 7385 MWt from 2006, and it is anticipated to produce heat higher than 1,000,000 MWt by 2050 from

Table 3. Worldwide installed capacity and capacity factor data for direct use application [33]

Region	No. of Countries	MWthermal	Capacity factor
Africa	8	140	0.575
Americas	16	19160	0.162
Asia	18	25369	0.325
Europe	32	24863	0.273
Commonwealth of Independent States	5	399	0.564
Oceania	3	504	0.555
Total	82	70885	0.265

Table 4. GSHP system details

S. No	Technique	Location	Capacity/ Area	Method	Citation	Application	Refri.	Borehole					COP/ SPF
								Type	No.	Length	Material	Fluid	
1	GSHP	USA	HW - 5.5 kW, SH - 7.56 kW	Experiment	[79]	Space and water heating	R410A	U-tube VGHE	2	94.5 m	HDPE	PG + water (20%)	COP = 3.57
2	GSHP	USA	11.7 kW	Experiment	[80]	Heating and cooling	-	U-tube VGHE	6	49 m	HDPE	EG + water (1 0%)	COP = 3 to 4
3	GSHP	USA	H - 225 kW, C - 392 kW	eQUEST 3.7	[81]	Heating and cooling	-	U-tube VGHE	72	76 m	HDPE	Water	-
4	GSHP	USA	H – 98 kW, C - 3456 kW	GLHEPRO and GLD	[82]	Heating and cooling	-	U-tube VGHE	36	25 m	-	Water	-
5	GSHP	USA	A - 228 m^2	Simulation	[83]	Heating and cooling	R410A	-	-	-	-	-	-
6	GSHP	USA	5.3 kW	Experiment	[79]	Water heating	R410A	U-tube VGHE	1	94.5 m	HDPE	PG + water (20%)	
7	GSHP	USA	7.56 kW, A - 253 m^2	Experiment	[84]	Heating	R410A	U-tube VGHE	1	94.5 m	HDPE	PG + water (20%)	COPh = 3.75 to 3.49 COPc = 5.16 to 3.72

Table 4. GSHP system details

S. No	Technique	Location	Capacity/ Area	Method	Citation	Application	Refri.	Borehole					COP/ SPF
								Type	No.	Length	Material	Fluid	
8	GSHP/ DX-GSHP/ Hybrid	USA	-	Data collection	[85]	Heating and cooling	CO_2						COPc = 5.91 COPh = 3.23
							NH_3						COPc = 9.07 COPh = 4.71
							Water						COPc = 8.75 COPh = 5.93
							Propane						COPc = 8.9 COPh = 4.6
							Isobutane						COPc = 9.2 COPh = 4.72
9	GSHP	USA Miami chicago	H - 24.9 kW, C - 38.2 kW	DOE - 2.1E (EnergyPro)	[86]	Heating and cooling	R410A	Double U-tube VGHE	-	-	-	-	COPh = 4.2 COPc = 5.9
			H - 35.8 kW, C - 54.7 kW										COPh = 4.2 COPc = 5.9
10	GSHP	USA	A = 2350 m^2	Experiment	[87]	Heating and cooling	-					Water	COPc = 5.31
11	GSHP	Chicago	A - 465 m^2	Energyplus	[88]	Heating and cooling	-	U-tube VGHE	13	76 m	K = 0.39 W/m K	Water	COPh = 3.55 COPc = 3.29
		Baltimore											
		Atlanta											
12	GSHP	USA	A - 120 m^2	TRNSYS	[89]	Heating and cooling	-	U-tube VGHE	-	-	PE	Water	COP = 2.28
13	GSHP	USA	A - 1161 m^2	eQUEST / DOE - 2.2	[90]	Heating and cooling	-	U-tube VGHE	-	76 m	-	Water	-
14	GSHP	USA	-	Monte Carlo simulation	[91]	Heating and cooling	-	U-tube VGHE	14	300 feet	-	-	-
15	GSHP	USA	-	Simulation	[92]	Heating and cooling	-	U-tube VGHE	32	-	-	Water	COP = 2.8
16	GSHP	Canada	100 kW	Engineering Equation Solver	[93]	Heating	R134a	U-tube VGHE	-	100 m	PE	PG + water (30%)	COP = 6.2 COPs = 4.8
17	GSHP	Canada	A - 8500 m^2	Simulation	[94]	Heating and cooling	-	U-tube VGHE	15	3317 m	-	Water	COP = 3.1
18	GSHP	Canada	H - 11.06 kW, C - 9.82 kW	TRNSYS	[5]	Heating and cooling	R-22	HGHE	-	-	-	Water	COPh = 3.05-3.44 COPc = 4.9-5.6
19	GSHP	Chile	H - 2.7 kW, A - 50-71 m^2	Simulation	[95]	Heating	-	U-tube VGHE	1	68 m	-	Water	-
20	GSHP	Chile	28-47 kW	Multiple Regression modeling	[96]	Heating and cooling	R410A and R134a	-	-	-	-	PG + water (15%)	COP = 5.5-8.5
21	GSHP	Spain	Condenser 22 kW, A - 115.9 m^2	Experiment	[97]	Space, water and pool heating	R410A	Double U-tube VGHE	1	150 m	PE	PG – water (30%)	
22	GSHP	Spain	H - 18 kW, C – 14 kW	IMST-ART	[98]	Heating and cooling	R290	U-tube VGHE	6	50 m	PE	Water	SPF = 5.24 SPFs = 2.47
23	GSHP	Spain	H – 19.2 kW, C – 17.2 kW	Experiment	[99,100]	Heating and cooling	R410A	U-tube VGHE	6	50 m	PE	Water	SPF = 4 (33% ↑)
24	GSHP	Spain	3 kW	Experiment	[101]	Heating	-	Double U-tube VGHE	2	20 and 40 m	PE	Water	COP = 4.02 to 4.27
25	GSHP	Spain	H-18 kW, C-14 kW	GLHEPRO software	[102]	Heating and cooling	-	U-tube VGHE	6	50 m	PE	Water	-
26	GSHP	Spain	A - 250 m^2.	GLHEPRO software	[103]	Heating and cooling	-	U-tube VGHE	8	50 m	-	Water	-

Table 4. GSHP system details

S. No	Technique	Location	Capacity/ Area	Method	Citation	Application	Refri.	Borehole					COP/ SPF
								Type	No.	Length	Material	Fluid	
27	GSHP	Spain	A - 250 m^2	Experiment	[23]	Heating and cooling	R290	-	6	50 m	-	Water	-
28	GSHP	Poland	7.53 kW, A - 156 m^2	Experiment	[104]	Space and water heating	R407C	Double U-tube VGHE	3	62 m	PE	EG + water (20%)	
29	GSHP	Turkey	3.1 kW A - 16.24 m^2	Experiment	[17,105]	Heating	R22	HGHE	2		PE	Antifreeze - water	COP = 2.81
30	GSHP	Turkey	5.7 kW	Experiment	[106]	Heating	R134a	Double U-tube VGHE	1	53 m	PE	Antifreeze - water	COPs = 2.07 to 3.04
31	GSHP	Turkey	8 kW	Experiment	[107] [108]	Heating	R134a	U-tube VGHE	2	53 m	-	Antifreeze - water	COPs = 3.1
32	GSHP	Turkey	-	Experiment	[18]	Heating	R134a	HGHE	4	0.18 m depth	PE	Antifreeze - water	COPs = 2.52 COPh = 4.15
33	GSHP	Turkey	A - 46 m^2	Exergo en-vironmental analysis	[109]	Heating and cooling	R410A	U-tube VGHE	-	60 m	PE	Water	-
34	GSHP	Turkey	A - 596 m^2	Experiment	[110]	Heating and cooling	R-22	U-tube VGHE	-	50 m	PE	Water	COP = 5
35	GSHP	Turkey		Experiment and COMSOL	[111] [112]	Heating and cooling	-	U-tube VGHE			HDPE	Water	
36	GSHP	Turkey	101 kW	Simulation	[113]	Heating	R116, R218 and RC318	-	-	-	-	-	
37	GSHP	Germany	50 to 80 kW	Experiment	[114]	Heating and cooling	-	U-tube VGHE	18	80 m	-	Water	COPh = 3.9 EERc = 8.0
38	GSHP	Germany	82 kW	Mixed-integer nonlinear programming	[115]	Heating	-	U-tube VGHE	16	150 m	PE	PG + water (25%)	COP = 7.04
39	GSHP	Germany	-	Analytical model	[27]	Heating	-	-	-	100 and 200 m	-	-	COP = 4
40	GSHP	Germany	-	FEFLOW	[38]	Heating	-	-	-	57 m	-	Water	-
41	GSHP	Cyprus	-	FlexPDE	[116]	Heating and cooling	-	U-tube VGHE	-	100 m	HDPE	Water	-
42	GSHP	Cyprus	A - 190 m^2.	FLEXPDE	[117]	Heating and cooling	-	HGHE	-	180 m	-	Water	-
43	GSHP	UK	6 kW and 10 kW	MATLAB	[118]	Space and water heating	-	U-tube VGHE	2	90 m	-	Water	
44	GSHP	UK	H – 16 kW	Experiment and EPS-r	[119]	Heating	-	HGHE (linear)	3 loops	300 m	HDPE	Water	SPF = 2.9
45	GSHP	UK	A - 7100 m^2	TRNSYS	[120]	Heating and cooling	-	U-tube VGHE	63	65 m	-	Water	-
46	GSHP	UK	-	Simulation	[121]	Heating and cooling	-	HGHE	-	1 m depth	-	Water	COP =2.5
47	GSHP	Italy	41 kW	Experiment	[122]	Heating and cooling	R410A	U-tube VGHE	18	40 m	PE	Water	COP = 5.75 COPh = 4.16 COPc = 4.38
48	GSHP	Italy	A - 152 m^2	Experiment	[123]	Heating and cooling	-	U-tube VGHE	2	80 m	-	Water	SCOP = 30% ↑
								Double U-tube VGHE	2				
49	GSHP	Italy	A - 200 m^2	Simulation	[124]	Heating and cooling	-	-	-	-	-	Water	COP = 12.24
50	GSHP	Italy	-	Thermo-dynamic analysis	[125]	Heating and cooling	-	HGHE	-	(0.91–1.83 m depth)	HDPE	Water	COP = 3-3.8
								U-tube VGHE		(30.5–120 m)			

Table 4. GSHP system details

S. No	Technique	Location	Capacity/ Area	Method	Citation	Application	Refri.	Borehole					COP/ SPF
								Type	No.	Length	Material	Fluid	
51	GSHP	Italy	A - 20 m^2	Experiment	[6]	Heating and cooling	R113a	Open-loop	-	-	-	Water	COP = 2.69
52	GSHP	Italy	A - 1840 m^2	Experiment	[13]	Heating and cooling	R410A	Double U-tube VGHE		40 m	PE	Water	COP = 4.27
53	GSHP	Sweden	-	Experiment	[126]	Heating	R407C	-	-	-	-	-	COP = 2.7 to 5.5 SPF = 2.5 to 3.2
54	GSHP	Sweden, Turkey, Qatar	A - 144 m^2	Meteonorm, EED	[127]	Heating and cooling	R134a	U-tube VGHE	-	120 m	-	Water	COPh = 3.1 COPc = 5.8
													COPh = 3.7 COPc = 4.7
													COPh = 6.2 COPc = 2.4
55	GSHP	Sweden	-	Simulation	[128]	Heating and cooling	-	U-tube VGHE	-	150 m	-	Water	COPh = 3-11.5 COPc = 4-11.5
56	GSHP	Sweden	65 kW	Simulation	[129]	Heating and cooling	R410A	-	-	-	-	Water	COP = 1-4.5
57	GSHP	Greece	A - 1350 m^2	Simulation	[219]	Heating and cooling	R22	U-tube VGHE	-	80 m	PE-MD	Water	COP = 4
58	GSHP	France	A - 100 m^2	Experiment and stimulation	[131]	Heating and cooling	-	Double U-tube VGHE	6	20 m	-	Water	-
59	GSHP	Finland	A - 3098.5 m^2	Simulation	[217]	-	-	-	-	-	-	-	-
60	GSHP	Italy and Germany	H – 7.6 kW, C – 8.7 kW	GeoHP-Calc	[133]	Heating and cooling	R410A	Helical VGHE	6	12 m	HDPE	EG + water (30%)	SCOPh = 5.5 SCOPc = 6.4
61	GSHP	Hong Kong	H - 13.10 kW, C - 13.24 kW	TRNSYS	[134]	Heating and cooling	R134a	Double U-tube VGHE	4	285 m	-	Water	COPh = 5.07 COPc = 4.45
		Kunming	H - 8.95 kW C - 8.71 kW							155 m			COPh = 5.80 COPc = 4.37
		Bejing	H - 12.17 kW, C - 14.26 kW							190 m			COPh = 5.44 COPc = 4.56
62	GSHP	Japan	H - 640 kW C – 648 kW	FEFLOW	[135]	Heating and cooling	-	U-tube VGHE	78	85 m	-	Water	COPs = 3.0
63	GSHP	Japan	10 kW	FEFLOW	[136]	Heating and cooling	-	Double U-tube VGHE	2	59 m	-	EG + water (20%) and PG + water (25%)	COP = 5.04 COPs = 3.97
64	GSHP	Tokyo, Japan	A - 4211250 m^2	Analytical model	[222]	Regional-scale heating and cooling system	-	U-tube VGHE	43200	234 m	PE	Water	COPh = 4.88 COPc = 4.84
65	GSHP	Japan	A - 130 m^2	Experiment	[228]	Heating and cooling	-	U-tube VGHE	-	100 m	HDPE	Water	COP = 4.6
66	GSHP	Japan		MS Visual Basic 6.0	[228]	Space heating and cooling	-	U-tube VGHE			HDPE	Water	

Table 4. GSHP system details

S. No	Technique	Location	Capacity/ Area	Method	Citation	Application	Refri.	Borehole					COP/ SPF
								Type	No.	Length	Material	Fluid	
67	GSHP	Tunisia	12.7 kW	Experiment	[139]	Heating and cooling	R410A	HGHE	-	100 m (1 m depth)	HDPE	Water	COP = 4.25 COPs = 2.88
68	GSHP	Tunisia	C – 12.7 kW	Experiment	[140]	Cooling	-	HGHE (linear)	4	100 (1 m depth)	HDPE	Water	COP = 4.46 COPs = 3.02
69	GSHP	Republic of Korea	100 kW	Experiment	[14]	Cooling	R410A	U-tube VGHE	25	175 m	PE	Water	COPs = 5.9 COPc = 8.3
70	GSHP	Republic of Korea	70 kW A - 500 m^2	GLHEPRO software	[141]	Heating and cooling	R410A	U-tube VGHE	5	150 m	HDPE	Water	COP = 6.9
								Double U-tube VGHE	3	150 m	HDPE	Water	COP = 7.6
71	GSHP	Republic of Korea	H - 251 kW, C – 486.4 kW	GLD	[142]	Heating and cooling	-	U-tube VGHE	-	Optimi-zation of length	SRD11	Water	COPh = 3.9 COPc = 5.38
72	GSHP	Republic of Korea	C – 5919 kW, H – 5633 kW	Simulation – GLD	[143]	Heating and cooling	-	U-tube VGHE	-	150 m	HDPE	Water + Ethanol 13.6%	-
73	GSHP	Republic of Korea	3 different building	GLHEPRO	[144]	Heating and cooling	-	U-tube VGHE	5 to 54	154 – 199 m	-	Water	COPh = 3.93 COPc = 4.53
74	GSHP	Republic of Korea	31 kW	Experiment	[145]	Heating and cooling	R410A	-	-	-	-	Water	
75	GSHP	Republic of Korea	-	LSM	[146]	Heating and cooling	-	U-tube VGHE	1	160 m	-	Water	-
76	GSHP	Republic of Korea	4 to 7 kW	Analytical model	[147]	Heating and cooling	R744	U-tube VGHE	-	-	-	Water	
77	GSHP	Iran	36 kW	Genetic Algorithm modeling	[148]	Heating and cooling	-	U-tube VGHE	-	-	-	-	-
78	GSHP	Iran	A - 120 m^2	Experiment	[199]	Heating	-	U-tube VGHE	-	1.2 m depth	PE	EG + water	COP=3.5
79	GSHP	China	1000 kW	DeST and Experiment	[150]	Heating and cooling	R134a	U-tube VGHE	280	80 m	PE	Water	COPh = 5.2 COPc = 5.4
80	GSHP	China	470 kW	Experiment	[235]	Heating and cooling	-	U-tube VGHE	201	150 m	HDPE	Water	COP = 5.0 COPs = 3.0
81	GSHP	China	H - 284 kW C - 272 kW HW - 140 kW A - 2923.2 m^2	TRNSYS	[152]	Heating, cooling and hot water	-	U-tube VGHE	104	100 m	-	Water	COPh = 3.8 COPc = 3.7
82	GSHP	China	15.6 kW	Experiment	[214]	Cooling	-	U-tube VGHE	6	100 m	PE	Water	COP = 2.1 to 4
83	GSHP	China	H – 700 kW	Experiment	[236]	Heating	-	U-tube VGHE	280	80 m	-	Water	COP = 5.2
84	GSHP	China	C – 7200 kW H – 2400 kW	FEFLOW (Version 6.0) and Experiment	[209]	Cooling and Heating	-	Double U-tube VGHE	596	80 m	-	EG + water	COP = 4.0
85	GSHP	China	H – 5416 C – 7730	Experiment	[156]	Heating and cooling	R134a	U-tube VGHE	650	80 m	HDPE	Water	COP = 3.3 to 5.9 EER = 1.9 to 4.3
			H – 8845 C – 10649						1323	80 m			
			H – 1657 C – 2002						520	55 m			
			H – 5919 C – 8193						1051	60 m			
			H – 2587 C – 3593						906	62 m			
86	GSHP	China	H – 610 kW C – 594 kW	Experiment	[223]	Heating and cooling	R134a	U-tube VGHE	280	80 m	PE	Water	COP = 5.4 COPs = 3.0

Table 4. GSHP system details

S. No	Technique	Location	Capacity/ Area	Method	Citation	Application	Refri.	Borehole					COP/ SPF
								Type	No.	Length	Material	Fluid	
87	GSHP	China	2 kW	Experiment	[158]	Water heating	-	-	-	-	-	Water	COP = 3.5 to 9.2
88	GSHP	China	A - 6400 m^2	TRNSYS	[159]	Heating and cooling	-	-	-	-	-	Water	COP = 2.28
89	GSHP	China	A - 11200 m^2	TRNSYS	[237]	Heating and cooling	-	U-tube VGHE	-	60 m	-	Water	COP = 3.78
90	GSHP	China	H - 618 kW C - 403 kW	Data-driven model	[161]	Heating and cooling	-	Double U-tube VGHE	140	50 m	-	Water	COP = 1.97
91	GSHP	China	-	ANSYS FLUENT	[212]	Heating	-	U-tube VGHE	-	100 m	PE	Water	-
92	GSHP	China	A - 8000 m^2	Experiment	[213]	Heating and cooling	R134a	U-tube VGHE	280	80 m	PE	Water	COP = 3.87
93	GSHP	China	A - 800~1500 m^2	Simulation	[226]	Heating and cooling	-	U-tube VGHE	-	-	-	Water	COP = 3.6
94	GSHP	China	-	Simulation	[11]	Heating and cooling	-	-	-	-	-	Water	COP = 5.4
95	GSHP	India	A - 120 m^2	RETScreen method	[165]	Heating and cooling	-	U-tube VGHE	-	-	-	Water	COPh = 4.4 COPc = 3.6
96	GSHP	India	H - 7 kW	Taguchi method	[210]	Heating and cooling	-	U-tube VGHE	-	-	HDPE	Water	COP = 2.19-3.75
97	GSHP	Australia	C – 32.8 kW H – 40.8 kW	Experiment	[205]	Heating and cooling	-	U-tube VGHE	3	91 m	HDPE	Water	COP = 4.98 COPs = 3.41
								HGHE (linear)	12	125 m	HDPE	Water	
98	GSHP	Australia	40 kW	Simulation	[168]	Heating and cooling	-	Coaxial tube VGHE	-	800 m	PE	Water	COP = 3
99	GSHP	Australia	H - 30.6 kW C - 37.2 kW	Simulation	[224]	Heating and cooling	-	-	-	60 m	-	-	COP = 4.3
100	GSHP	Sweden, Doha and Turkey	A - 144 m^2	EED	[170]	Heating and cooling	R134a	U-tube VGHE	-	180 m	-	-	-
101	GSHP	China, USA and India	594 kW	Analytical model, TRNSYS 17.1 and METEOTEST	[171]	Heating and cooling	R744	U-tube VGHE		60 to 200 m	-	Water	

GSHP systems [40]. 4.19 million GSHP systems have been mounted in the USA and western European homes as in 2012 [33]. In the European Union, including the UK, more than 0.6 million units of GSHP systems have been installed only in Sweden, Germany, and France [39,41]. Around 50000 GSHP systems have been installed in Sweden in which 10000 are open-loop, and the remaining systems are closed-loop systems. The horizontal GSHP systems are widespread in Germany, and the average capacity of the system varies from 10 kW to 14 kW for residential applications. It has been estimated that around 163000 GSHP units are installed in France. From the above review, it is concluded that most of the systems are installed for heating-dominated buildings in the global north. In the global south, other than China, the utilization of GSHP for the cooling-dominated building is minimal.

Asia contributes less than 5% in the global GSHP market even though it has a huge contribution in direct utilization, and the leading Asian countries are China, Turkey, Japan, and South Korea [42,43]. In China, more than 2537 GSHP systems have been installed as in 2005, and the GSHP market started in 1997 with two systems [44,45]. The average growth rate of the installed system has been reported as 46% between 2000 to 2013 [46]. Shenyang and Beijing provinces contribute 22.4% and 15.1%, respectively. The utilization of geothermal energy in Turkey for power generation, heating, and cooling application has increased, and Turkey is one of the top five nations based on GSHP installed units

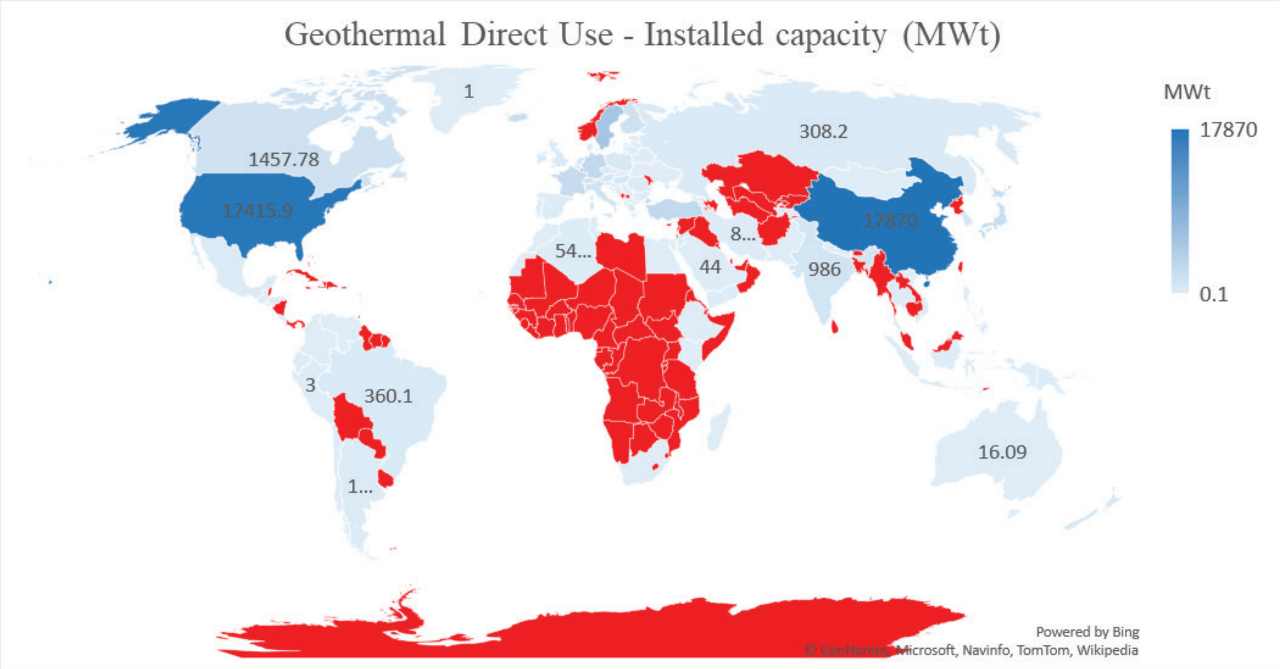


Figure 5. Installed status of GSHP system for direct use application [33].

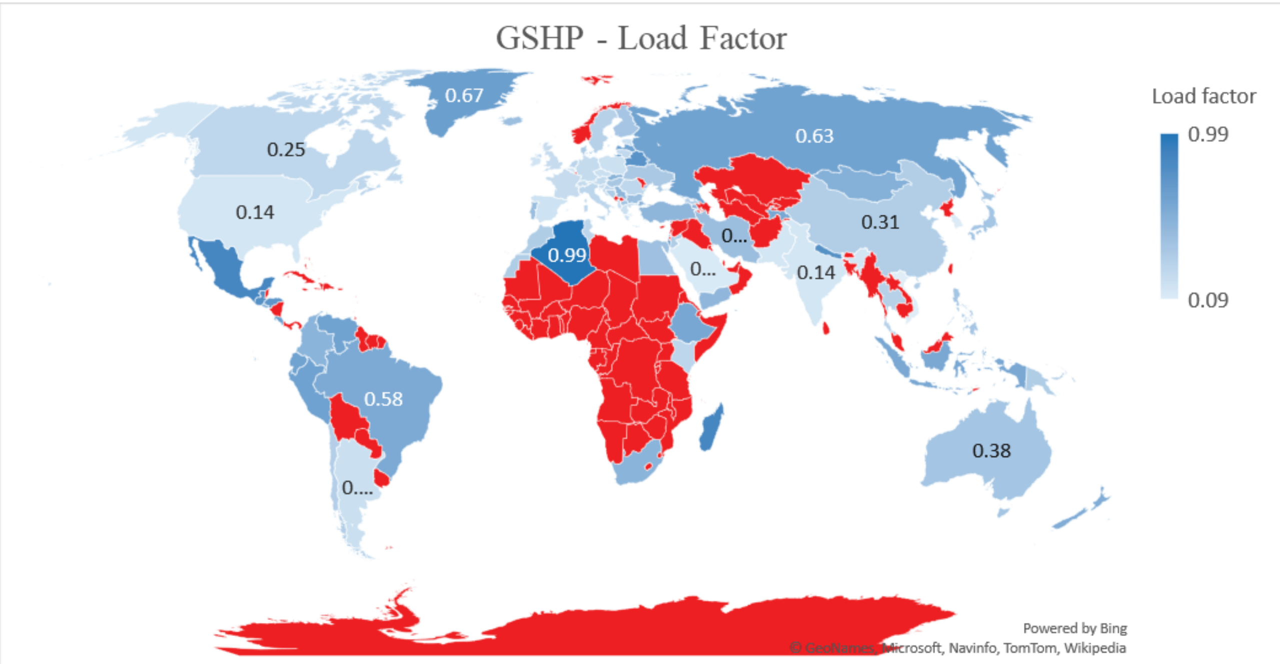


Figure 6. Load factor for GSHP system [33].

[47,48]. The cumulative installed capacity reached 99.92 MW in 2015, in which closed systems and energy pile systems have a contribution of 64.3% and 1%, respectively. In Japan, most of the systems have been installed at Hokkaido, and the contribution of open-loop and closed-loop systems are 15% and 84%, respectively. In South Korea, two GSHP systems have been installed in 2000, and it crossed 550 installations in 2008 [49]. The total installed unit crossed 7000 in 2014, of which vertical, horizontal, and open-loop contribute 75%, 9%, and 16%, respectively.

The average load factor of the globally installed system is 0.265, as shown in Table 3, which means only 2321 hours, the system capacity is fully utilized in the year-round operation. In the southern part of the USA, most of the units are calculated for peak load, and it increases the capacity for the heating (Figure 6). Hence, the system becomes oversized with a capacity factor of 0.23. In Europe, including the UK, the GSHP system has been sized for the building baseload, and the peak demand has been met using fossil fuel. Hence the system capacity factor would be 0.68. The technical guidelines for the installation of the GSHP system in the top six European unions, including the UK, are presented [50]. These guidelines provide the details of system design and operation, and maintenance by considering the environmental factors.

Shallow Geothermal Energy Availability

The SGE potential and their assessment techniques have been reviewed in major cities around the world. The extensive geothermal availability mapping has been carried out in the global north for heating application. The review is based on the demand of the city and availability. From the review, it is found that enormous thermal energy is available at shallow depth, and the heat energy could be integrated at a large scale based on the local-specific factor. However, high installation costs, investors' awareness, and lack of promotion affects effective utilization [51]. This article contains an introduction for conceptually enhancing comprehension in regions with minimal degrees of shallow geothermal energy penetration. It gives direction to project estimation and examines the institutional and social strategies to help SGE systems access [52].

The SGE potential has been carried out for different countries in the Americas (global north) such as the USA [53], South-Central USA [54], Canada [55]. Low-temperature (maximum - 90 °C and minimum - 10 °C) geothermal potential assessment has been carried out in the USA [53]. Similarly, shallow temperature variation due to weather has been predicted using a data-driven approach for three different climates such as dry, warm, and cold [56]. This geological survey gives the details of the total energy available (71 GW for 30 years) in the USA. National Renewable Energy Laboratory studied the geothermal energy system feasibility for the different climatic conditions in the USA [40]. The system feasibility map has been drawn for the direct and indirect application of SGE. It is concluded that all the regions of the US territory are fit for the GSHP system. The temperature distribution has been mapped for various ground depths from 50 m to 250 m in Canada [55]. It has been found that global warming also plays a significant role in the ground surface temperature variation. From the above literature, the Americas has an excellent shallow geothermal energy potential. Hence there is good potential for energy and environmental saving.

The SGE potential mapping has been carried out for different countries in the Europe (global north) such as North-Western Italy [57–59], Southern Italy [60], Spain [61], Switzerland [62], Southern Switzerland [63], Germany [64], South-West Germany [65], Sweden [66], France [67], Poland [68], Croatia [69], Slovenia [70], Finland [71], Belgium [72], Denmark [73], Ireland [74], Cyprus [75], Turkey [76], Serbia [77] and Hungary [78]. The GSHP system potential in Barcelona, Spain, has been investigated with groundwater flow using the GIS technique for both open-loop and closed systems [61]. The authors claimed that the proposed methodology could be used for worldwide prediction. The SGE system potential in Ludwigsburg, Germany, has been investigated for both space and water heating applications [64]. Integrating all the available geothermal energy with existing buildings for space and water heating applications will reduce CO_2 emissions by 29.7% in the city. The optimum borehole length for different locations based on groundwater availability in the city has been mapped. The borehole length is very high in the northeast, whereas the borehole length is shallow nearby the river since drilling is prohibited. The SGE potential in south-western Germany (the Black Forest, the Upper Rhine Valley, and SW-Germany) has been mapped using GIS [65]. The heat extraction potential differs according to the local condition. The maximum heat extraction per borehole is 3.5 kW and 7.5 kW for the depth of 50 m to 100 m, respectively, and the mean specific heat extraction is 50 W/m.

The legislation issues on the effective utilization of SGE at fourteen different countries in Europe have been discussed from the extensive data collection from the national legislation and expert's experience [172,173]. The borehole length is usually kept a maximum of 100 m due to legal guidelines in most of the European countries, and it varies from 100 to 400 m in some of the countries. The high deviation has been noted in the legislation, including guidelines, and institutional support among the European countries. This deviation dramatically affects the development of SGE. By considering the above factors, the SGE management framework has been developed among 13 European counties based on the geological survey [174]. The proposed governance model is approved among the countries to deliver a roadmap for SGE growth, especially on the urban scale, which is independent of local hydrological conditions. The governance model displays a substantial potential to support EU initiatives on decarbonization.

SGE (up to 10 m depth) has been analyzed in Europe, including the UK, based on the climatological, pedological, and topographical data [175]. The thermal conductivity varied from 0.8 to 1.2 W/m K. From the detailed investigation, the maximum potential is found in Iceland, Finland, Norway, and Liechtenstein. The techno-economical potential of a closed-loop SGE system has been analyzed in five different countries in Europe, such as Greece, Ireland, Belgium, Croatia, and Switzerland [176]. The energy savings varied between 10-30% based on the local climatic conditions. Similarly, SGE potential mapping has been carried out in nine European countries, which includes Austria, Belgium, France, Germany, Greece, Hungary, Iceland, Romania, and UK [177]. The climatic condition and soil structures are discussed in detail, and the thermal conductivity and heat capacity are modeled. From the extensive analysis, it can be implied that this approach (national repositories or case studies) could be used for local and landscape scales.

The SGE potential mapping has been carried out for different countries in Asia (global north), Japan (Tsugaru [178], Fukui [179], Tokyo [180]), New Zealand [181], South Korea [146], and Australia [182]. Thermal conductivity has been mapped in the province of Tsugaru, and it varies from 1.5 to 2 W/mK. The value of thermal conductivity increases with increasing groundwater velocity. The heat extraction varies from 50 to 110 W/m in the province of Fukui, and the maximum heat extraction rate is 42 W/m in the province of Tokyo. The ground temperature and specific heat capacity of the soil have been mapped in three different cities of New Zealand, such as Wairakei, Raukura, and Lincoln. Thermal Response Test (TRT) has been carried out to find the thermal properties at 208 locations in South Korea, and the conductivities vary from 1.73 and 8.56 W/m K [143].

The SGE potential mapping has been carried out for different countries in the Americas (global south) such as Chile [95], Argentina [183], and Brazil [184]. The borehole depth required for operating a 2.7 kW system for different locations in the Santiago basin has been mapped based on the ground thermal properties. The urban area required more than 100 m depth. SGE availability and variation in temperature have been found for eight different bio-climatic zones in Brazil. The results are desirable for the development of the GSHP system.

The SGE potential mapping has been carried out for different countries in Asia (global south) such as China [185] (Qingdao [186], Yangtze River Basin [187], Tibet [188]), India (Gujarat [189,190]) and Iran [148]. A review of the SGE potential of 287 cities in China has been carried out [185]. The total shallow geothermal energy available potential reached 77.1 x 10^{12} kWh/yr (~9.486 x 10^{3} million tons of standard coal). The GSHP system potential in Qingdao, China has been analyzed using spatial data, and the system can be installed closer to the sea area since it has higher heat energy and low drilling cost [186]. An extensive review has been carried out to investigate the geothermal resources in the province of Yangtze [187]. The variations in thermal conductivity, borehole thermal resistance, heat transfer rate, and initial ground temperature are highlighted. By considering the local climate, building energy consumption, and geothermal resources, the potential has been ranked for eleven cities. A sub-surface temperature, thermal conductivity, and groundwater flow have been modeled on a regional scale using 3D FEFLOW software [178]. The use of SGE for heating is drastically reduced from 30000 to 5000 m^2 due to corrosion in the province of Tibet (Himalayas). The corrosion and temperature losses are the major issue for the system installation, and it has to be overcome by advanced technology. Also, the groundwater quality must satisfy the standards in order to prevent corrosion and scale formation. However, the available energy is projected as 1 m^2 of soil that can fulfill a heating demand of 4 m^2 of space [188].

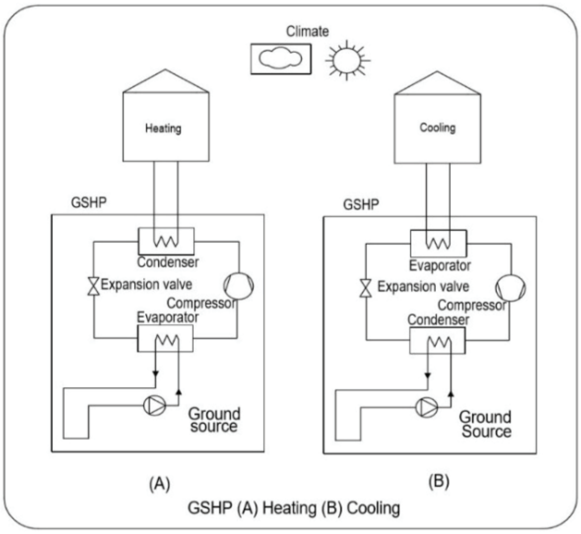
The SGE potential mapping has been carried out in Tunisia [140], Algeria [191] and Africa (global south). The GSHP potential in Tunisia has been studied. The climate has been classified as hot and dry during summer and mild winters in most provinces and the potential mapping shows excellent availability of resources [140]. Algeria is the leading country of the direct use of geothermal energy in Africa with a total amount reaching 54.64 MWt installed thermal power, and also among the first five countries in the world in air conditioning application [191]. Based on the extensive literature search, the direct utilization of geothermal energy is very limited in the global south nations. China has extensively analyzed the shallow geothermal potential. Similarly, it has to be carried out for other global south countries. Further, research and developments are essential for the effective utilization of SGE in African countries.

Ground Source Heat Pump

The GSHP system has five components, namely, compressor, condenser, expansion device, evaporator, and GHE. The arrangements of the above components are shown in Figure 7. In a heating mode, the evaporator is connected with the GHE. The ground temperature is relatively greater than the atmospheric temperature. The liquid refrigerant in the evaporator engages the heat energy from the ground using heat transfer fluid (HTF) available in the GHE, and the phase change takes place from fluid to liquid-vapor. The low-temperature vapor enters the compressor, which is powered by electrical energy, and it raises the pressure and temperature of the refrigerant. The high-temperature vapor refrigerant losses its heat energy to the heat distribution system without any change in pressure inside the condenser, and again phase chase takes place from vapor to liquid. The heat distribution unit is involved in transporting heat energy to the building and water. The pressure and temperature are reduced again using an expansion device. The refrigerant enters the evaporator, and the process is repeated.

In the cooling mode, the condenser will act as an evaporator and vice versa. The condenser unit is coupled with the GHE. The ground temperature is relatively less compared to the atmosphere. The refrigerant drops the heat energy to the ground through HTF circulated in the GHE. The liquid refrigerant from the expansion device absorbs the heat energy from the cool-distributed system in the evaporator, and the phase change occurs from liquid to vapor. The cool-distributed system is used to cool the building and cool the water if needed. The compressor compresses the refrigerant from the evaporator, and it enters the condenser. The cycle is closed and repeated for continuous production.

The GSHP design depends on local climatic conditions. The methodology for calculating COP for ASHP and water-water heat pump is given in ISO 13256-1 and ISO



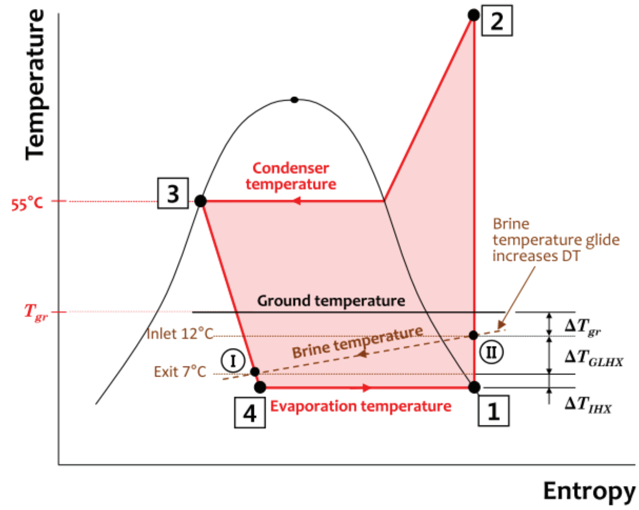


Figure 7. a) Working principle of a GSHP system for both heating and cooling mode b) T-S diagram [192].

13256-2, respectively. Since the system depends on the climatic condition, the term Seasonal Performance Factor (SPF) has been introduced to calculate the performance over the period. SPF is defined as the ratio of cumulative useful energy (heat or cool) to cumulative input (electricity) in the study period. The methodology for calculating SPF for a heat pump is given in ANSI/ASHRAE 116, KS C 9306, and JIS C 9612 standards [193]. However, there is no methodology available for SPF calculation in the GSHP system [194].

The GSHP manufacturing industries prepare a performance data sheet based on the ISO standards. The performance of the system is measured based on a fixed source and sink temperature in a steady flow condition. The performance data-sheet is compared between industry and real-time measurement, and the values significantly vary due to the variations in source and sink temperature [96]. Most importantly, the source and sink temperatures directly vary the refrigerant pressure in the condenser and evaporator. The thermophysical properties of the refrigerant also play a dynamic role in system performance. Usually, the manufacturers select the refrigerant based on the application and cost by considering boiling and condensation temperature and pressure. Thereby, the variation in pressure and volumetric capacity may modify the compression ratio, and this process will affect the compressor performance. Hence, it is crucial to develop a testing methodology by considering the dynamic environmental conditions of the source and sink type of refrigerant. From the above data collection, the GSHP system performance highly depends on the type of compressor, refrigerant, and geothermal energy.

A comparative analysis between the heat pump (variable speed scroll compressor) and GSHP system has been done and found that the GSHP system has higher energy efficiency (9.4 to 24.1%) than the variable speed heat pump

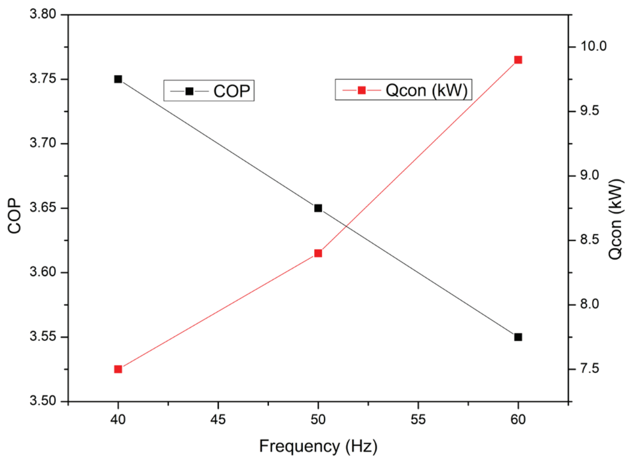


Figure 8. The effect of supply voltage frequency on performance and condenser load at an evaporator temperature of -2.5 °C [104].

[86]. The GSHP and Air Source Variable Refrigerant Flow (ASVRF) systems are highly competitive technologies for both heating and cooling applications. Both systems are compared for three different climatic zones in the USA (Chicago, Baltimore, and Atlanta). It is concluded that the GSHP system reduces the primary energy consumption (PEC) compared to ASVRF, and it also reduces the building peak demand (31% to 40 %) for the studied climatic conditions [88]. A few research studies have been conducted using a variable speed compressor due to its merits [97,104], and variable speed pump [106] in the GSHP system to attain the maximum performance.

Despite being ‘green’ in terms of carbon- pollution, there is a need to move towards low GWP working fluids

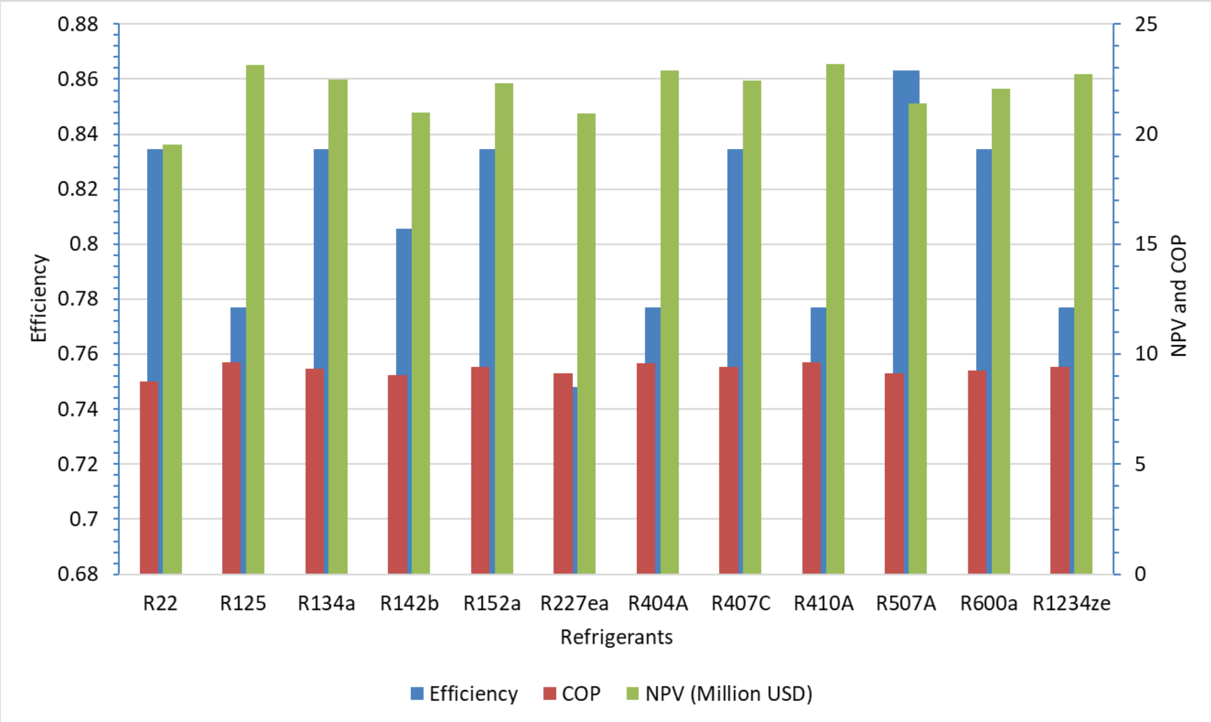


Figure 9. Maximum performance of 12 different working fluids [195].

in heat pump systems to ensure minimal impact on the environment. Low GWP fluids are fundamentally different from conventionally used ones, but their performance has some promising features [196]. The performance analysis of the 12 different working fluids (R22, R125, R134a, R142b, R152a, R227ea, R404A, R407C, R410A, R507A, R600a, and R1234ze) for district heating application has been done as shown in Figure 9. The result based on the NPV and system COP shows that better performance has been achieved using R410A [195]. Table 4 shows the GSHP system detail and the refrigerant used in the literature. An experimental investigation of GSHP has been done using R134a for heating application and the obtained mean system COP is 3.1, and it depends on local climatic conditions [107,108]. Energy and Exergy analysis of the GSHP system using R116, R218, and RC318 working fluid has been done. The COP of the GSHP using R116, R218, and RC318 is 3.08, 2.92, and 3.84, respectively. The R116 has a maximum of 68% exergy efficiency compared to others [113,197]. The NH_3 and CO_2 refrigerants have been studied to a greater extent in the GSHP system. However, propane has been rarely investigated. The exploration of natural refrigerants in the GSHP is extremely less related to the convection heat pump.

The GHE is used to extract or reject thermal energy to the ground using a bundle of tubes, and it can be classified into open-loop, closed-loop, and other systems. Table 4 shows different GHE arrangements, and the punctual information of results of various authors have been summarized. The depth of the vertical borehole varies between 30 m and 250 m with 5 m separation from each, as shown in Table 4. Similarly, Horizontal GHEs are most commonly laid in trenches at a depth of 0.9– 3 m. In the open-loop structure, underground water is used as HTF. Underground water from the bore well absorbs/delivers the heat energy from the heat pump, and it is drifted on the soil surface, or it can be returned to underground using bore well. The closed-loop GHE collects the heat energy from the ground using vertical, horizontal, and spiral coil pipe, and the HTF is circulated continuously without any change in the volume. The antifreeze HTF typically consists of water and ethanol, as shown in Table 4. Other systems: standing column wells, mine water or tunnel water are examples for this class. To select the correct system for a connection, numerous aspects have to be considered: geothermal and environmental conditions, area and utilization on the surface, presence of possible heat sources like mine shaft, and the building load. In the design stage, accurate information for the important parameters for the selected technology are essential; to size the GHE in such a way that the best performance is reached with the lowest cost. The detailed research and development of the above factors are presented in the energy demand reduction in the built environment using shallow geothermal integrated energy systems – A comprehensive review: Part I [198]. This will help to identify and design a suitable GHE system based on the local climatic conditions.

Simulation of the GSHP System

The software packages, used to simulate the GSHP performance, are Energy Plus, TRNSYS [152], RET Screen [165], ASPEN plus [199], eQUEST [81], ESP-r [119], DeST [150], IMST-ART [98], COMSOL Multiphysics [200,201], FEFLOW [135,136], Ground Loop Heat exchanger (GLHEPro) [141], FlexPDE [116], Earth Energy Designer (EED) [127], GeoHP-Calc [133] and Ground Loop Design (GLD) [142]. Table 5 shows different software packages details. These software packages help to calculate the annual performance of the system for different climatic conditions.

- Primary and secondary circuits are used for HVAC modeling in EnergyPlus. The primary circuit has HVAC equipment including chillers, boilers, and TES, and the secondary circuit has heat rejection equipment such as GHE, condenser, and cooling towers. EnergyPlus uses long- [5] and short-time g-functions [6] to handle simulations of GHEs.
- TRNSYS, a simulation program used to analyze the different new energy systems, has been developed by the University of Wisconsin-Madison, USA [202]. Three different types, such as Type 557 (Hellström), TYPE 451 (EWS, Huber, and Wetter), and Type 281 (long-time g-functions, Eskilson), are used for the GHE model. In these methods, borehole thermal capacitance is not considered. For performance prediction, the effect of climate change on the GSHP unit is studied using TRNSYS [159,170] [121] [89].
- The Quick Energy Simulation Tool (eQUEST)used for building energy simulation, has been invented by the Department of Energy (DoE), USA [203]. The eQUEST software has the capability of designing a conventional

Table 5. Simulation tools

Simulation tool	Developer	License	Application
EnergyPlus	Lawrence Berkeley National Laboratory, USA	Free	Building simulation
TRNSYS (Transient Systems Simulation Program)	University of Wisconsin-Madison, USA	Commercial	Renewable energy engineering simulation
RET Screen (Renewable Energy Project Analysis Software)	Natural Resources Canada	Free	Renewable Energy Project Analysis
ASPEN plus	AspenTech	Commercial	Process simulation software
eQUEST (Quick Energy Simulation Tool)	Department of Energy, USA	Free	Building simulation
ESP-r	University of Strathclyde, UK	Free	Building simulation
DeST (Designer's Simulation Toolkit)	Tsinghua University, China	Free	Building simulation
IMST-ART	Polytechnic University of Valencia	Free	Vapour-compression refrigeration system
COMSOL Multiphysics	COMSOL, Sweden	Commercial	Multiphysics simulation software
FEFLOW (Finite Element subsurface FLOW)	DHI – Institute for Water and Environment, Denmark	Commercial	Hydraulic and hydrological modeling software
GLHEPro (Ground Loop Heat Exchanger Professional)	Oklahoma State University, USA	Commercial	GHE design
FlexPDE (Multi-Physics Finite Element Solution Environment for Partial Differential)	PDE Solutions Inc	Commercial	Multi-Physics PDE problem
Earth Energy Designer (EED)	BLOCON AB, Sweden	Commercial	VGHE design
Ground Loop Design (GLD)	Thermal Dynamics	Commercial	GSHP
EnergyGuage	Florida Solar Energy Center, USA	Commercial	Building simulation
HAP (Hourly Analysis Program)	Carrier Corporation	Free	Building simulation
TRACE (Trane Air Conditioning Economics)	Trane	Commercial	Building simulation
IESVE	IES	Commercial	Building simulation
TAS	Environmental Design Solutions Limited, UK	Commercial	Building simulation
Design Builder	Design builder software limited	Commercial	Building simulation

and hybrid GSHP system, and it helps the users to analyze the performance and cost of the system for different applications [90]. A comparative analysis of GSHP and boiler integrated GSHP has been done using eQUEST to reduce the GTI [81]. The result reveals that the hybrid GSHP system reduces the GTI and borehole depth. The detailed research and development of the hybrid GSHP systems are presented in the comprehensive review part II [204].

- Designer's Simulation Toolkit (DeST) used for the building energy simulation has been developed by Tsinghua University, China [205]. The experimental setup of the GSHP system with 1000 kW capacity has been constructed in Shanghai, China, and the GSHP system has been simulated for four different climate cities using DeST [150]. The payback period of the higher capacity system is only two years, and only 55.8% of the operating cost has been reduced. It is inferred that the GSHP unit is highly appropriate for mild and cold climate regions, and other climate regions require a hybrid GSHP structure.
- GLHEPro, developed by Oklahoma State University, USA, is used to design the GHE. This program is operated based on Eskilson's method [206]. The economic and environmental analysis of the hybrid GSHP system has been analyzed using GLHEPRO software. The results imply that the GSHP system operated using solar PV reduces global warming and acidification potential [144]. In terms of economic, the saving to investment ratio decreases while operating the GSHP system using 100% solar PV.
- Ground Loop Design (GLD) is used for coupling the ground thermal energy with the HVAC system, and it has been developed by GAIA Geothermal, LLC., USA [207]. The effect of borehole length has been analyzed by varying different operating parameters. The outcome of the study reveals that thermal conductivity and thermal resistance of the GHE are the deciding factors of the heat pump design [142]. When increasing the thermal conductivity from 2.0 to 3.2 W/mK, reduces the heat pump capacity by 19% for cooling and 16% for heating. In the same way, an increase in the thermal resistance by 6% increases the borehole length by 3%.
- Earth Energy Designer (EED) is used for the design of the GHE, and it has been developed by the Swedish Council of Building Research, Stockholm [208]. This program is operated based on g-functions. The research study predicts that the building envelope performance in 2050 will be simulated on an hourly basis using EED [128,170]. The influence of global climate change on the length of the borehole has been analyzed and the results imply that a higher borehole length is needed to achieve the same space heating and cooling demand of the building in 2050. The system COP is reduced by 10% when the global temperature increases by 1.5 °C.
- GeoHP-Calc tool is used to simulate the GHE system, and this simulation tool combines the CaRM-He model [133]. This model considers the axial direction of heat conduction. The heat balance of the ground also considers the effect of weather parameters, including the long-wave radiation.
- FlexPDE is used to find a numerical solution based on FEM, and it has developed by PDE Solutions Inc. [209]. The effect of diameter, specific heat, thermal conductivity, grout, and HTF has been successfully analyzed and validated with experimental results [116]. The author concludes that bentonite could be used as grout material, and an increase in the U-tube size rises the heat dissipation to the soil.
- A finite Element subsurface FLOW and transport system (FEFLOW) is used to model the GHE, and it has been developed by MIKE POWERED BY DHI, Denmark [210]. Performance and emission of the GSHP unit have been experimentally investigated, and the model has been established to forecast the system performance for the next ten years using FEFLOW [135]. The results show that 20% of CO_2 emission has been reduced using GSHP related to ASHP, and the maximum COP of the unit is 3.75 in year-round operation.
- The performance of the individual component of the vapor compression system can be analyzed using IMST-ART, and this software is developed by the Polytechnic University of Valencia, Spain [129]. The IMST-ART simulation result shows that the maximum SPF of 5.24 for the heat pump and 2.47 for the GSHP system has been achieved [98]. This simulation model considers the following independent variables, namely, speed of compressor and circulation pump, entry, and exit temperature of the GHE.
- ASPEN plus can be used for the heat exchanger design apart from the process engineering systems, and it has been developed by Aspen Technology, Inc., USA (Aspen Technology, 2000). The GSHP system COP has been simulated using ASPEN Plus software varies from 3.5 to 6.0 [199].
- COMSOL Multiphysics software can also be used for heat transfer, fluid flow, and optimization analysis, and it has been developed by the KTH Royal Institute of Technology, Sweden [212]. This software is based on FEM. Experimental investigation of the GSHP system using nine spiral GHE has been presented, and the thermal behavior of the GHE has been analyzed using COMSOL software [111]. The results are in good agreement with experimental results because this software considers both conduction and convection heat transfer. The energy pile GHE has been simulated using COMSOL Multiphysics for nearly 100 years, and the results are very much in agreement [201]. The borehole pipe diameter and length, the conductivity of soil and pipe, ground density, and specific heat capacity have been assumed for the GSHP simulation using COMSOL Multiphysics, and it has also been assumed that ground is homogeneous [168]. The author concludes that

COMSOL Multiphysics is highly suitable for performance predicting the deep GHE.

- RETScreen is used to examine the energy, economic, and environmental benefits of different new energy systems, and it has been developed by the Natural Resources of Canada [213]. The economy and environmental benefits of the GSHP unit in ten different towns of India under cold and composite climate have been investigated using RETScreen software and found that the payback period of the GSHP system in a cold climate is less compared to composite climate [165].

The GSHP system has been simulated for five years using GLHEPRO and TRNSYS and compared with experimental results. The author suggests that the TRNSYS model can be used for the control strategies and a 2% deviation has been reported between TRNSYS and experimental results [102]. A comparative analysis of GLD and GLHEPRO revealed that the GLD program is quite reliable [82]. A hybrid model (3D) based on FDM was developed and tested with experimental results [131]. It has also been compared with DeST. The inlet temperature of HTF based on the experiment has been used as input for both the models and the integration of experimental and simulation input parameters helps to achieve the results quickly. Two evaluation methodology has been adopted for the GHE performance, namely, TRT and constant heat injection. The TRT test reveals that the accuracy of the DeST model is relatively less for the first seven hours of operation. The heat has continuously been injected into the ground for 16 hours, and the author concludes that the FDM model has good accuracy compared to DeST. The above few comparative simulation studies are only available from this extensive review. Therefore, further comparative research is needed in order to find the best suitable software.

Feasibilities of the System for Different Climatic Conditions

The GSHP performance highly depends on metrological (ambient temperature, humidity, and radiation), geological (geothermal properties), and hydrological conditions. The feasibility study of the GSHP unit for the different climatic conditions would help for project planning. Summer and winter temperatures are determining factors for peak load calculation and system sizing. Hence, the Heating Degree Days (HDD) and Cooling Degree Days (CDD) are essential for any place. HDD can be defined as the variation between base temperature and daily average temperature. Similarly, CDD can be defined as the variation between daily average temperature and base temperature.

A study concerning the feasibility of the GSHP system carried out for sixteen locations in seven climate zones of the USA is based on weather, ground temperature, energy, and cost benefits [214] [215]. The International Energy Conservation Code (IECC) has been adopted in the reference study, and it divides the world into eight climatic zones on the basis of moist (A), dry (B), and marine (C) features. The eight climate zones are hot-dry (3), mild-dry (1), cold-dry (2), hot-humid (3 cities), mild-humid (1), cold-humid (2), very cold (1), extreme cold (1), and marine (2). The feasibility has been ranked as moderate, excellent, and high as shown in Table 6. The adaptation of the GSHP technology in a cold climate (dry, humid, very cold, and extreme) is high. The dry climate (hot and mild) has been ranked as good, and the humid climate (hot and mild) has been ranked as moderate. Similarly, the payback period of North America, including the above climatic conditions, has also been investigated. The results reveal that the payback period is a maximum of seven years [216].

Table 6. Feasibility scores [214]

S.No	City, State	Climate Zone	score	FL	Ranking
1	Duluth, MN	7	70	H	1
2	Helena, MT	6B	63	H	2
3	Minneapolis, MN	6A	62	H	3
4	Chicago, IL	5A	56	G	4
5	Denver, CO	5B	53	G	5
6	Baltimore, MD	4A	47	G	6
7	Seattle, WA	4C	43	G	7
8	Las Vegas, NV	3B-Other	43	G	8
9	Phones, AZ	2B	42	G	9
10	Albuquerque, NM	4B	41	G	10
11	Houston, TX	2A	41	G	11
12	Atlanta, GA	3A	40	M	12
13	Milami, FL	1A	38	M	13
14	SF,CA	3C	25	M	14
15	LA, CA	3B-CA	24	M	15

Potential GHG emission reduction of GSHP, PV integrated GSHP, and energy-efficient appliances have been investigated using RETScreen software in five different locations (Toronto, Ottawa, Calgary, Vancouver, and Montreal) in Canada which has different climatic conditions [217]. PV integrated GSHP system significantly reduces the overall GHG emission, and the integrated system (energy-efficient appliances and GSHP) further reduces GHG emissions. In the overall GHG calculation, the source of electricity has a considerable effect. The climate has a considerable effect on energy demand reduction.

Performance Analysis

The performance analysis of the installed GSHP system in the Republic of Korea on evaluation reveals that 90% of the installed systems are water to water GSHP [218]. The average heating and cooling COP of the system is shown in Figure 10, and it is strong that the COPc is greater than the COPh. The testing standards used for the performance analysis of water to water, water to air, and water to air multi-system are NR GT 101, NR GT 102, and NR GT 103, respectively. In the Republic of Korea, an experimental investigation reveals that the typical cooling COP of the GSHP unit is 8.3 [14]. Table 4 shows the country-wise research details includes borehole depth, number of boreholes, and performance of both heat pump and system. Three different GSHP systems from different manufacturers are examined, and findings reveal that the COP/EER of the system given in the catalog will always be higher than that of the actual condition [96]. Hence, there is a need to find the performance of the system according to the local operating conditions.

Similarly, based on the performance analysis of the GSHP system fitted in Tunisia the COP of the entire system and heat pump is 2.88 and 4.25, respectively [139]. Factors influencing the performance of the GSHP system, including compressor cycling, have been carried out for ten similar systems installed in the UK for dwelling applications [219]. From the analysis, it can be concluded that the peak occurs due to the starting of the compressor for DHW. The compressor cycling in all the ten houses varies, and it highly depends on occupant behavior. Further, the performance of the system is poor during winter (due to high on/off cycle). Also, it has been found that there is a GTI.

The performance (EER, COP, and water temperature) of fifty installed systems in different types of buildings such as residential, office, and others located in Jiangsu, China, has been investigated [220]. Based on the statistical analysis, the average COP and EER for cooling are 4.62 and 3.41, and for heating are 4.34 and 3.22, correspondingly. The typical temperature gradient between the entry and exit of the HTF is reported as 3.07 °C in the GHE. An experimental investigation of five GSHP systems has been carried out during summer and winter in China. The results reveal that in a year-round operation, heat extraction from the ground is greater than heat injection [156]. The COP and EER vary

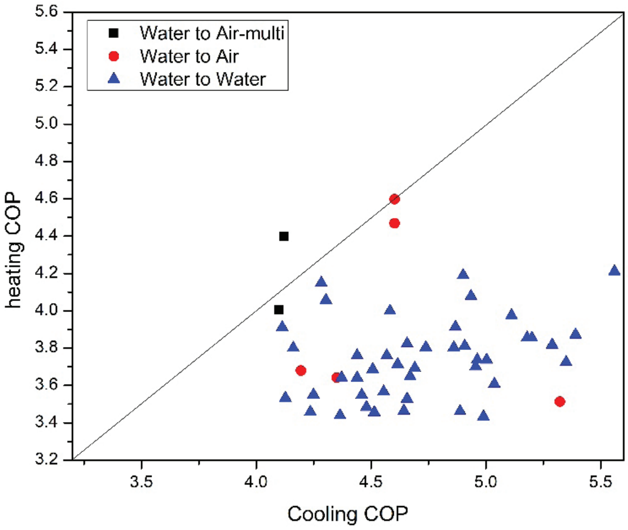


Figure 10. Variation of heating and cooling COP for a different type of heat pump [218].

from 3.3 to 5.9 and 1.9 to 4.3. The system mostly functioned below the part-load circumstances, and most of the equipment is idle.

It is tough to examine the long-term performance of the GSHP since there would be a significant variation in ground temperature and groundwater flow and velocity [161]. The long-term system performance has been predicted using an experimental method, a data-driven approach, and physical-based models. The variation in the GTI has been experimentally monitored on a continuous basis for five years in Valencia, Spain [103]. The temperature remains constant at the beginning of every year, and there is no variation in ground temperature since the ground has a higher recovery capability. The system performance has been modeled using GLHEPro software for 25 years and therefore resulted in an increase in the ground temperature by 1.2 K. A comparative analysis of installation and long-term (10 years) operating cost of gas-fired, oil-fired, and GSHP systems has been carried out for 200 m^2 residential buildings located in Italy [124]. The total cost (installation and operating cost in Euros) of gas-fired, oil-fired, and GSHP systems are 28,800 (10000 and 18800), 30300 (9000 and 21300), and 27500 (18500 and 9000), respectively. The total CO_2 emission associated with this long-term operation for gas-fired, oil-fired, and GSHP systems is 59.7, 75.2, and 23.3 tonnes, respectively.

The failure of the GSHP system will cause environmental damage and a reduction in performance. The faults in different components are grouped into two, namely hard faults and soft faults. Hard faults are compressor stoppage, valve choke problem, air distribution failure, and so on, and these faults can be detected easily. However, the soft faults are hard to find, and it includes refrigerant overcharge or leakage, fouling, borehole leak, and so on. The fault diagnosis in the GSHP system has been carried out using a Bayesian network approach [221]. The research work mainly focused on heat pump components. However, no research is available on GHE. Most of the fault diagnosis methods are established to find the hard faults precisely in ASHP systems. Hence, a lot of research is required on soft fault detection in the GSHP system.

Energy and Exergy Analysis

The energy efficiency of GSHP usually involves the COP, the EER, and the input energy ratio (kW/TR) as indices. All such approaches to evaluating the energy efficiency of GSHP are based on the first law of thermodynamics. However, the first law of thermodynamics states the conservation of energy and the transformation of energy from one form to another. Preserving the quality of energy and increasing the energy efficiency of GSHP are major concerns to engineers, and the second law provides the necessary means to determine the quality as well as the extent of degradation of energy during a process. Recent studies have increasingly applied energy and exergy analysis in the fields of refrigeration, air-conditioning, and heat pump systems.

The energy of the GSHP system (5.3 kW) has been monitored continuously for twelve months for domestic water heating and space heating applications [79]. The energy has been distributed for the compressor and other electrical devices (pump and control system) as 89% and 11%, respectively. The system efficiency is 32% of the Carnot efficiency. The major reasons for the system inefficiency are the low performance of the compressor, expansion valve, and GHE. The performance of the GSHP system has been tested experimentally in the cooling-dominated building for four continuous years with regard to space heating and cooling application. The COP of the system for heating increases by 6.5%. On the other hand, the COP of the system for cooling reduces by 4.0% annually [114,118]. In a heating-dominated building, the SPF reduces by 14% in the second year for space heating due to the GTI [97].

The second law analysis, also known as the exergy analysis: this law allows taking into account the degradation of the energy due to irreversible processes. The stand-alone earth air heat exchanger (EAHE) technique based on a geothermal source presents a great potential for the pre-heating, pre-cooling, and natural ventilation of dwellings and buildings in arid regions [222]. Hence the EAHE has been integrated with ASHP for energy conservation. Exergy analysis of GSHP (both horizontal and vertical GHE) and ASHP (conventional, EAHE) has been carried out for space heating and cooling application, and the system performance has been predicted for thirty years [149]. The annual exergy efficiency of GSHP - VGHE, GSHP - HGHE, ASHP - EAHE, and conventional ASHP systems are 42.4%, 40.5%, 31.5%, and 29.4%, respectively for thirty years of operation. The thirty years of continuous operation reveals that there is a change in exergy destruction for space heating and cooling mode. The total seasonal exergy destruction increases by 7.2% during cooling and decreases by 5.5% during heating for both GSHP systems.

A detailed review of the exergy and energy analysis of the GSHP system is presented [109,110]. The exergy and energy efficiency of the vertical borehole GSHP is 29.90% and 74.85%. Similarly, Maximal exergy and energetic efficiencies of the Helicoidal water-air geothermal heat exchanger, reaching 89% and 92%, respectively, are obtained at 0.035 kg s^{-1} mass flow rate [223]. The exergy analysis of a year-round continuously operated GSHP system has been done experimentally for space heating applications [84]. From the exergy and environmental outlook, it is concluded that GSHP is a viable technology, and it can be used as an alternative to fossil fuel. The system performance highly depends on the climate, circulating pump, and application. The entropy and exergy of the individual component of the GSHP system are summarized [125]. From the review, the authors conclude that entropy generation optimization might reduce 5.5% of installation cost. The exergy efficiency (seasonal average) of the GSHP system is reported as 68%, and it shows the potential of energy saving.

System Optimization

Different control strategies, namely the ON/OFF system based on the building load ratio and variable speed compressor, variable speed pump, variable flow control, and the fluid flow rate have been analyzed to increase the energy and exergy efficiency of the unit using TRNSYS. It is inferred that the variable speed technique has a maximum COP of 3.8 and 3.7 for both heating and cooling, respectively [152]. A model-based optimization strategy has been created to increase the GSHP performance using a variable speed pump for space heating and cooling application. From the experimental investigation, the author concludes that considerable energy savings could be realized for heating (8%) and cooling (9%) [167]. The integration of a variable speed pump with multi-stage GSHP has been proposed, and the system optimization reveals that 32% of energy savings could be achieved [99]. Similarly, in another study, the authors try to enhance the GSHP performance in part-load conditions by controlling the HTF flow rate [224]. This control strategy increases the SPF by 20% for heating and 40% for cooling, respectively.

Integrating intermittent operation strategy and design of the system according to the local climatic condition (site-specific ground properties) may reduce the required borehole length. This integration also helps to reduce the installation cost and financial barrier for full adoption [80]. A thermo-economic optimization has been conducted to improve the GSHP performance. The results demonstrate that this model quickly designs the GSHP system compared to the other conventional models [115]. Likewise, to reduce the GTI, cost-effective optimized operating conditions are proposed in this study, and the annual saving is reported as ~3000 Euro [155].

The Taguchi method is used to optimize the GHE length and evaporator, and condenser temperatures of the GSHP unit. The findings show that the suitable layout of GSHP units is necessary to decrease their primary expenses and life cycle expenses [167]. Optimization of borehole length to reduce the GTI has been investigated using the Taguchi method and utility concept [166,225]. The optimum design has been carried out for 1.5 TR system using horizontal and vertical GHE. Eight different parameters (specific heat, thermal conductivity, density, viscosity, pipe thermal conductivity, the mass flow rate of HTF, pipe diameter, and center to center distance) are considered for the optimum design. It is concluded that specific heat and thermal conductivity (26% and 46%, respectively) in cooling mode, and pipe diameter and thermal conductivity (44% and 26%, respectively) for heating mode play a vital role for the optimum length.

A multi-objective genetic algorithm for the optimization of the GHE has been proposed in this paper to identify influencing parameters and its optimum value [162]. A dynamic approach using second law optimization has been used on the basis of the minimum entropy generation by considering the HTF flow rate and considerably increasing the performance of the system [125]. The major influencing parameters and the size of the GSHP system have been investigated. The length to unit (L/Q) increases with increasing borehole heat transfer resistance. However, L/Q decreases with increasing thermal conductivity. Similarly, L/Q decreases when increasing the entry water temperature in cooling mode, whereas L/Q increases in heat mode. If the initial ground temperature is high, L/Q value will also be high in cooling mode, whereas less for heating mode. Increasing pipe center distance decreases the L/Q.

Several kinds of researches have been done on improving the GSHP performance on the system side by optimizing various parameters. However, the potential impact of the indoor environmental (air) parameters has not been studied extensively, and only a few kinds of researches are available. The set-points are typically fixed during the mode of operation. However, it will be varied corresponding to the internal load, ambient and wet bulb temperature, and higher cooling set-point will increase energy consumption [81]. The indoor set-point temperature optimization could lessen the GTI, and it is advantageous in the long-term [163]. The effect of ventilation rate on the GSHP system has been studied and the resulted system COP significantly improves when reducing the ventilation rate from 4 to 2.1 without affecting the indoor thermal comfort [153]. Optimization has been carried out by considering the thermal comfort during extreme weather conditions [100]. In order to maintain user comfort, the author developed an optimization strategy by combining the indoor supply temperature and pump frequency variation. The result reveals that the seasonal performance factor has been improved by 33%.

Life Cycle and Economic Analysis

Life cycle analysis (LCA) of the packaged ASHP reveals that the hot climate region emits more emissions compared to the cold climate region [83]. Life cycle analysis of four different heat pumps such as GSHP, ASHP, AWHP (Air-Water Heat Pump), and EAHP (Exhaust Air Heat Pump) with and without solar collector has been done for obtaining nearly zero energy building [132]. The results reveal that the GSHP unit is suitable. LCA analysis has been carried out in the hot and humid climate using a deterministic and probabilistic approach. The payback period of the system is 15 years for hot climate and 12 years for a hot and humid climate [91]. The author concludes that the GSHP system is more suitable with 35% incentives, and the payback period is reduced to 2 years.

LCA has been carried out during the manufacturing, transportation, utilization, final disposal, and associated emissions using SimaPro 7.1.8 software [130]. The following factors have been taken into consideration for manufacturing and transportation, such as the manufacture of raw materials (aluminum, copper, pipes, plastic, steel, rubber), heat pump, transportation of all the above materials, drilling, and assembly. The following factors have been considered in the emission, such as ozone depletion, acidification, Greenhouse Gas (GHG), winter smog, eutrophication, and heavy metals. ISO 1997 and 2006 have been followed for the LCA analysis. From the extensive analysis of 11 GSHP systems, which has a total capacity of 280 kW of cooling, 73.49% of the emission is caused by acidification. This acidification mainly contains SO_2 and NOx. The GHG emission accounts for 14.54%.

The economic barrier and emission reduction potential by retrofitting the GSHP system in a residential building in the USA have been estimated based on the residential energy consumption data [226]. From the analysis, only 10% of residential buildings are suitable to install the system without any subsidy, and thereby it can reduce 12.1 million tons of CO_2eq. The installation will further increase from 10% to 30% with 30% tax credit, and thereby the payback period reduces from 9.1 to 4.8 years. The economic and environmental analysis of 32 GSHP systems located in a severe cold climate in the USA has been analyzed [92]. The GSHP system saves energy by 44–86% and 70–77% compared to natural gas furnaces and electricity rates, respectively. The CO_2 emission is reduced by 23%–61% compared to natural gas furnaces. The potential emission reduction by replacing ASHP with the GSHP system in the 1 km^2 region of Japan has been studied. The CO_2 payback period is 1.7 years, and 87% of CO_2 has been emitted during the VGHE installation [137]. A comparative analysis of cost has been carried out in China between ASHP and GSHP. The operational expenditure of the GSHP unit decreased by 55.8%, and the payback period reduced by two years [157].

Economic analysis of the system has been carried out for residential buildings located in Melbourne, Australia, and the results imply that the economic feasibility of GSHP does not vary due to climate change [169]. The payback period investigated for a residential building in Cyprus (moderate climate condition) has a heating and cooling demand of 20.78 kW and 11.56 kW, respectively [117]. It is reported that the payback period would be 21 years using 400 m GHE. In another study, it is reported the payback period is four years without environmental prevention cost and 4.29 years with environmental prevention cost [164]. The authors conclude that improper design would increase the installation and maintenance costs. The oversizing of the system to meet the peak demand may also be the reason for the higher payback period. Incorporating the safety factor increases the GHE length. Hence, proper design standards and technology development are essential to reduce the cost.

A study has been carried out to find the financial risk involved in oversizing the GHE and compared it with four various heating and cooling systems [120]. Similarly, four systems cost, the lifetime of the component, payback period, and CO_2 emissions are compared using MS Visual Basic 6.0 [138]. The above analysis [120,138] implies that the design of the GSHP unit with the auxiliary unit to meet the peak demand would potentially reduce the payback period. This integration significantly reduces the GHE length. Further, the auxiliary unit can be designed according to the local climatic condition. The GSHP system has been integrated with a radiant wall system for building heating applications and increasing the thermal mass as the radiant wall could help to operate during peak hours [101]. Also, the energy savings could be achieved between 19.97% and 40.72%. Integration of GSHP and conventional heating and cooling has been studied to reduce the peak demand, and a new technique is proposed for sizing the GSHP. The payback period of the system is 12 years when 48% of cooling demand is met by GSHP [94].

The techno-economic feasibility mapping of a closed-loop SGE system for several places in Europe has been carried out [227]. The Decision Support System (DSS) tool will help the researchers to understand the system feasibility, which has been created by the Cheap-GSHPs project. This one tool is competent to describe all the attributes involved in the design of SGE systems, including geological, economic, and building demand. The DSS tool creates various feasible solutions based on initial costs, life cycle assessment, and energy performance. It will facilitate the user to find the best solution based on his specific preferences. Similarly, techno-economic mapping needs to be carried out for global south countries.

Summary and Future Perspectives

The aim of the research collection is to find the various possible opportunities for space heating and cooling, and water heating applications using shallow geothermal energy and to save energy and environment in the built environment. The focus on the effective utilization of shallow geothermal energy through GSHP, DX-GSHP, and hybrid GSHP systems has been increasing around the globe due to its energy and environmental benefits.

This paper comprises previous research work related to major components of GSHP such as compressor, refrigerant, and GHE. The energy-saving benefit encourages the variable speed compressor, and the environmental benefit encourages the development of the system using R744 refrigerant. The components of the GSHP system are sized independently. Most of the software packages are focused on the design of VGHE using different input from other components such as HP performance specifications, building demand, weather details, and ground properties as parameters. The following valuable points can be noted.

1. Most of the systems are installed for heating-dominated buildings in the global north. The direct utilization of geothermal energy is very limited in the global south nations. China has extensively analyzed the shallow geothermal potential. Similarly, it has to be carried out for other global south countries.
2. The future work may be to describe more explicitly SGE potential for both heating and cooling and to discuss important power densities when active resupply of thermal shortfalls is accounted for.
3. Further, research and developments are essential for the effective utilization of SGE in global south countries. Development of the new database to represent the SGE conductivities and prospective (different length) and viability of GHE systems. Also, techno-economic mapping needs to be conducted.
4. The NH_3 and CO_2 refrigerants were studied to a greater extent in the GSHP system. However, propane has been rarely investigated. The exploration of natural refrigerants in the GSHP is extremely less related to the convection heat pump.
5. Various types of studies were done on improving the GSHP performance on the system side by perfecting various parameters. However, the potential impact of the indoor environmental (air) parameters has not been studied extensively. Design integration of the SGE and building with respect to optimal energy use and operational plan must be developed.
6. Very few comparative simulation studies are only available. Therefore, further comparative research is needed in order to find the best suitable software. There is a need to find the performance of the system according to the year-round local climatic conditions.
7. The future work may be to develop transparent and crucial evaluation plans for the data point and uncertainties, vulnerabilities, and essential modeling statements. Different design computer software must be further verified by data from the field and a detailed assessment is intensively required to examine their precision and feasibility for engineering practices.
8. There are some limitations because of the initial investment and complexity of the GSHP system. The extensive

review reveals that the payback period of the system is quite high. There are possibilities for technological advancements, which will help to reduce the investment cost.

9. The improper design would increase the installation and maintenance costs. The oversizing of the system to meet the peak demand may also be the reason for the higher payback period. Incorporating the safety factor increases the GHE length. Also, considerable attention needs to be paid to grout, and this will significantly reduce borehole length and fitting cost. Hence, proper design standards and technology development are essential to reduce the cost.
10. The best design of the individual system dramatically reduces the investment cost and energy consumption. Still, further research is necessary for the optimization and control strategy of the integrated system according to the climatic conditions, building demand, and GTI. The influence of building load on the thermal plumes must be investigated. The traditional approach to deciding on thermal plumes is insufficient.
11. Exergy analysis may be considered under a dynamic approach, since the design running conditions could vary greatly, during a peak day and the season. The exergy optimization could be applied to a control algorithm
12. Available theories to review the economic possibilities of SGE in urban areas, however, are still not ready. The economic barrier and emission reduction potential of retrofitting the GSHP system in a building could be estimated. Modernization studies need to be carried out for effective integration with the existing building.
13. Most of the earlier findings are taken into account GHE heat transfer and ignore financial and environmental aspects.
14. The effects of the Carbon trading mechanism (CTM) are limited because it is still in the early stage of growth and has little volatility. Hence, to progress further, the CTM and proper guidelines are also beneficial for the development of GSHP.
15. A greater part of the research work focused on heat pump components' fault detection. However, no research is available on GHE. Most of the fault diagnosis methods are established to find the hard faults precisely in ASHP systems. Hence, plenty of research is needed on soft fault detection in the GSHP system.
16. The strong guidelines and administration plans for the intensified shallow geothermal energy use are still missing primarily due to the shortage of system insight and process experience.
17. The evolution of SGE in global south counties is inadequate due to factors such as rules and policies, as well as a lack of financial assistance from the government. If rules and policies become efficient and policy structures are introduced, the SGE growth can quickly accelerate in the country.
18. The dissemination plans need to be developed that can help to access the technology, and it may be focused on governing and technology advancements, fiscal subsidies, and knowledge sharing activities, with tax benefits suitable for GSHPs, people's awareness of the system and its advantages.
19. Explanation of the technical capabilities, and proof of thriving SGE use theories for cities, is essential to foster the adoption. Social considerations as part of the adoption potential are rarely argued.
20. The system growth in the cities based on planning by private owners is questionable to deliver practical future results, as the costs of the discovery and supervising are expected to go beyond the reasonable economic constraints. Hence, investor participation and dedication require to be supported so that a growth plan can be realized at the community and city scale.

CONCLUSION

Many more can be done to ensure GSHP is better, i.e. highly efficient, cheapest, simpler, preventing any threat to geothermal and groundwater, expanding the area of application on the existing building, industries, etc. In conclusion, SGE is a clean, trusted, and greener source, which can promote social sustainable growth and help protect the global environment. For this reason, state initiatives and efforts are critical to emphasize and promote the exploration, utilization, and evolution of SGE in the country.

NOMENCLATURE

A	Area
ACOP	Average coefficient of performance
ASHP	Air source heat pump
ASVRF	Air source variable refrigerant flow
CHP	Local fired cogeneration
COP	Coefficient of performance
CTM	Carbon trading mechanism
DEH	Direct electric heating
DeST	Designer's simulation toolkit
DSS	Decision support system
EAHE	Earth air heat exchanger
EAHP	Earth air heat pump
EED	Earth energy designer
EER	Energy efficiency ratio
EG	Ethylene glycol
eQUEST	Quick energy simulation tool
ES	Energy storage/energy source
FEFLOW	Finite element subsurface flow
GB	Gas fired boiler
GHE	Ground heat exchanger
GLHE	Ground loop heat exchanger
GLD	Ground loop design
GSHP	Ground source heat pump
GTI	Ground thermal imbalance

HDPE	High-density polyethylene
HGHE	Horizontal ground heat exchanger
HGSHP	Green electricity + GSHP
HTF	Heat transfer fluid
LCA	Life cycle analysis
LCH	Large coal-fired heating
LTGB	Low temperature system + gas boiler
OB	Oil-fired boiler
PB	Polybutylene
PE	Polyethylene
PEC	Primary Energy Consumption
PVC	Polyvinyl chloride
RCH	Regional coal-fired boiler
Ref	Refrigerant
SCOP	Seasonal coefficient of performance
SPF	Seasonal performance factor
SGE	Shallow geothermal energy
SWHP	Surface water heat pump
VGHE	Vertical ground heat exchanger
WGH	Wall hanging gas boiler

Subscripts

h	Heating
c	Cooling
s	System

ACKNOWLEDGMENTS

The author worked as a project fellow in a DST-EPSRC funded project title "Zero Peak Energy Building Design for India" (ZED-I) at the Indian Institute of Technology Roorkee. ZED-I is a collaborative research project lead by IIT Roorkee along with IIT Delhi and CSIR-CBRI from India and the University of Bath from the UK. Department of Science and Technology (DST) and Engineering and Physical Sciences Research Council (EPSRC) are jointly funding this research under the "Energy Demand Reduction in the Built Environment" program (Grant numbers: DST/TMD/UK-BEE/2017/17(c) and EP/R008612/1). This project aims to eliminate peak energy demand and minimize mean energy demand from buildings, under a changing Indian climate, through a new science of zero peak energy building design. This review was carried out as a part of the development and demonstration of low-energy cooling and heating technologies. The part of the work was carried out at IIT Roorkee. Later, the author started working as Assistant Professor at Vellore Institute of Technology, Vellore, India, and the remaining part of the review work was carried out. The author would like to thank all the investigators and team members for their constant support.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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