Renewable and Sustainable Energy Reviews 48 (2015) 558–570

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

A comparative study of the status of GSHP applications in the United States and China

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ARTICLE INFO

Article history:
Received 13 December 2013
Received in revised form
21 January 2015
Accepted 3 April 2015

Keywords:
Ground source heat pump
Applications
Markets
Policies
Standards and certifications

ABSTRACT

Ground source heat pump (GSHP) or geothermal heat pump technology was first developed and commercially introduced in the late 1970s, and GSHP units representing approximately 3.9 million tons of cooling had been installed in the United States by 2012. Applications of GSHP technology also have grown rapidly in China since it was introduced into China in the 1990s through collaboration between the Chinese and US governments. It is estimated that by 2013, about 400 million m^2 (4.3 billion ft^2) of building floor space in China was heated and/or cooled by GSHP systems. Governments in both China and the United States have programs that in some way support and/or promote the use of GSHP technology. After decades of practice, both countries have accumulated abundant experience in applying GSHP technology, but both also are confronted with various challenges to rapidly deploying this technology. Under the sponsorship of the US–China Clean Energy Research Center for Building Energy Efficiency, researchers reviewed and compared the current status of GSHP applications in the United States and China, including related policies, standards, technologies, equipment, costs, market development, and barriers. Based on this comparative study, future collaborations between the two countries are recommended to improve the application of the GSHP technology and fully realize its energy saving potential.

Contents

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http://dx.doi.org/10.1016/j.rser.2015.04.035
1364-0321/

1. Introduction

The United States and China account for over one third of global primary energy consumption and greenhouse gas emissions [1,2]. China has surpassed the United States to become the world's largest emitter of greenhouse gases (GHGs) since 2010 [2]. Both countries have aggressive goal for GHGs emissions. President Obama of the United States recently announced a new target to cut net greenhouse gas emissions 26–28% below 2005 levels by 2025. At the same time, President Xi Jinping of China announced targets to peak CO_2 emissions around 2030, with the intention to try to peak early [3].

Buildings contribute significantly in primary energy consumptions and associated GHGs emissions in the two countries: roughly 25% in China and 39% in the United States [1,4]. More than 50% of the energy consumed in buildings in China and the United States is for space heating, space cooling, and domestic water heating [1,5]. Improving energy efficiency of these essential services presents one of the best opportunities to economically reduce energy consumption and limit GHGs emissions.

Ground source heat pumps (GSHPs), also referred to as a geothermal heat pumps (GHPs), have been proven capable of producing large reductions in energy use, GHGs emissions and peak electricity demand in buildings while satisfying the demands for space heating, space cooling, and domestic water heating. GSHPs utilize the ground, groundwater, or surface water as a heat source and sink [6]. Other monikers used for variations of this technology include ground-coupled heat pump (GCHP), groundwater heat pump (GWHP), and surface water heat pump (SWHP).

GSHP technology was initially developed and commercially introduced in the United States in the 1970s. The application of GSHP technology has grown rapidly in China during the past decade. Governments in both China and the United States have programs that in some way support and/or promote the installation of GSHPs. After decades of practice, both countries have accumulated abundant experience in the application of GSHP technology, but both also are confronted with various challenges to rapidly deploying this energy-saving technology.

There have been many literatures reviewing various aspects of GSHP applications in the United States and China [7–13]. It is of interest to the policy makers and GSHP industry of the two countries to compare the difference in applying the GSHP technology in the two countries, analyze the underlying reasons, and identify areas that each country can learn from each other to make most use of the GSHP technology for achieving the aggressive GHGs emissions reduction goal. However, there has not been any side-by-side comparison on the state-of-the-art of GSHP applications in the two countries.

Under the sponsorship of the US–China Clean Energy Research Center for Building Energy Efficiency, a comparative study is conducted on the current status of GSHP applications in the United States and China. This comparative study is performed based on extensive information collected from literature review, surveys to industry experts, and decades of experience of the authors in the GSHP industry.

This paper summarizes the results of this comprehensive study in six areas: characteristics of GSHP applications, applied technologies, market development, policies and incentives, standards and certifications, and barriers and problems. Based on the results of this comparative study, recommendations are given for collaboration in the application and advancement of the GSHP technology between the two countries.

2. Characteristics of GSHP applications

Based on the available information, the current status of GSHP applications in the United States and China is depicted in Table 1 via a side-by-side comparison in three categories: geographical distribution, building characteristics, and cumulative GSHP applications in the two countries. As can be seen from Table 1, GSHPs have been used in all climate zones and all types of buildings in both countries. Although GSHP application in China began about three decades later than in the United States, cumulative GSHP use in China is already larger than in the United States as a result of the rapid growth of GSHP installations in China in recent years.

Figs. 1 and 2 graphically show the distribution of GSHP applications in the United States and China. The distribution of US applications shown in Fig. 1 is based on 2009 data on the destinations of GSHP unit shipments in the United States [14] and is color-coded based on the total rated capacity (in cooling ton[1]) shipped in that year. The distribution of Chinese GSHP applications shown in Fig. 2 is based on a survey conducted by Chinese Geological Survey [15] and is color-coded by the cumulative building floor space conditioned with GSHP systems by 2010. Various climate zones in each country are indicated by solid lines in the two figures. It appears, in both countries, GSHP applications are more concentrated in areas with a cold climate and high population density. As shown in Fig. 2, GSHP systems applied in cold climate zones account for nearly 70% of the total floor space conditioned by GSHP systems in China. In addition, GSHP systems are more widely used in the middle and eastern parts of China, where the population is larger. The unique advantages of GSHP systems are thought to be the main reason for such a distribution, including high heating efficiency, especially when the GSHP is integrated with low-temperature radiant floors, and elimination of on-site combustion and emissions. High heating fuel costs and the financial incentives offered by local governments and/or utilities also contributed to the relatively higher concentration of GSHP applications in those areas [10].

3. Applied technologies

3.1. Heat sinks and sources

The vast majority of GSHP systems in the United States use closed-loop ground heat ex-changers (GHXs) buried in the earth in either a vertical or horizontal configuration. It is estimated that vertical and horizontal closed-loop GHXs are used in 46 and 38% of GSHP systems in the United States, respectively, with the remaining 16% of GSHP systems using groundwater or surface water in an open-loop or closed-loop configuration [11]. The first GSHP system in the United States that directly uses filtered raw sewage water as a heat sink and source was commissioned in April 2012 [16].

In contrast, the heat sinks/sources used in GSHP systems in China are widely diversified. Closed-loop GHXs are used in only about 32% of GSHP systems in China, groundwater is used in nearly 42% of the systems, and other less-conventional resources (i.e., surface water and wastewater) are used in the remaining 26% [8]. Several Chinese companies have developed patented filter technologies that allow direct use of raw sewage water as the heat sink and source for GSHP systems [17]. In a few GSHP systems, including the main building of the 2010 Shanghai World Expo, closed-loop GHXs were integrated into the building foundation pilings to reduce drilling costs and land area requirements [18]. Different types of heat sinks and sources are applied in different climate zones. Groundwater is widely used in Beijing, Liaoning, Hebei and Shandong Provinces, which are mainly in the cold climate zone. Ground-coupled closed-loop GHXs are mainly applied in Beijing, Hubei, and Jiangsu provinces, which are mainly in the cold and “hot summer and cold winter” climate zones. Surface water (i.e., lake, river, and ocean) is mainly used in the

[1] A cooling ton is equal to 3.5 kW cooling capacity.

Table 1
Comparison of current GSHP applications in the United States and China.

	Geographical distribution	Building characteristics	Cumulative GSHP applications
US	Used in all the 50 states and the District of Columbia. About 52% of domestic GSHP shipments went to ten states: Florida, Illinois, Indiana, Michigan, Minnesota, Missouri, New York, Ohio, Pennsylvania, and Texas [2]	The split between the cumulative residential and commercial GSHP applications by 2012 is 3.5:1 [34]. It is estimated that 75% of residential applications are in new construction and 25% in retrofits of existing homes [40]	Approximately 3.9 million tons of GSHP units have been installed by 2012 [34]. This corresponds to roughly 199 million m^2 (2.14 billion ft^2) of building floor space[a]
China	Widely applied in all climate zones. About 50% of GSHP-conditioned floor space is in four provinces (municipalities): Shandong, Liaoning, Beijing, and Jiangsu. GSHPs are relatively more common in urban areas with developed economies and less common in rural areas, small towns, and western China	All types of buildings, including residential, commercial, and industrial buildings [36]. Used more in residential buildings in the northern region, while more popular in commercial/public buildings in climate zones with hot summers and cold winters	In total, approximately 400 million m^2 (4.31 billion ft^2) of building floor space is conditioned with GSHP systems as of 2013 [9,37]

[a] The total floor space conditioned by GSHP systems is estimated with the typical floor space per ton ratio in the US—400 ft^2 per ton for commercial buildings and 600 ft^2 per ton for residential buildings.

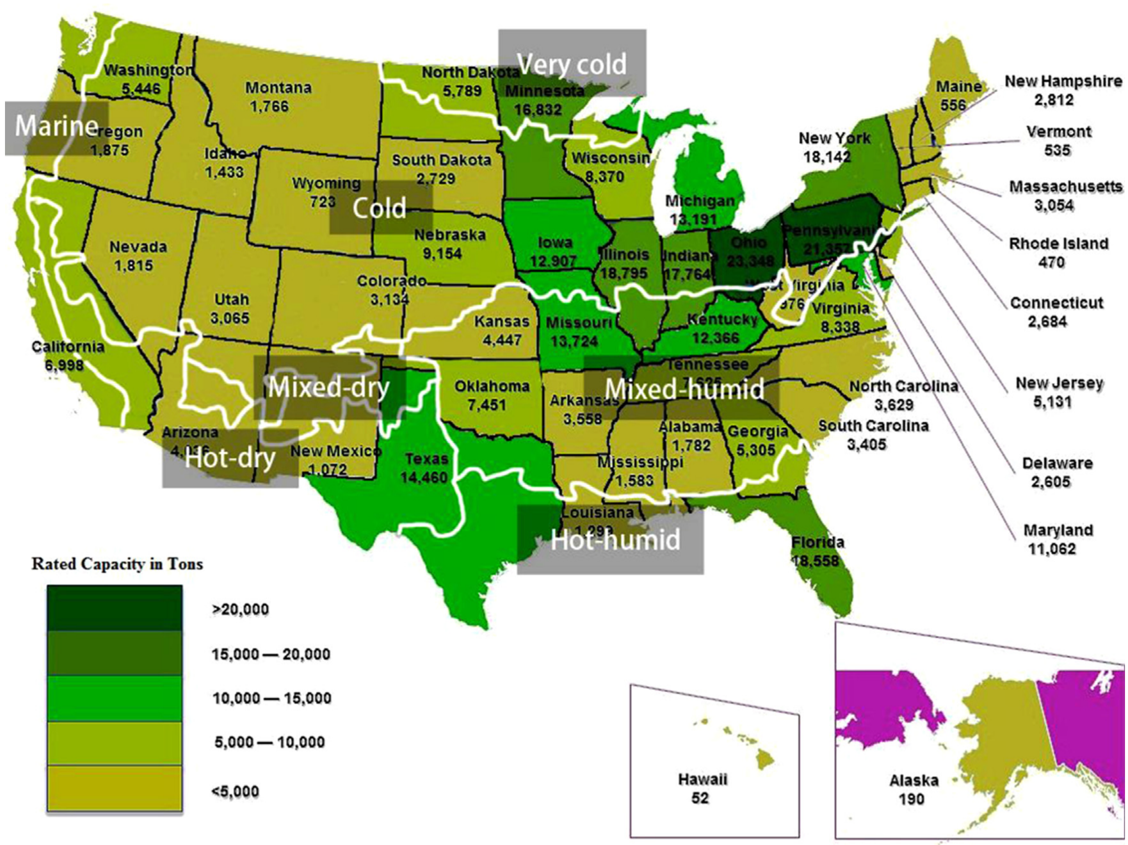

Fig. 1. Distribution of GSHP unit shipments in the United States in 2009 [14].
Note: The number below each state name indicates the total capacity of GSHP shipment in 2009 in the particupar state; the white lines indicate various climate zones in the US)

"warm" and "hot summer and warm winter" climate zones and at places where surface water is abundant.

The difference in the heat sources and sinks used in the United States and China is thought to be due, at least in part, to the fact that the building size and the required heating, ventilation, and air-conditioning (HVAC) system capacity for a typical GSHP application in China is larger; but the available land for installing closed-loop GHXs is more limited. Since groundwater can provide a large capacity using a minimal amount of land, GWHPs have been widely adopted in China, especially in the East-North region, with strong support from local governments. For example, the usage of groundwater in GWHP applications is free of charge [19,20]. Only time will tell, but in some cases, environment protection may not have been given adequate consideration during the development process in China. On the other hand, the use of groundwater for space conditioning through GWHP systems is limited in the United States partly by the complex regulatory framework for obtaining permits to drill groundwater wells. According to a recent survey of geothermal heat pump regulations in the United States [21], although there is no nationwide consensus among regulators concerning appropriate regulations for drilling water wells and using groundwater in open-loop GSHP systems, each state tends to apply its water well regulations to these systems with an intent to protect groundwater. The Environmental Protection Agency's (EPA's) National Pollutant Discharge Elimination System (NPDES) regulations specifically govern surface discharge of groundwater. A state or other governing body can adopt regulations that are more strict than the NPDES. Some

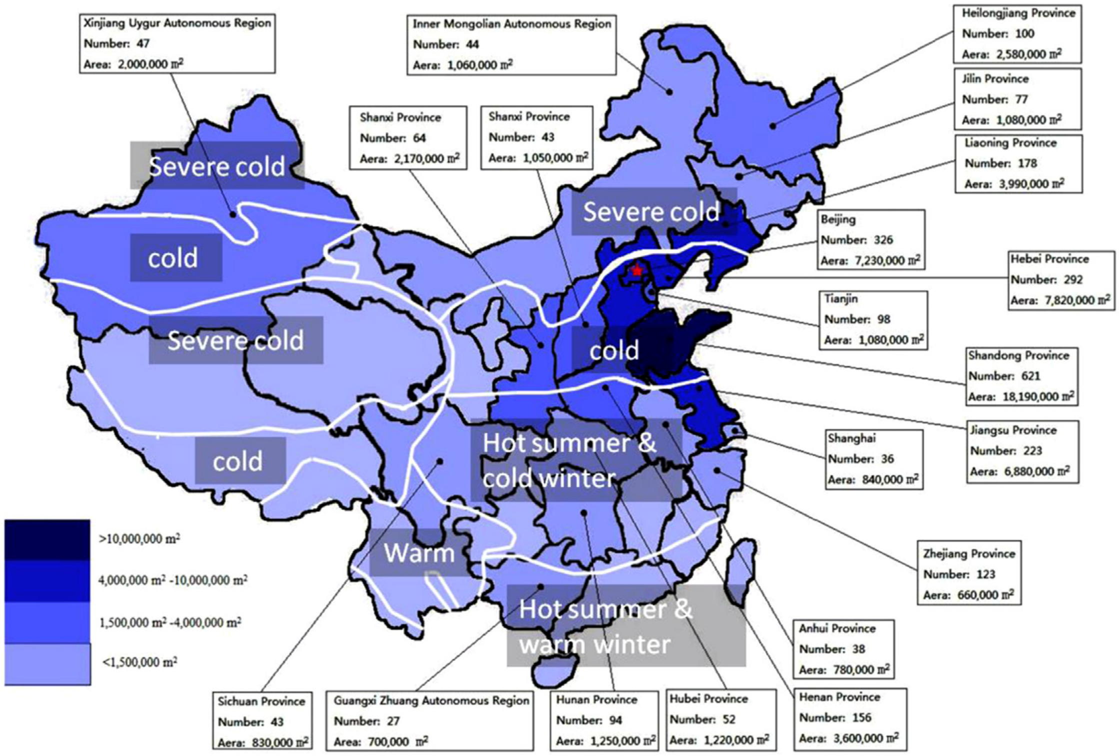

Fig. 2. Distribution of GSHP applications in China [15].
Note: The number in the boxes indicates the total number of GSHP projects in a particular province in China)

states prefer surface discharge for GWHP systems and others forbid it. Many states are concerned about surface discharge only if the change in the water temperature through the GWHP system is large, which is typically not the case. If the groundwater is re-injected underground through return wells, those wells are covered by Underground Injection Control regulations. Many states have regulations governing the spacing of wells, allowable depths, and other factors. An EPA reporting requirement exists for injection of water to a return well for GWHP systems.

3.2. Equipment

In the United States, there were 27 known domestic manufacturers of GSHP equipment at the latest count [14]. Domestic manufacturers are well established in the US GSHP market, and direct import of GSHP equipment manufactured in other countries is rare there. A couple of international brands have recently penetrated the US market through acquiring domestic manufacturers.

Most of these manufacturers produce water source heat pump (WSHP) units not only for GSHP systems but also for water-loop heat pump (WLHP) systems, which use more conventional cooling towers and boilers instead of GHXs. Small packaged or split water-to-air heat pump units with cooling capacities ranging from 0.5 to 20 t (1.74–70 kW) are most commonly used in the United States. Large central water-to-water heat pump chillers or modular water-to-water heat pump units have recently captured some market share in large commercial GSHP systems [22]. The efficiency and applicability of GSHP units have been improved significantly in recent years as a result of a number of technological advancements, including inverter–compressor technology with communicating controls, along with improvements and refinements to refrigerant coils and to all aspects of variable-speed motors [23]. The latest GSHP models launched by a few manufactures have energy efficiency ratios (EERs) for cooling higher than 40[2] and coefficients of performance (COPs) of up to 5.3 for heating. At least one of these new GSHP models can provide not only space heating and cooling but also 100% of the domestic hot water [24]. These GSHP units can vary their heating or cooling outputs in a wide range – from 20 to 130% – provide good humidity control and can even eliminate the need for auxiliary heat in cold climates. More and more GSHP manufacturers offer online control and monitoring capabilities to provide homeowners with key data on their energy usage and tools to control it. These features also help contractors diagnose and fix problems more efficiently [23]. According to the US Energy Information Administration, direct employment in the GSHP manufacturing industry accounted for 1832 person-years in 2009 [14].

High-density polyethylene pipes are predominantly used in closed-loop GHXs in the United States. Truck-mounted rotary or sonic drilling equipment, which is usually designed for water well or oil drilling, is most commonly used to drill the boreholes for vertical closed-loop GHXs [25]. Directional drilling technology, which is primarily used in the oil and natural gas industry, has been adapted recently to drill angled or horizontal boreholes to reduce land requirements and disturbance of the ground surface [26].

In China, many GSHP equipment manufacturers have emerged in the past 10 years, and now the total number is more than 200. Most of these manufacturers are located in Shandong province, Beijing, Shenzhen, Dalian, Hangzhou, Suzhou, and Guangzhou [7]. The domestically made GSHP equipment is mostly of the large central water-to-water heat pump variety, using screw compressors and shell-tube heat exchangers. There are also modular GSHP units using scroll compressors and flat-plate or shell-tube heat exchangers. The cooling capacity of large central units in China ranges up to 2000–3000 kW (570–860 t) but typically is in the 50–

[2] It is equivalent to a cooling COP of 11.7.

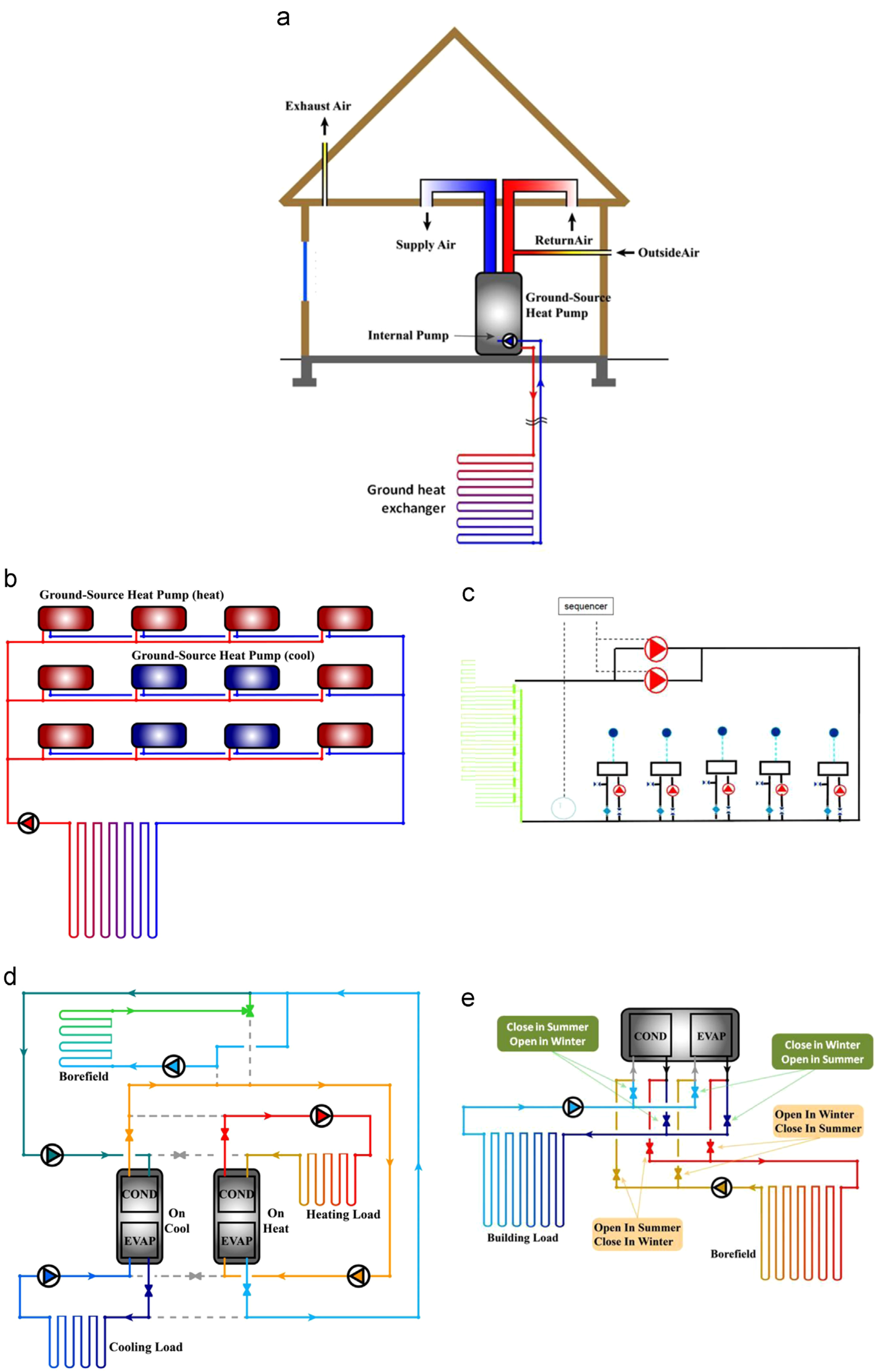

Fig. 3. Typical configuration of GSHP systems used in United States and China. (a) Typical configuration of residential GSHP system in the United States, (b) Typical configuration of decentralized GSHP systems (with a two-pipe loop), (c) Schematic chart of a decentralized GSHP system with a one-pipe loop [27], (d) A cascaded central GSHP system with multiple chillers to simultaneously provide both chilled and hot water [redrawn based on the schematic given in reference #29] and (e) Typical configuration of central two-pipe loop GSHP systems in China.

2000 kW range (15–570 t). Small GSHP units with 10 kW (3 t) cooling capacity also are manufactured for residential applications. In addition to the domestic brands, many internationally renowned brands have become active in China by establishing a manufacturing base directly or through joint-venture companies to serve the Chinese market locally.

In addition to heat pump manufacturers, there are more than 100 other manufacturers of specialty products unique to the GSHP system. The design and installation infrastructure of the GSHP industry has grown rapidly in China, and it is estimated that the total current workforce exceeds 100,000 people.

3.3. System configurations

The most common GSHP system configuration used in US homes consists of a packaged water-to-air heat pump with a centrally ducted forced-air distribution system that conditions one floor of a multi-story home, or the entire house, as seen in Fig. 3(a). A combination of this forced-air system with a hydronic radiant floor is often used in high-income housing in cold northern regions to provide both forced-air cooling in summer and combined forced-air and radiant heating in winter for better thermal comfort and quicker response to varying heating demands. In those cases, a water-to-water heat pump is connected to the GHX in addition to the water-to-air heat pump; a control strategy is needed to determine the priority between the forced-air and the radiant heating based on the heating demands and occupancy schedule.

For commercial buildings – such as offices, schools, hotels, or large residential buildings with multiple dwelling units – decentralized GSHP systems are predominantly used in the United States [22]. With a decentralized GSHP system, each zone of the building is conditioned with an individual heat pump unit, and the multiple units are connected to a common water loop. Traditionally, a two-pipe water loop is used with a central pumping station as shown in Fig. 3(b). To save pumping energy, the central pump is usually operated with a variable-speed drive. Recently, a one-pipe loop design has been introduced as shown in Fig. 3(c) [27]. In this design, all the heat pumps are connected in series with a one-pipe water loop. Each individual heat pump has a dedicated circulator to extract water from and reject it back to the water loop after exchanging heat in the heat pump. A pair of central pumps circulates water through the one-pipe loop and the GHX. The operation of the central pumps is controlled based on the loop temperature. This design can reduce the piping cost and save pumping energy without using more expensive variable-speed pumps and the associated flow control devices at each heat pump [27,28]. However, the drawback of such a pumping configuration is that the operating efficiency of the heat pumps downstream of the one-pipe loop could be lower because of the change in water temperature along the one-pipe loop.

Central GSHP systems, which use large heat pumps or modular water-to-water heat pumps to generate hot and/or chilled water for delivery to the conditioned space, have also been used in the United States, especially for retrofitting existing central chiller and boiler systems (e.g., a central district GSHP system at Ball State University in Indiana). As shown in Fig. 3(d), to satisfy the simultaneous demands for heating and cooling in different zones of a building, central GSHP systems in the United States usually have four-pipe distribution systems: two pipes for supply and return of chilled water and another two pipes for supply and return of hot water. Recently, Trane introduced a cascade configuration for central GSHP systems that uses multiple heat pump chillers, which could improve heat pump efficiency at the central plant by taking advantage of the simultaneous heating and cooling operations of different heat pump chillers [29].

In China, central GSHP systems are the most commonly used type. However, unlike the four-pipe configuration used in the United States, most of these central GSHP systems use a two-pipe distribution as shown in Fig. 3(e). Two-pipe systems can provide only heating or cooling at any given time and cannot provide simultaneous heating and cooling to different zones in a building. The application of decentralized GSHP systems is very limited in China as of this writing.

Central and decentralized systems have their particular advantages and disadvantages, as summarized in Table 2. The dominance of the central system with a two-pipe configuration in China is thought to be due to the following reasons [30,31]: (1) the low initial investment requirements, (2) its familiarity to designers, (3) potential energy savings compared with a four-pipe central configuration (with a sacrifice of thermal comfort, especially during shoulder seasons), and (4) the convenience of using it to retrofit existing conventional HVAC systems, which typically use central two-pipe distribution systems in China. However, given the increasing demand for individual indoor environmental control during all seasons and individual metering, continuous strong government support for renewable energy application in buildings, and the mandatory requirements for reducing energy use, it is foreseeable that decentralized GSHP systems will be adopted in China eventually. According to the Ministry of Housing, Urban, and Rural Development (MoHURD) of China and the Ministry of Finance (MoF) of China [32], more than 15% of the energy consumed in the Chinese building sector will be renewable energy (including GSHP, solar thermal, and solar photovoltaic) by 2020. In addition, China is developing a new standard to regulate energy use intensity in various buildings [33]. The many advantages of decentralized GSHP systems (Table 2) could help realize the aggressive goals in renewable energy utilization and energy conservation in China.

Table 2
Comparison of advantages and disadvantages of central and decentralized systems.

	Advantages	Disadvantages
Central system	• Central location for service and maintenance • Relatively easy to retrofit existing conventional central HVAC systems	• Mechanical room is needed and the system is more complicated • System efficiency degrades at part-load conditions • Requires more highly skilled technicians to service central plant • Central equipment redundancy is required unless failures impacting the entire building are acceptable
Decentralized system	• Simple design and limited floor space requirement • Isolated impact of equipment failure and larger pool of technicians capable of providing service • Superior energy efficiency at part-load conditions and capability for individual metering of energy consumption • Inherent heat recovery in the common loop	• Decentralized service and maintenance • Difficulty of retrofitting existing conventional central HVAC systems

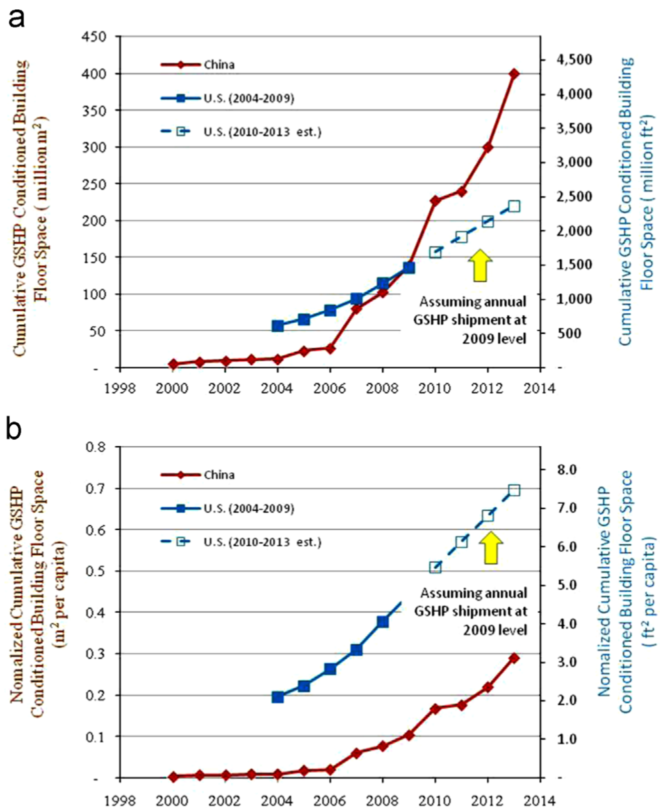

Fig. 4. Cumulative GSHP conditioned building floor space in the United States and China [8,9,14,34] (a) Cumulative floor space and (b) Cumulative floor space normalized with population.

4. Market development

A recent Navigant Research report [34] indicates that the United States represented 29% of global GSHP installations by capacity with 13,564 MWt (3.9 million tons) installed in 2012. These GSHP systems provide space conditioning to roughly 199 million m^2 (2.14 billion ft^2) of residential and commercial buildings in the United States[3]. Shipments of US domestic GSHP units increased rapidly between 2004 and 2008. Total shipments of GSHP units increased by more than 40% in 2008 to 121,243 units, compared with 86,396 units in 2007. The rated capacity of the shipped units grew by 43% in 2008 to 416,105 t, compared with 291,300 t in 2007. However, the total shipments dropped by 2% in 2009 when the economic recession reached the GSHP market segment. It is estimated that the total revenue from sales of domestic GSHP units was approximately $319.5 million in 2009[4] [14]. A report issued by Priority Metrics Group [35] estimated that the GSHP market in the United States was about $3.7 billion in 2009, including design, equipment, and installation.

The US GSHP market has been recovering slowly since the bottom of the economic recession in 2009. Based on US Energy Information Administration manufacturer surveys (last updated in 2010), Navigant Research forecast an 11% compound annual growth rate for new GSHP annual shipments between 2013 and 2020. It predicted that annual US GSHP shipments will rise to 256,436 units by 2020 [34].

In China, the GSHP industry has experienced explosive growth since 2005 because of strong promotion and financial incentives offered by the Chinese central government for renewable energy technologies such as GSHPs [36,37]. As shown in Fig. 4(a), the growth rate of building floor space conditioned by GSHP systems in China exceeded 50% in 2006–2013, which is much faster than in 2000–2006 (about 35%); and the average annual growth rate of GSHP applications was nearly 46% between 2000 and 2013, which is much larger than the growth rate worldwide in the same interval [8].

As can be seen in Fig. 4(a), the cumulative building floor space conditioned by GSHP systems in China grown from zero to 400 million m^2 (4.3 billion ft^2) in just one decade. It has already surpassed that in the United States since 2010. However, if the cumulative floor space numbers are normalized by the population of the two countries, the United States has about four times higher GSHP conditioned building floor space per capita than that in China (Fig. 4b).

A few surveys have been conducted in the United States to collect cost information for GSHP systems. According to those surveys, the average cost of a commercial GSHP system increased by 129%, from $9.07/ft^2 in 1995 to $20.75/ft^2 in 2012, or about 1.5% annually over the 17 year period [38]. In contrast, the average annual inflation rate was 2.5% during the same time period [39]. This same study determined that the cost increase (177%) for the interior portion of the GSHP system (including the heat pump and other major equipment, controls, piping, and duct work) exceeded the cost increase for the closed-loop GHX portion (52%) over the 17 year period. In other words, costs for the indoor components, for which the technology is relatively mature, rose at a slightly higher rate (3.4% annually) than inflation; whereas the cost of the newer underground components rose more slowly, presumably as a result of innovations in cost reduction and increased competition in the market. The typical price of a GSHP system installed in a new home is in the range of $3000–5000 per ton [40]; the average price for large-scale housing retrofits is $4600 per ton in 2006 dollars [41].

The simple payback period for a GSHP retrofit project in the United States is usually 8–14 years [12,13]. For new construction, the simple payback period is shorter, but a payback period of more than 5 years is still common [12].

Table 3 summarizes the costs of various GSHP systems in the United States and China. The cost data for GCHP systems that use vertical closed-loop GHXs are from a recent *ASHRAE Journal* article [38], except the cost of the heat pump equipment, which is estimated based on data from a recent Energy Information Administration report [14]. The cost data for GWHP systems in the United States were taken from an informal survey of a few industry experts. Cost data for GCHP, GWHP, and SWHP systems in China were obtained through a survey of GSHP equipment manufacturers and building owners [42]. As can be seen in Table 3, the cost for a GCHP system in the United States is about 2–3 times higher than its counterpart in China; and the cost of a GWHP system is 4–5 times higher in the United States than in China. This cost difference is thought to be due to several factors, including the applied technologies/equipment (i.e., the decentralized system in the United States vs. the central system in China), economies of scale (GSHP systems in China are typically much larger than those in the United States), the cost of labor (the average manufacturing wage in the United States was about 10 times that in China in 2010[5]), and government subsidies. For example, in

[3] The split between cumulative residential and commercial GSHP applications by 2012 is 3.5:1 [34]. The total floor space conditioned by GSHP systems is estimated based on the typical floor space per ton ratio in the United States—400 ft^2 per ton for commercial buildings and 600 ft^2 per ton for residential buildings.

[4] Revenue includes charges for cooperative advertising and warranties but does not include excise taxes and the cost of freight or transportation.

[5] http://mjperry.blogspot.com/2011/11/wage-gap-with-china-continues-to-shrink.html.

Table 3
Costs of various GSHP systems in the United States and China.

System type	Total/itemized cost	United States	China
GCHP(with vertical closed-loop GHX)	Total system	$13–26/ft^2$	¥400–640/m^2 ($6.7–10.7/$ft^2$)
	GHX	$6.76–15/ft	¥40–140/m ($2.0–7.1/ft)
	Heat pump	$2.5–4/ft^2$	¥48–80/m^2 ($0.7–1.2/$ft^2$)
GWHP	Total system	$7.5–12.5/ft^2$	¥108–190/m^2 ($1.7–2.9/$ft^2$)
SWHP	Total system	NA	¥100–180/m^2 ($1.5–2.8/$ft^2$)

Beijing, a GWHP system can obtain a 35 Yuan/m^2 ($0.6/$sf^2$) subsidy from the municipal government; and if reclaimed water is used as the heat sink and source in a GSHP system, it can receive a 50 Yuan/m^2 ($0.8/$sf^2$) subsidy [43].

5. GSHP-specific policies and incentives

In the 1990s, policy makers in the United States noticed GSHPs. The Department of Energy's (DOE's) Energy Information Administration, in a report supporting development of the National Energy Strategy, estimated the GSHP energy savings potential at 2848 quadrillion joule (2.7 quadrillion Btu) by 2030 [38].

In October 1993, the Clinton administration launched the Climate Change Action Plan, as well as the voluntary Climate Challenge, a partnership between DOE and major electric utilities that pledged to reduce their greenhouse gas emissions. The Climate Challenge attracted more than 50 utilities, whose chief executive officers sent letters to the Secretary of Energy stating their intent to either stabilize their greenhouse emissions at or below their 1990 levels or reduce their emissions to a different measurable performance level [45]. The electric utility industry selected GSHP technology as one of its five initiatives under the President's Climate Change Action Plan. The GSHP market mobilization and technology demonstration initiative became known as the National Earth Comfort Program, and the Geothermal Heat Pump Consortium, Inc. (GHPC) was formed to implement it [46].

At about the same time, DOE's Federal Energy Management Program (FEMP) was formed to reduce the cost and environmental impact of the government by advancing energy efficiency and water conservation, promoting the use of renewable energy, and improving utility management decisions at Federal sites. Aggressive US federal energy goals, expressed in terms of energy intensity (site usage in Btu per building area), were established by Executive Order [47]. The goals for 2005 and 2010 were 30 and 35% reductions, respectively, in energy intensity in all federal agencies (excluding industrial and laboratory facilities) compared with energy consumption in 1985. To assist agencies in meeting these goals, FEMP established a comprehensive GSHP program including technical assistance and use of energy savings performance contracts to privately finance GSHP retrofit projects in federal buildings.

The GSHP programs implemented by GHPC for privately owned buildings and by FEMP for federally owned buildings clearly accelerated the growth of the GSHP industry. Annual sales of GSHPs nearly doubled from 1994 to 1999, and GSHP shipments to the federal market increased more than tenfold from FYs 1999 to 2001 [48].

Although this authority has seldom been used because of administrative challenges, federal legislation in 2007 authorized the US Department of Agriculture Rural Utilities Service to provide 35 year loans from government funds to rural electric cooperatives (RECs) for the purpose of installing GHXs for customers. The RECs recovered the cost of repaying the funds through a tariff on customer electricity bills [49].

The federal 2007 Energy Bill directed the General Services Administration to establish a program to accelerate the use of more cost-effective energy-saving technologies and practices in General Services Administration facilities, starting with lighting and GSHPs [50].

As a result of a sequence of pieces of federal legislation, tax credits are provided for GSHP systems installed between December 1, 2009, and December 31, 2016, so long as the heat pump meets Energy Star® requirements. The residential tax credit is for 30% of the entire installed cost of the GSHP system with no maximum cap; the commercial tax credit is for 10% of the entire installed system, and the GSHP system is subject to a 5 year depreciation period [51].

In 2009 the US economy was faltering, and federal legislation was passed to create jobs and stimulate the economy [52]. Energy provisions were a prominent feature of this legislation. Congress directed that $400 million of DOE funds be committed for geothermal energy, and DOE used its discretionary powers to allocate $67 million to GSHP programs. Almost all of this funding was used to competitively select GSHP demonstration projects to receive subsidies [53].

In 2011 federal legislation directed the US Department of Commerce Economic Development Administration to establish a utility-run, on-bill financing pilot program for small business customers for energy efficiency projects, including GSHP installation [54]. The Burlington Electric Department in Vermont was selected to run the pilot program. Under the program, GSHP systems are financed with payments on monthly utility bills, converting the large upfront installation costs into small payments that are more than offset by the monthly energy cost savings realized. In addition to incentives from the federal government, a growing number of states offer tax credits or other incentives for GSHP systems [55].

Unfortunately, since the US Energy Information Administration discontinued its survey of US GSHP unit shipments in 2010, there is not sufficient data available to analyze the impacts of these incentives/programs for promoting GSHP applications in the United States.

In China, financial subsidies for GSHP applications have been provided by the Chinese central government in two stages. In 2006, the Ministry of Construction enacted the *Interim Measures on the Management of Special Funds for Use of Renewable Energy in Building Construction*, in which GSHP systems are identified as one of the key technologies qualifying for the special fund [56]. Before 2009, the subsidies were mainly for pilot demonstration projects. In July 2009, MoHURD (formerly the Ministry of Construction) and the Ministry of Finance jointly rolled out a program to subsidize applications of renewable energy, including GSHP and solar thermal, in buildings in competitively selected cities and rural areas [57]. The subsidization level is 50 to 80 million Chinese Yuan ($8–13.5 million) per selected city based on factors such as economic development level of the city, types of proposed technologies, and potential of energy savings.

In addition to the subsidies from the central government, many local governments have GSHP-specific supporting policies and financial incentives. For example, in Shenyang City, the price of electricity used in commercial buildings that are conditioned by GSHP systems is the same as the residential rate (e.g. 0.5 RMB/kW h, or $0.08/kW h), rather than the normal commercial rate (e.g. 0.85 RMB/kW h, or $0.14/kW h). Some city governments

Table 4
Examples of GSHP-specific policies and financial incentives offered by local governments in China.

District	Policies	Financial incentives	Incentive levels (on a "per building floor area basis" unless otherwise noted)
Beijing City	Beijing city municipal government developed a plan to apply GCHP and waste water heat pump (WWHP) technologies in 18 million m^2 (194 million ft^2) of building floor area during the 12th five-year development plan (issued in September 2011)	Provided one-time subsidies for GSHP systems (issued in May 2006)	GWHP and SWHP:¥35/m^2 ($0.6/$ft^2$) GCHP and WWHP: ¥ 50/$m^2$($0.8/ft^2)
Tianjin City	Tianjin City municipal government developed temporary regulations for the development, installation, and operation of GSHP systems (issued in 2006)	Established a financial support mechanism for encouraging development of green economy and low carbon technologies (issued in 2011)	For GCHP and SWHP system installations with individual metering devices: ¥ 30–50/m^2($0.5–0.8/$ft^2$) with a cap of ¥2 million ($333 K) per project
Liaoning Province	Shenyang City municipal government issued a management method for the development and application of GSHP systems and requested all appropriate buildings in Shenyang City to use GSHP systems	The Department of Construction of Liaoning Province issued a plan in 2008 for promoting GSHP and other renewable energy technologies	GSHP systems receive discounted electricity rates and waivers of the water resource fee (if GWHP system)
Shandong Province	The provincial municipal government developed a plan to demonstrate a group of large GSHP (especially GWHP) projects during the 12th five-year development plan and to increase GSHP applications to 30 million m^2 (322 million ft^2) of building floor area by 2015	Yantai City was awarded ¥100 million ($ 16.7 million) in grants from MoHURD and Ministry of Finance for demonstrating a large-scale city-level application of GSHP technology	For GSHP: ¥20/m^2($0.3/$ft^2$);for integrated solar thermal and GSHP: ¥25/m^2($0.4/$ft^2$)
Henan Province	In 2006 the provincial municipal government requested all public buildings funded by the government to use GSHP systems	Hebi City announced in 2010 temporary rules for managing the city-level demonstration of renewable energy applications in buildings, including GSHP systems	For GSHP systems providing either heating or cooling:¥15/m^2 ($0.25/$ft^2$); for GSHP systems providing both heating and cooling:¥19.5/m^2 ($0.3/$ft^2$)
Zhejiang Province	In 2009 the provincial municipal government developed a detailed plan for implementing GSHP systems in 1 million m^2 (11 million ft^2) of building floor space	Ningbo City issued administrative procedures for securing financial incentives for energy conservation measures, including GSHP systems	Energy service companies receive financial incentives from both the central government (¥240 per ton of coal saved) and Ningbo City (¥60 per ton of coal saved) based on the achieved energy savings of their projects

convinced local banks to provide commercial loans to support GSHP projects with a reduced interest rate (60% of the normal interest rate) to alleviate the financial burden of businesses [19]. Table 4 provides more examples of the policies and financial incentives adopted by local governments.

As a result of the strong government support, GSHP applications in China have grown rapidly since 2006, with an average annual growth rate of more than 50%, which is 43% faster than the rate during the period from 2000 to 2006 [9]. The high growth rate persisted in 2013 and it may be even higher in the future because of increased mandatory requirements and governmental investment in fighting the severe air pollution in China. For example, the Hebei provincial government required that at least 45% of new governmental and large public buildings in large/medium cities shall use GSHPs. The policy also stated that for schools, hospitals, and governmental buildings, the costs for implementing GSHPs shall be included in the budgets of all levels of governments [58].

Table 5
Energy Star minimum efficiency requirements for GSHP equipment in various applications.

Energy Star specifications (effective January 1, 2012)			
Product type		EER	COP
Water-to-air	Closed-loop	17.1	3.6
	Open-loop	21.1	4.1
Water-to-water	Closed-loop	16.1	3.1
	Open-loop	20.1	3.5

Notes:
- The "closed-loop" and "open-loop" applications refer to "ground loop" and "groundwater" applications as defined in ISO/AHRI/ASHRAE Standard 13256, respectively.
- EER=energy efficiency ratio, used to evaluate the cooling efficiency of heat pump equipment. The numbers shown in the table are expressed in Btu/W.
- COP=coefficient of performance, used to evaluate the heating efficiency of heat pump equipment. The numbers shown in the table are expressed in W/W.

6. Standards and certifications

6.1. *Heat pump efficiency standards*

In the United States, several industry standards specify the minimum energy efficiencies of GSHP units in groundwater and ground loop applications, including ASHRAE Standards 90.1 [59] and 189 [60], as well as the Energy Star criteria of the EPA [61]. The heat pump efficiencies referenced must be measured in accordance with International Standards Organization/Air-Conditioning, Heating, and Refrigeration Institute/American Society of Heating, Refrigerating and Air-Conditioning Engineers (ISO/AHRI/ASHRAE) Standards 13256-1 (for water-to-air heat pumps) and 13256-2 (for water-to-water heat pumps) [62,63]. It is the prerogative of federal, state, and local governments and administrators of utility ratepayer-funded incentive programs to adopt the GSHP unit efficiency levels they deem appropriate for their various programs (e.g., building energy codes, procurement requirements, or qualifications for financial incentives). For example, Energy Star certification is a prerequisite for obtaining federal tax credits for GSHP installations [51]. The Energy Star minimum efficiency requirements for GSHP equipment in various applications are listed in Table 5. Currently, more than 3600 GSHP models have been certified by Energy Star.

The Chinese central government published a standard for WSHP equipment in 2003 entitled *Water-Source Heat Pump—Testing and Rating for Performance NEQ* (GB/T 19409-2003), which is based on ISO standard 13256 [62,63] with some revisions and additions. The separate minimum efficiencies for water-to-air and

Table 6
Minimum efficiency requirements for GSHP equipment in various applications specified in Chinese water-source heat pump standard GB/T 19409-2003.

Water-to-air Heat Pump	Unit nominal cooling capacity Q kW (t)	EER		COP	
		GWHP SWHP	GCHP	GWHP SWHP	GCHP
	$Q \le 14$ (4)	13.65	13.31	3.10	2.65
	14 (4) $< Q \le 28$ (8)	13.82	13.48	3.15	2.70
	28 (8) $< Q \le 50$ (14.2)	13.99	13.65	3.20	2.75
	50 (14.2) $< Q \le 80$ (22.8)	14.16	13.82	3.25	2.80
	80 (22.8) $< Q \le 100$ (28.4)	14.33	13.99	3.30	2.85
	$Q > 100$ (28.4)	14.51	14.16	3.35	2.90
Water-to-water heat pump	Unit nominal cooling capacity Q W (t)	EER		COP	
		GWHP SWHP	GCHP SWHP	GWHP	GCHP
	$Q \le 14$ (4)	14.51	13.99	3.25	2.8
	14 (4) $< Q \le 28$ (8)	14.68	14.16	3.3	2.85
	28 (8) $< Q \le 50$ (14.2)	14.85	14.33	3.35	2.9
	50 (14.2) $< Q \le 80$ (22.8)	15.02	14.51	3.4	2.95
	80 (22.8) $< Q \le 100$ (28.4)	15.19	14.68	3.45	3
	$Q > 100$ (28.4)	15.36	14.85	3.5	3.05
	150 (42.7) $< Q \le 230$ (65.4)	15.53	15.02	3.55	3.1
	$Q > 230$ (65.4)	15.70	15.19	3.6	3.15

Notes:
- EER = energy efficiency ratio, used to evaluate the cooling efficiency of heat pump equipment. The numbers shown in the table are expressed in Btu/W.
- COP = coefficient of performance, used to evaluate the heating efficiency of heat pump equipment. The numbers shown in the table are W/W.

water-to-water heat pump equipment specified in this standard are listed in Table 6.

Comparing the minimum efficiency requirements in Tables 5 and 6, it is clear that the Energy Star criteria in the United States are more stringent than the standard in China. However, note that Energy Star is a voluntary program. In the United States, even for mandatory programs such as building energy codes, efficiency levels are set by state and local jurisdictions; and mandatory levels in force on average across the entire country are far lower than those suggested in the most recent ASHRAE Standard 90.1 [59]. In contrast, standards set by the central government in China have a better chance of being implemented nationwide.

6.2. GSHP system design and performance evaluation standards

The International Ground Source Heat Pump Association (IGSHPA), located at Oklahoma State University in the United States, originally developed and maintains a series of manuals and tools for the design and installation of GSHP systems that use closed-loop (horizontal or vertical) GHXs and are applied in residential and light commercial buildings [26]. ASHRAE has published several guides on the design, operation, and commissioning of commercial GSHP systems [64,65]. ASHRAE also maintains a chapter dedicated to the application of GSHP technologies in its *Handbook of HVAC Applications* [6]. The National Ground Water Association has published guidelines for the construction of vertical boreholes for closed-loop GSHP systems, the scope of which includes loop field design, test holes and samples, borehole construction, piping, borehole grouting, loop field identification, and permanent loop piping decommissioning [66]. These publications have been widely accepted by the US GSHP industry.

Properly sizing the closed-loop GHX is very important because this component represents a significant share of the overall system cost. The sizing methodology needs to account for many factors, including the heat rejection and extraction loads imposed on the GHX by the GSHP system—both cumulative thermal energy and loads at peak, the physical layout of the GHX, the thermal properties of the soil/rock formation at the job site, and the thermal properties of the grouting material used to fill the gaps between the pipes and the vertical borehole wall. Several software programs are used in the United States to size closed-loop vertical borehole GHXs, including GLHEPRO, GlheCal, EES, GLD, and GeoDesigner. These software programs require the user to provide building heating and cooling loads at design conditions and estimates of the cumulative loads. In addition, these software programs cannot perform a comprehensive energy analysis of a whole building with a GSHP system. There are a few integrated simulation tools, including eQUEST [67], TRNSYS [68], and EnergyPlus [69], that can be used in sizing the GHX and optimizing the design of GSHP systems. These simulation tools perform all the related building load calculations and HVAC system simulations within one program. They are often used to determine energy savings and other benefits achieved by GSHP systems for LEED (Leadership in Energy and Environmental Design) certification, qualifications for energy efficiency incentives, and so on.

The central government of China issued a national standard for GSHP systems entitled *Technical Code for Ground-source Heat Pump Systems* in 2005 and issued a revision in 2009 [70]. It provides guidance on the design, installation, and commissioning of GCHP, GWHP, and SWHP systems. Additional guidance on GSHP system design is provided in other related standards [71,72]. These standards are similar to the related standards published by IGSHPA and ASHRAE, but they are adapted to Chinese climatic and geographical characteristics.

To evaluate the performance of GSHP systems, both the United States and China have developed protocols for collecting data and assessing the performance of GSHP demonstration projects [36,73]. The two protocols are quite different in their methods for evaluating the performance of heat pump equipment and the GSHP system, as well as for assessing the energy, environmental, and economic benefits of GSHP systems. Whereas the US protocol requires time-interval measurements during a full year of operation, the Chinese protocol relies on short-term measurements (e.g., 1 h for equipment efficiency and 2–3 days for system efficiency). Although the US approach probably will better capture actual

Table 7
Barriers preventing sustainable rapid growth of GSHP applications in the United States and China.

Barriers	United States	China
Tier one	• High initial cost of GSHP systems to consumers	• Lack of standards governing the quality of equipment, design, installation, and operation of GSHP systems [9,10,76–82]
Tier two	• Lack of consumer knowledge of and/or trust in GSHP system benefits • Lack of policymaker and regulator knowledge of and/or trust in GSHP system benefits • Limitations in GSHP design and business planning infrastructure • Limitations in GSHP installation infrastructure	• Less than expected performance and energy-saving benefits [7,80–83] • Legacy of many large projects done in a hurry without adequate capture of lessons learned for continual improvement [75,84–86].
Tier three	• Lack of new technologies and techniques to improve GSHP system cost or performance	• Unqualified system operators [7,82,87] • Lack of performance data feedback and inability to evaluate the long-term performance of GSHP systems [8,10,81,85] • Lack of technologies to avoid blockage in GWHP reinjection wells and properly size GHXs [75,79,84,85]

GSHP system performance, the Chinese approach is far less costly and can be completed in a shorter time.

6.3. Professional certification standards

Proper professional licenses or certifications are usually required in the United States to design and install GSHP systems, especially for commercial projects. In all states, it is required that designers of GSHP systems must be registered Professional Engineers, and in some states they must also be accredited by IGSHPA as Certified Geo Exchange Designers. Many states require that ground loop installers be IGSHPA-accredited installers and/or drillers and that the installer of the indoor portion of the GSHP system be an HVAC technician certified by the Air-Conditioning Contractors of America. However, there currently is no certification for other disciplines involved in GSHP projects. Recently, the Geothermal Exchange Organization developed the first national certification standard for all the disciplines involved in GSHP projects [74]. This standard addresses applicable qualifications for all primary personnel involved in the design, installation, commissioning, operation and maintenance of GHP systems, including their knowledge, skills and abilities.

In China, there has not yet been any development of GSHP-specific certification systems for the various disciplines involved in the design and installation of GSHP systems. Where requirements exist, they generally simply refer to the qualifications for related disciplines, such as geotechnical engineers and water well installers.

7. Barriers and problems

To identify barriers and problems preventing wider adoption of GSHP technology in the two countries, an extensive literature review (in China) and interviews with industry experts (in the United States) were conducted. In 2008 several dozen US GSHP industry experts were asked to respond to the question "What are the key barriers to rapid growth of the GSHP industry?" After the list of barriers was assembled, the same group prioritized the barriers into three tiers (tier 1 being the most important) [12]. The literature review in China focuses on current situation of GSHP applications, and the method includes three steps: firstly, a keyword search in two databases—CNKI (China National Knowledge Infrastructure) and Elsevier; Secondly, a quantitative analysis on the search results, including citations of the identified literature, the influence of journals where the literature are published, and the experience/occupation of the authors; finally, a detailed review of the literature with high citations and influence to find the specific barriers and problems about GSHP applications. Totally, 17 literatures [7–10,75–87] were identified and reviewed in detail.

Table 7 lists the identified barriers in the United States, along with the barriers identified by the China-side co-authors. It appears that the main barrier to sustainable growth of GSHP applications in China is the lack of sufficient quality control and the resulting under-performing GSHP systems. Because of the fast pace of real estate development in China, many GSHP systems were implemented in a short time and without adequate feasibility study and optimization in the system design and control. The lack of a stringent performance evaluation standard, and of a systematic training and certification program for personnel involved in GSHP projects, also contributes to the inconsistent quality and performance of GSHP systems in China. On the other hand, it is the high initial cost and the lack of public awareness and governmental support that prevent wider adoption of GSHP technology in the United States.

8. Conclusions

Based on this comparative study, it is clear that the use of GSHP technology has been established in both the United States and China. GSHP systems have been used for various types of buildings in all climate zones in both countries. Within one decade, GSHP installations in China have grown from zero to 400 million m^2 (4.3 billion ft^2) of building floor space. The total GSHP installed base in China has already surpassed that in the United States (roughly 199 million m^2, or 2.14 billion ft^2), which has been developing since the 1970s. The average annual growth rate of GSHP applications in China was nearly 46% in the time period from 2000 through 2013. It may be even higher in the future, at least in some provinces where GSHP technology is promoted as a part of the solution to reducing the severe air pollution in China—especially during the heating season. GSHP applications in the United States increased rapidly (with an annual growth rate of 30%) between 2004 and 2008 but declined in 2009 because of the economic recession. The US GSHP market has been recovering slowly since then. It is forecast that new GSHP shipments in the United States will grow at an 11% compound annual growth rate between 2013 and 2020.

The rapid growth of GSHP applications in China is due to a combination of three factors: (1) the massive construction boom in China that started at the end of the 20th century and is ongoing; (2) the shortage of energy supplies and the severe air pollution, which is partly due to conventional low-efficiency and high-emission heating systems; and (3) the strong support from various levels of governments in terms of favorable policies, financial incentives, and widespread education about and demonstrations of GSHP technology.

Innovative applications of GSHP technology have been motivated and implemented in China to serve the fast-growing market of large buildings in highly populated areas. It is reflected by the widely diversified heat sinks/sources used in GSHP systems in China—groundwater is used in nearly 42% of GSHP systems in China, and other less-conventional resources (i.e., surface water and wastewater) are used in another 26%. Closed-loop GHXs, which are used in 84% of GSHP systems in the United States, are used in only about 32% of GSHP systems in China.

It is also observed that, while most GSHP systems in the United States are in a decentralized configuration, central GSHP systems with two-pipe distribution (which cannot provide simultaneous heating and cooling to different zones) are most commonly used in China. Decentralized GSHP systems have some advantages over central systems, such as higher system efficiency at part-load conditions, individual indoor environmental control during all seasons, and individual metering. It is thought that decentralized GSHP systems will be adopted in China eventually, given the continuous strong governmental support for renewable energy applications in buildings and the mandatory requirement to reduce building energy use.

Although there has been great success in applying GSHP technology in the United States and China, both counties also have barriers and issues that hinder wider adoption of the technology and sustainable growth of the GSHP industry. Whereas high initial cost is the primary barrier for potential GSHP consumers in the United States, the lack of standards governing quality of equipment, design, installation, and operation of GSHP systems is the main barrier in China. As a result, the real performance of some GSHP systems in China is not as good as expected, and there is not adequate capture of lessons learned from these projects for continual improvement. In some cases, environment protection may not have been given adequate consideration during the development process. A stringent performance evaluation standard and a systematic training and certification program for personnel involved in GSHP projects could help improve the quality of GSHP systems and thus realize their energy-saving potential.

There is much for these two countries to learn from each other through continued collaboration in the application and advancement of GSHP technologies. Aspects in which China may learn from the United States include (1) more stringent standards and training programs for every stage of the implementation process for GSHP systems, including feasibility study, design, installation, commissioning, and operation; (2) control and operation management for GSHP systems, as well as the application of decentralized GSHP systems; and (3) data collection and analysis for long-term performance of GSHP systems. The United States may learn from China in the areas of (1) experience in utilizing less-conventional heat sinks/sources for GSHP applications (i.e., filtered raw sewage water and building foundation piles); (2) policies and financial incentives for promoting GSHP applications; and (3) implementation of GSHP systems for large commercial and high-rise multifamily buildings.

Acknowledgment

This work is supported by the US–China Clean Energy Research Center for Building Energy Efficiency (2010DFA72740-05-03).

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