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Investigation and feasibility study of ground source heat pump for office buildings in China

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Technical-economic evaluation of ground source heat pump for office buildings in China

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Abstract

The adoption of ground-source heat pump (GSHP) in building sector for space heating/cooling, has increased rapidly during the past several decades around the world, especially in China. Meanwhile, it also exposed a lot of problems such as poor economic and energy efficiency, and even failure to operate properly. The purpose of this paper is to post-assess the application of existing GSHP projects, and to analyze the feasibility of ground-coupled heat pumps(GCHP) applied to office buildings in different climatic zones in China. More than one hundred GSHP cases are investigated through literature surveys and field data collection. Based on the post-evaluation results, a model for assessing the adaptability of GCHP is established. The feasibility evaluation of GCHP applied to office buildings are carried out, and key indicators, such as available capacity, energy savings, and cost-efficiency, etc. are presented among different climatic zones in China.

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Keywords: ground source heat pump ;post-evaluation ;feasibility study; cost-efficiency; energy savings

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1. Introduction

Energy consumption and oil prices have been increasing all over the world. In addition, the increase of energy usage gives rise to global warming and environmental pollution[1]. To solve these problems, many countries have dedicated to develop new & renewable energy technologies such as Geothermal energy. Direct-use of geothermal energy is one of the oldest and common forms of utilizing geothermal energy[2] The total installed capacity reported through the end of 2014 for geothermal direct utilization worldwide is 70,885 MW_t, a 46.2% increase over WGC2010, growing at an annual compound rate of 7.9%[3]. World leaders in geothermal direct-use energy (with heat pumps) installed capacity (MWt) are: China, USA, Sweden, Finland and Germany accounting for 65.8% of the world capacity, and China has the largest annual energy use (with heat pumps)(TJ/year) accounting for 38.3% of the world capacity. Geothermal heat pumps are the fastest growing direct use of geothermal energy-available anywhere for heating and cooling. The installed capacity of Geothermal heat pumps is 50,258 MWt accounting for 70.90% and the annual energy use is 326,848 TJ/year accounting for 55.15%. China is the leading country in application of Geothermal heat pumps.

In China, coal-fired boilers for heating are prohibited gradually, and heat pumps provide an obvious alternative. With the strong advocacy and incentive by the Chinese government, GSHP installations are increasing sharply in the past decades with an annual growth rate of above 30%, and the central government has funded 291 GSHP projects, 21 pilot municipalities, and 52 pilot counties from 2004 to 2014. By the end of 2015, application of GSHP systems for building heating and air conditioning reached 392 million of building space. According to China's 13th Five-year Plan of Geothermal Energy Development and Utilization[4], China plans to add more than 700 million square meters of ground source heat pump applications across the country within five years, which means the heating (cooling) area of GSHP applications will exceed 1100 million m^2 at the end of 2020.

With the rapid development of ground source heat pump applications, many problems have also been exposed, such as poor economic efficiency and energy saving, and even failure to operate properly. Therefore, it is meaningful to investigate the situation of GSHP application and evaluate the feasibility of GSHP technology in different climate regions. In recent years, many researchers have studied GSHP systems through case studies and simulations. Most of them are concerned with a single or a few individual cases [5–11], while feasibility investigations of large amount of GSHP systems are not much [12–15], which is statistically significant.

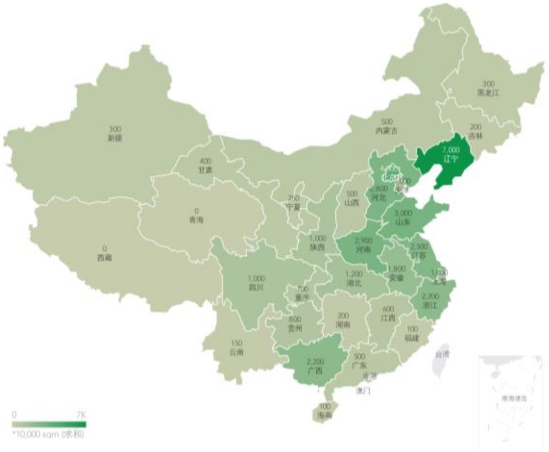
The purpose of this paper is to post-assess the application of existing GSHP projects, and to analyze the feasibility of GSHP for office buildings utilization in different climatic zones in China. In this study, through literature surveys and field data collection, more than one hundred GSHP cases are investigated including the features of GSHP systems in different climate regions, the performance, the influence of ground source heat exchanger system and the economic efficiency. Based on the GSHP projects investigation and empirical research, a model for assessing the adaptability of ground-coupled heat pumps (GCHP) is established. The feasibility evaluation of GCHP applied to office buildings are carried out, and key indicators, such as available capacity, energy savings, and cost-efficiency, etc. are presented among different climatic zones in China.

2. Investigation of ground source heat pump

2.1. Characteristics of GSHP application

By the end of 2015, the total floor area of GSHP projects in building sector has reached 392 million m^2. According to the statistics of the China's 13th Five-year Plan of Geothermal Energy Development and Utilization, GSHP systems are geographically distributed in almost all Chinese provinces except Tibet and Qinghai province as shown in Fig.1. This figure shows that the distribution of GSHP projects in different climate region are significantly different. The GSHP projects are mainly distributed in cold zone and hot summer and cold winter zone, which take account for about 80% and that include Liaoning(LN), Beijing(BJ), Tianjin(TJ), Hebei(HI), Henan(HA), Shandong(SD), and Jiangsu (JS) provinces etc. On the other hand, the GSHP projects are mainly distributed in the middle and east part of China, where the population is larger and is relative richer than the other regions. Fig.2 presents the distribution of the planned application of GSHP at 2020. The total floor area of GSHP projects will be four times as many as at 2015, and the application of GSHP be extended from cold region and to hot summer and cold winter region.

The ground source heat pump can be divided into two types by heat sources: ground-coupled heat pump (GCHP) and water source heat pump (WSHP), and the water source heat pump can be divided into underground water source heat pump and surface water source heat pump according to different water quality. For the application proportion of GSHP types, underground water heat pump and ground-coupled heat pump are the mainly application types, with the proportion of 42% and 32% respectively.



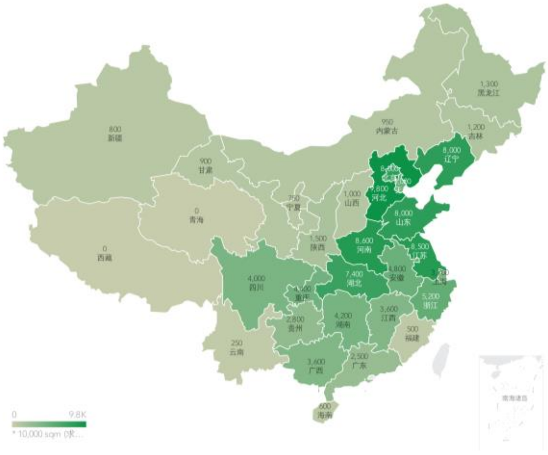


Fig. 1. The distribution of GSHP by provinces at 2015

Fig. 2. The planning distribution of GSHP by provinces at 2020.

2.2. Performance of the investigated GSHP projects

The rated energy efficiency of GSHP units was investigated among eighteen main manufacturers, as shown in Fig.3. It suggested that the rated energy efficiency fluctuated considerably among different manufacturers, about 30% for each type. The average rated energy efficiency in summer and in winter respectively is 5.3 and 4.4. As shown in Fig.4, the investigated actual heating seasonal system energy efficiency (SCOP) is among 1.46 to 3.93 with an average value 3.14, and the investigated actual cooling seasonal system energy efficiency (SEER) is among 1.93 to 5.03 with an average value 3.49.

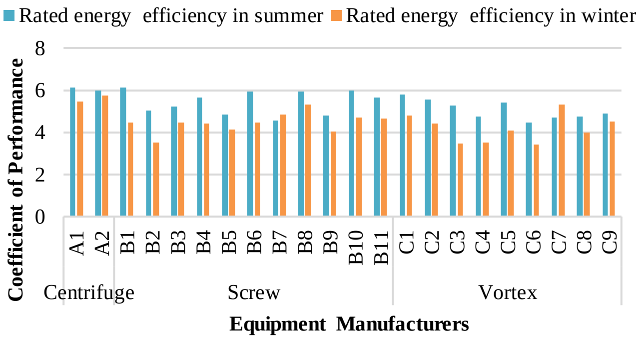


Fig. 3. Rated energy efficiency ratio in summer and winter among different manufacturers.

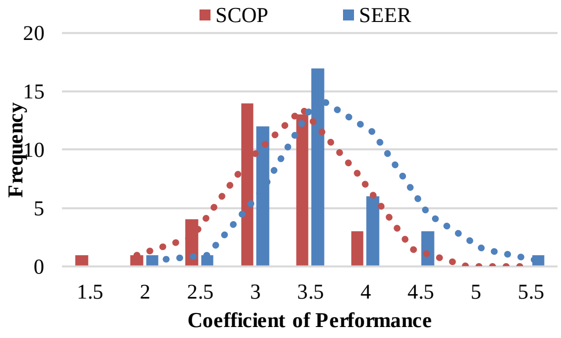


Fig. 4. Seasonal energy efficiency in summer and in winter.

The ground heat exchanger type also has mental influence on the system performance. As shown in Fig.5, the average heat rejection of single U exchanger is 56 W/m (Borehole) and the average heat rejection of double U exchanger is 64 W/m (Borehole) which has increased 20% compared to single U exchanger. The borehole depth in different climate regions was in little difference and the average lowest depth was 60 meters and the average highest depth was 150 meters, as shown in Fig.6.

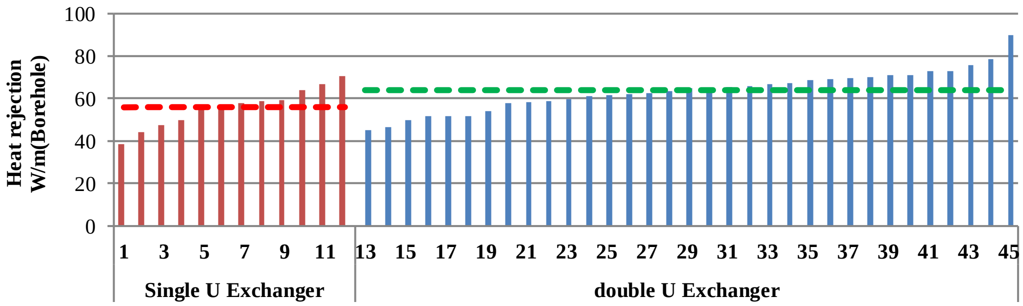


Fig.5. Heat rejection of single U Exchanger and double U exchanger. (data source: thermal response testing reports)

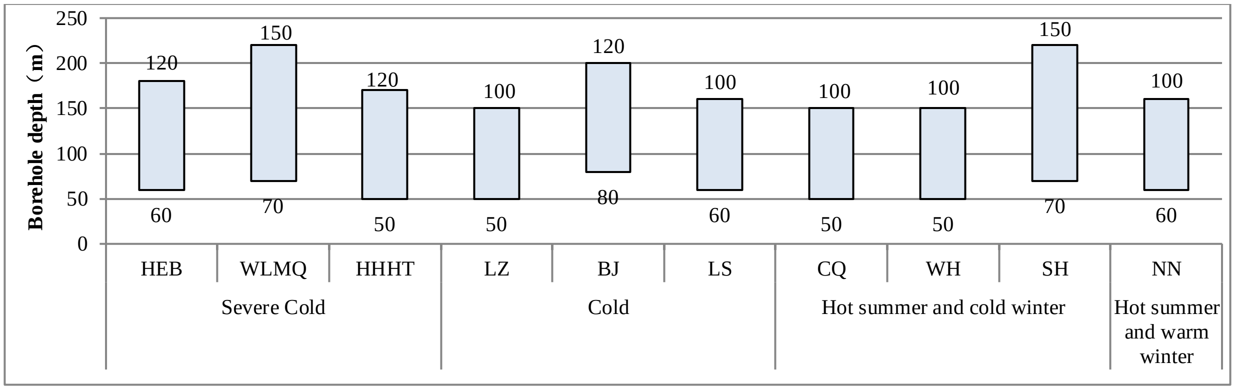


Fig.6. Variation of Borehole Depths in Different Climate Regions.

2.3. The economic efficiency investigation of GSHP

The cost of heat pump units is about 0.45~1.00 RMB/W (cooling capacity). Drilling costs vary from 25 to 100RMB/m (depth of borehole). Compared to traditional HVAC system, the incremental investment of GSHP projects is about 30-150 yuan/m^2 (building area). In some area, the GSHP projects can get government subsidies from 20 to 50 yuan/m^2 (building area) which is shown in Fig.7. The incremental investment payback period is about six years as shown in Fig.8.

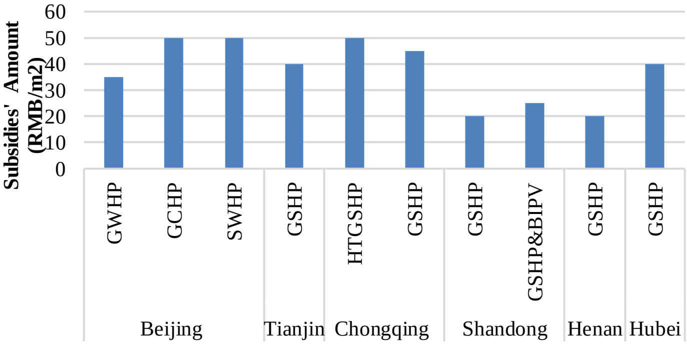


Fig. 7. Government subsidies for GSHP projects in different region.

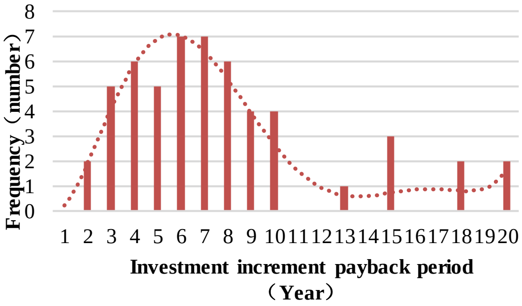


Fig. 8. Statistics of investment increment payback period.

3. Feasibility Evaluation

To evaluate the climate adaptability of ground source heat pump applications, an adaptive assessment model is established based on the above findings, as shown in Fig.9. From the aspects of availability, energy saving, cost-efficiency, etc., the feasibility of using vertical ground-coupled heat pump in office buildings in different regions is analyzed.

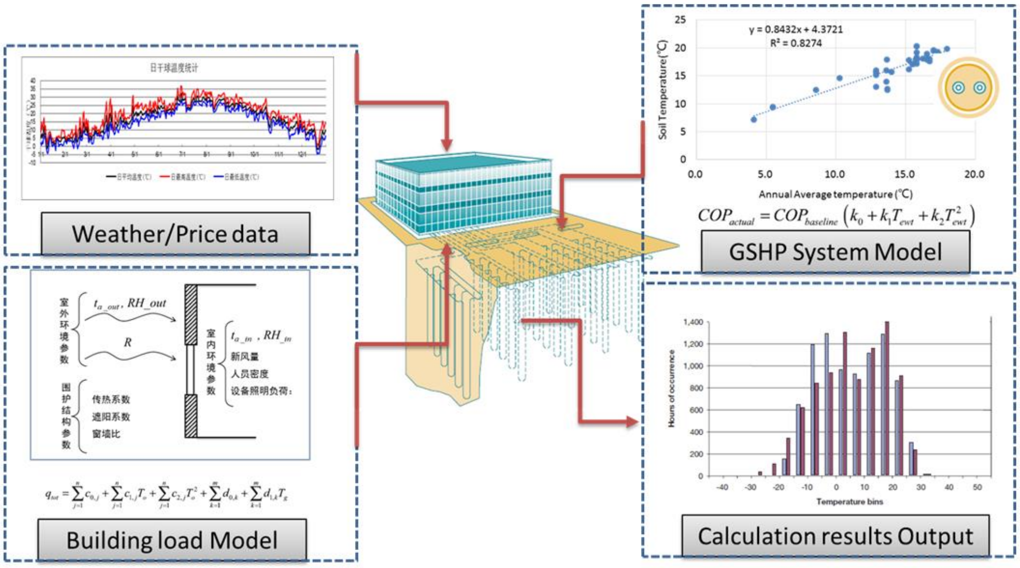


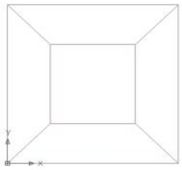
Fig. 9. Assessment model flowchart.

3.1. Model description

Fig. 9 shows the flowchart of the evaluation model which consists of four modules as follows:

1) The input data sets, which include hourly weather data (temperature, humidity, solar radiation, etc.) of the typical meteorological year (TMY) for 270 meteorological stations in China, the thermal parameters of buildings in each climate zone, the latest energy prices (gas, electricity) in various regions, and some other relevant data based on above investigations.
2) The building thermal load module, which is for calculating the hourly cooling and heating load of the building, is based on the transient overall energy balance equation as described by Mattia De Rosa [16]. A typical office building, which was established by Xu Peng [17], is selected for analysis of its cooling and heating thermal demand in different regions. Table 1 gives the key parameters of the building.

Table 1. Parameters of the typical office building

Basic characteristic	Parameter	Severe cold	Cold	Hot summer & cold winter	Warm	Hot summer & warm winter
	U_{wall} (W/m^2.K)	0.427	0.567	0.888	1.218	1.490
	U_{roof} (W/m^2.K)	0.325	0.569	0.638	0.509	0.700
	U_{window} (W/m^2.K)	2.670	2.670	2.670	3.159	2.951
	SHGC	0.821	0.821	0.821	0.762	0.701
Total area: 19,200 m^2	sqm /person	10	10	10	10	10
Windows area ratio: 40% Floor height: 4 m	Equip rate(W/m^2)	12	12	12	12	12
Num. of layers: 12	Light rate(W/m^2)	8	8	8	8	8

3) The GSHP system energy efficiency calculation module includes underground vertical heat exchanger heat transfer calculation model and heat pump performance model. A detailed description of the above two calculation models can be found in Hua Qian [18]. The supply/return water temperature of GSHP system is assumed 7/12℃ in summer and 45/40℃ in winter, respectively.
4) The economic analysis module. Taking the air-conditioning system commonly used in office buildings (chiller + boiler) as a reference, the static payback period of incremental investment in GSHP system is analyzed. Compared to the reference system, the incremental investment of GSHP systems is mainly

composed of installation costs of vertical ground-coupled heat exchanger (GHE). Due to the variation of drilling speed caused by geological conditions, the installation cost varies greatly everywhere. Based on shallow geological surveys of various provinces in China, Fig.10 shows the regional variation of drilling speed.

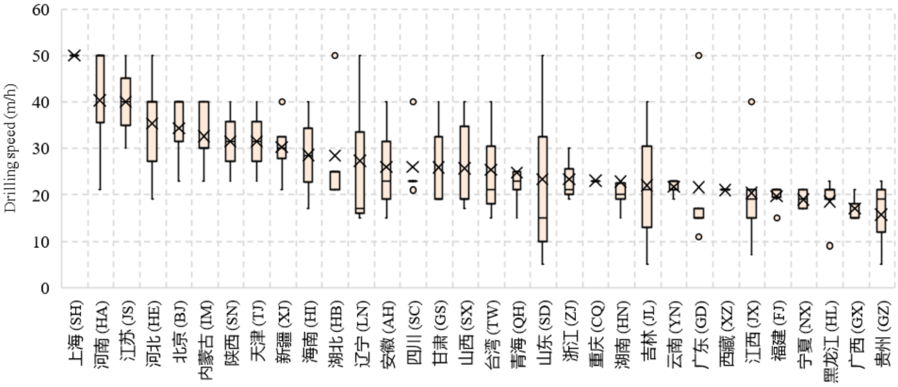
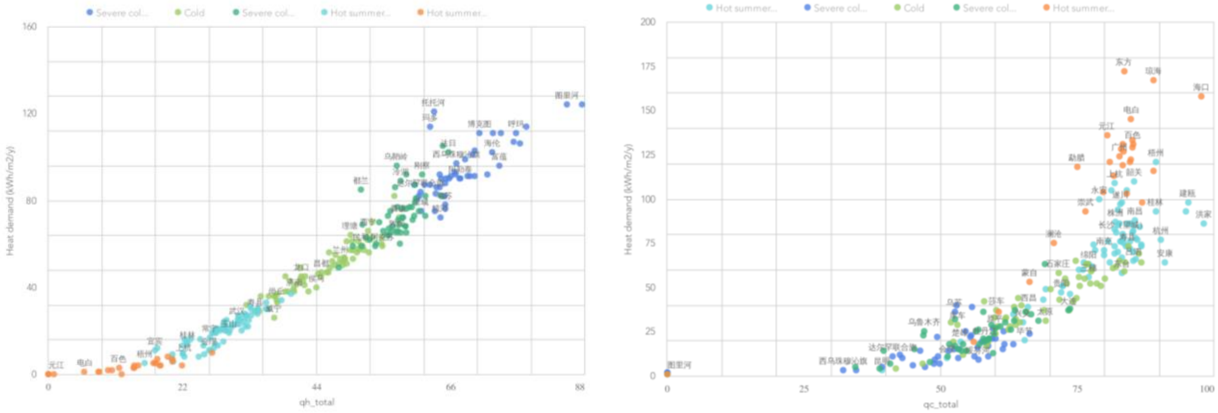


Fig. 10. Regional variation of drilling speed

3.2. Building thermal load analysis

The peak heating/cooling load and thermal energy demand of the typical office building in the areas represented by the 270 weather stations are analyzed, as shown in Fig.11. These two figures (Fig.11. (a) and (b)) indicates a perfect positive linear relationship between peak heating/cooling load and thermal energy demand. During the heating season, peak heating load and heat energy demand in hot summer and warm winter climate zones are very low, within a range of 0-27 W/m^2 and 0-10kWh/m^2/yr, respectively. And the peak heating load and heat energy demand in severe cold climate zones are highest compared to other zones, within a range of 60-88 W/m^2 and 72-125 kWh/m^2/yr, respectively. Similarly, there is a huge gap both in peak cooling load and cold demand among different climatic zones during cooling season. In contrast to the heating season, the peak cooling load and cold energy demand in the hot summer and warm winter regions are both the highest, within a range of 70-100 W/m^2 and 75-158 kWh/m^2/yr, respectively. In severe cold climate zones, there is less demand for cooling, and some places do not even need cooling in summer.

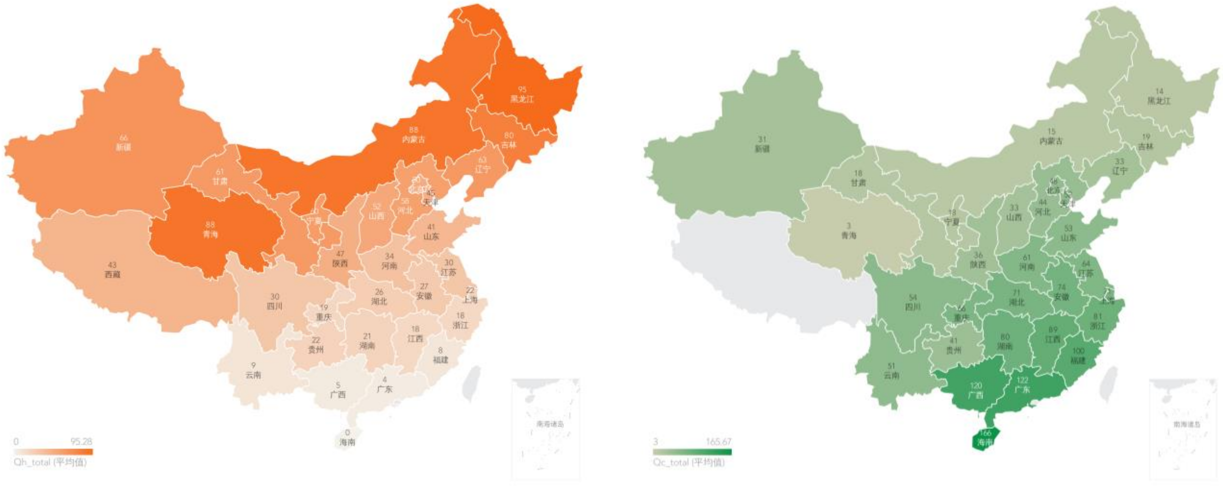


(a) Heating season.

(b) Cooling season.

Fig. 11. Variation of peak heating/cooling load vs thermal energy demand in different regions.

As shown in Figure 11, there is a significant difference in cooling (or heating) demand among different weather stations in the same province. In order to promote the adaptability evaluation analysis on the provincial level, we averaged the cooling/heating demands of the meteorological stations in each province. Figure 12 shows the differences in cooling and heating needs across the provinces. The results suggest that the maximum annual thermal demand for heating and cooling is 95kWh/m^2/yr in Heilongjiang(HL) province, and 166 kWh/m^2/yr in Hainan(HI) province, respectively. And the minimum annual thermal demand for heating and cooling is 0 kWh/m^2/yr in Hainan(HI) province, and 3 kWh/m^2/yr in Qinghai(QH) province, respectively.



(c) Heating season.

(d) Cooling season.

Fig.12 Distribution of thermal energy demand (kWh/m^2/yr).

3.3. *Results of feasibility evaluation*

The results of the adaptability evaluation analysis on the provincial level are presented in Table 2 and Figure 13. Abbreviations in the Table 2 represent the following meanings: Q_C / Q_h — annual thermal energy demand for cooling/heating; *EFLH(c)* / *EFLH(h)* —equivalent full-load cooling/heating hours; *Price_elc* / *Price_gas* — purchase price of electricity/gas; *App_Cap* / *App_rate*—applicable capacity/rate of GSHP based on underground thermal balance; *EC_Sum* / *EC_Win* / *EC_Ann*—summer /winter /annual primary energy savings by GCHP system compared to reference system(chiller +gas boiler); *Paybak_yr*—the static payback period of the GCHP system compared to reference system. Figure 12 reflects the energy savings, cost-efficiency, and availability of GCHP applications in each province. The size of bubbles in the figure represents the availability of GCHP in the region, and the labels in the figure indicate the province name, availability, primary energy savings, and payback period, respectively.

Table 2. The results of the adaptability evaluation analysis on the provincial level

PROVINCE -	Qc kWh/m²/yr	Qh kWh/m²/yr	EFLH(c) hr	EFLH(h) hr	Price_elc CNY/kWh	Price_gas CNY/Nm³	App_Cap W/m²	App_rate -	EC_Sum kgce/m²/yr	EC_Win kgce/m²/yr	EC_Ann kgce/m²/yr	Paybak_yr yr
海南/HI	166	0	1851	0	0.85	3.30	0.0	0%	0.00	0.00	0.00	0.0
青海/QH	3	88	150	1503	0.58	1.70	15.6	27%	0.03	0.10	0.14	50.0
广东/GD	122	4	1457	237	0.99	4.85	14.2	17%	0.00	0.23	0.23	18.0
广西/GX	120	5	1411	306	0.91	4.20	15.9	19%	0.00	0.30	0.30	22.1
福建/FJ	100	8	1195	365	0.87	3.42	21.2	25%	0.01	0.43	0.44	24.8
云南/YN	51	9	811	315	0.73	3.40	19.2	34%	0.01	0.46	0.46	17.8
黑龙江/HL	14	95	285	1369	0.94	4.30	49.5	71%	0.27	0.53	0.80	18.8
内蒙古/IM	15	88	310	1355	0.73	2.00	45.8	71%	0.20	0.64	0.84	50.0
浙江/ZJ	81	18	925	621	0.95	4.84	28.2	32%	0.06	0.91	0.97	8.3
江西/JX	89	18	1073	644	1.06	3.44	27.3	33%	0.05	0.93	0.97	18.9
重庆/CQ	66	19	845	713	0.84	2.78	25.5	33%	0.05	0.93	0.99	20.1
贵州/GZ	41	22	580	688	0.95	4.00	31.2	45%	0.08	1.00	1.08	14.3
湖南/HN	80	21	948	736	1.03	3.88	28.4	34%	0.07	1.07	1.14	10.6

宁夏/NX	18	60	303	1178	0.77	2.24	52.8	100%	0.16	1.01	1.17	50.0
吉林/JL	19	80	312	1283	0.95	4.30	58.3	93%	0.31	0.87	1.18	15.3
甘肃/GS	18	61	315	1205	0.81	2.64	54.5	100%	0.17	1.01	1.18	32.5
上海/SH	71	22	907	679	0.92	3.79	32.4	41%	0.08	1.10	1.18	6.0
西藏/XZ	20	43	400	1040	0.85	1.60	50.0	100%	0.19	1.15	1.33	50.0
湖北/HB	71	26	872	811	0.98	4.08	31.6	39%	0.10	1.27	1.37	6.4
安徽/AH	74	27	877	838	0.89	3.60	32.5	38%	0.12	1.33	1.45	8.9
四川/SC	54	30	707	812	0.86	3.25	33.7	46%	0.17	1.30	1.47	10.7
江苏/JS	64	30	754	878	0.88	3.65	34.5	41%	0.16	1.43	1.59	5.6
河南/HA	61	34	753	919	0.79	3.53	37.0	46%	0.17	1.57	1.74	5.1
山东/SD	53	41	703	1014	0.75	4.14	40.6	55%	0.23	1.80	2.03	6.0
新疆/XJ	31	66	531	1155	0.69	2.11	57.7	100%	0.21	1.94	2.15	29.7
陕西/SN	36	47	504	1037	0.87	2.30	44.5	66%	0.23	1.93	2.16	42.5
天津/TJ	52	45	711	1004	0.86	3.25	44.8	61%	0.24	1.95	2.20	9.0
北京/BJ	48	50	681	1051	0.82	3.65	47.1	67%	0.29	2.08	2.37	5.6
辽宁/LN	33	63	500	1152	0.89	3.90	65.5	100%	0.44	1.95	2.39	7.6
山西/SX	33	52	478	1078	0.71	3.60	66.0	100%	0.30	2.15	2.45	8.2
河北/HE	44	58	623	1146	0.86	3.45	49.5	73%	0.38	2.21	2.59	5.6

From the evaluation results we can draw the following conclusions:

1) From the perspective of maintaining the underground thermal balance, vertical ground coupled-heat pumps are not suitable for application in Hainan(HI) province because there is only cooling load but no heating demand throughout the year. GSHP can be fully used in Liaoning(LN), Shanxi(SX), Ningxia(NX), Gansu(GS), Xinjiang(XJ), and Tibet(XZ) to meet all summer cooling and winter heating needs, and partly meet cooling or heating needs in the other provinces where should combine with auxiliary cold or heat source system.
2) Compared to reference system (chiller +gas boiler), energy savings by GCHP system in heating season are much greater than in cooling season in all regions. The highest energy saving area in summer is Liaoning (LN) province with 0.44 kgce/m^2/yr, due to its low underground temperature (low condensing temperature) and high applicable rate of GSHP. And there are almost no energy savings during cooling season in Guangdong(GD), Guangxi(GX), and Fujian(FJ) provinces, etc. There are 8 provinces with annual energy savings exceeding 2 kgce/m^2/yr, namely Hebei(HE), Shanxi(SX), Liaoning(LN), Beijing(BJ), Tianjin(TJ), Shaanxi(SN), Xinjiang(XJ), and Shandong(SD). And the highest annual energy saving area is in Hebei Province, reaching 2.59 kgce/m^2/yr.
3) From the perspective of cost-efficiency, the payback period varies greatly among regions. There are 10 provinces with a payback period of more than 20 years, and 12 provinces less than 10 years.
4) Considering both energy-saving and economic indicators, it can be divided into five groups as shown in Figure 13. The group A is outstanding in terms of energy and cost-efficiency, and it is the most suitable area for promoting GCHP in office buildings. The group C has a certain amount of energy savings and an acceptable investment payback period. It is the second most suitable area for promoting ground source heat pumps after the group A at this stage. The group B and D have a long payback period due to the very low local energy prices, especially low purchase price of gas, and they will change to group A and group C under the scenario of rising gas prices or subsidizing electricity prices. The group E, including Guangdong(GD), Guangxi(GX), Yunnan(YN), Fujian(FJ), and Qinghai(QH) province, is not suitable for GSHP application in office buildings, due to its poor energy and cost efficiency.

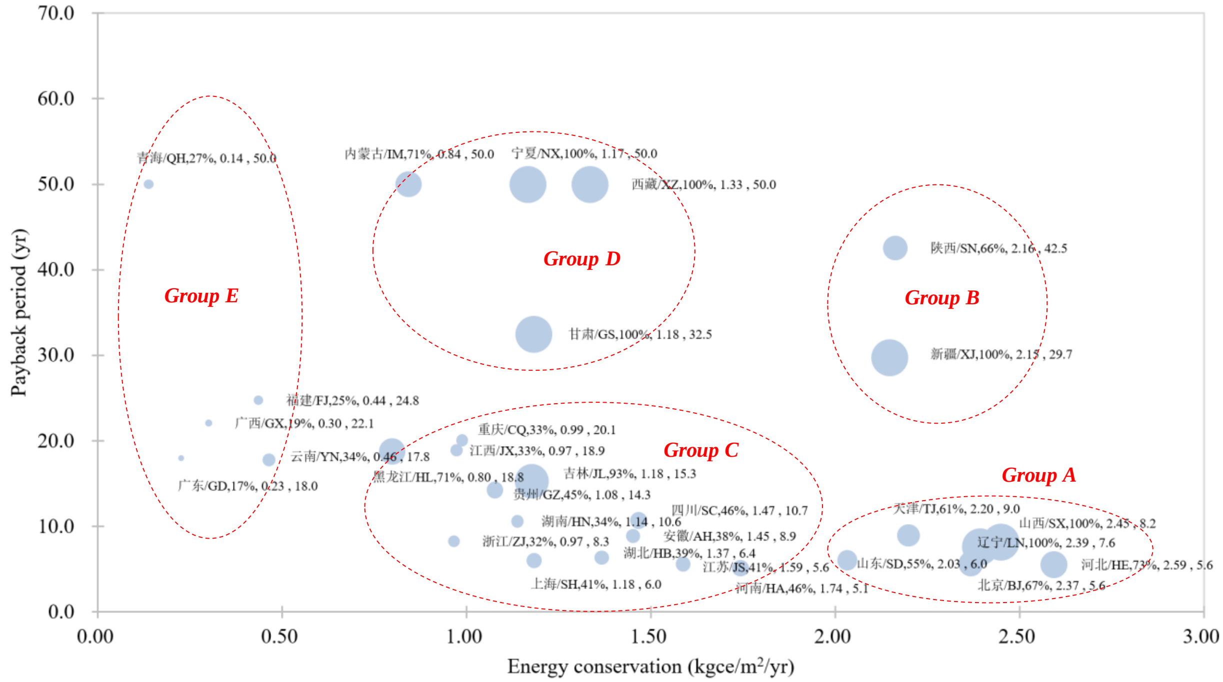


Fig.13 Technical-Economic evaluation of GSHP.

4. Conclusions

In this paper, more than one hundred GSHP cases are investigated through literature surveys and field data collection. Based on the post-evaluation results, a model for assessing the adaptability of GCHP is established. The feasibility evaluation of GCHP applied to office buildings are carried out. Based on the above analyses, some important conclusions could be drawn:

1) There are significant energy savings (more than 0.8 kgce/m^2/yr) by GSHP applications in almost all regions, except for Guangdong(GD), Guangxi(GX), Yunnan(YN), Fujian(FJ), and Qinghai(QH) province.
2) In general, the payback period for GSHP applications are still a bit too long. The government needs to give such projects initial investment subsidies or electricity price concessions, especially in areas where gas prices are relatively low.

Acknowledgements

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