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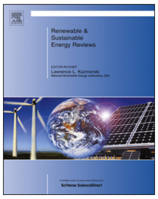

Integrating bibliometrics and roadmapping: A case of strategic promotion for the ground source heat pump in China

Pin-Chao Liao [a], Kenan Zhang [a], Tao Wang [b,*], Yanqing Wang [a]

[a] Department of Construction Management, Tsinghua University, China
[b] School of Management Science and Engineering, Central University of Finance and Economics, No.39, South College Road, Haidian District, Beijing 100081, China

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ABSTRACT

The ground source heat pump (GSHP) is one of the most promising energy-efficient technologies in development. However, the degree to which the application of GSHP has been promoted in China remains unsatisfactory. Critics of GSHP development in China have asserted that a more thorough understanding of GSHP is paramount for technology road mapping. This, in turn, has affected policy-makers' development of regulations that facilitate R&D related to GSHP. Because many researchers have proposed specific terms and categorization approaches in relation to GSHP, it is imperative to transform and analyze a substantive knowledge system derived from massive amounts of qualitative information to produce a roadmap for the development of GSHP. To this end, we employed a bibiliometrics approach to analyze patent information. First, we engaged in semantic labeling of patent files and recorded the co-occurrence of the terms associated with the GSHP's ontology. Second, we employed an algorithm called the Fuzzy Overlapping Cluster (FOPC) to analyze the co-occurrence information. In doing so, we sought to classify patent data and further define sub-technologies associated with GSHP. Third, we used accumulative patent numbers to develop a logistic model for observing development trends related to each GHSP sub-technology. Fourth, we leveraged social network analysis to calculate and graphically illustrate interdependence among GSHP sub-technologies. The results these analytic approaches produce allowed us to conclude that (a) GSHP should be categorized into four sub-technologies: the water source heat pump, the ground coupled heat pump, the heat pump/system operation technique, and central air-conditioning system, and (b) the government should revise building codes and standards with a consideration of GCHP, as well as the heat pump/system operation techniques.

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* Corresponding author. Tel.: +86 13811180036.
E-mail address: wangtaothu@163.com (T. Wang).

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1. Introduction

According to the 12th Five-Year Plan (FYP) issued by the National People's Congress, China's top legislature [52], coal equivalent energy consumption (EC) will be 300 million tons lower in 2015 than it was 2010. In 2010, the building sector accounted for 27.8% of total energy consumption in China, 65% of which could be attributed to heating, ventilation, and air conditioning (HVAC) [1]. Given the degree to which HVAC accounts for EC within the Chinese building sector, it should be prioritized when policymakers consider energy reduction techniques for various building systems.

Of the natural resources available for replacing electricity to reduce carbon emissions associated with HVAC, ground source heat represents one of the most remarkable. The ground source heat pump (GSHP) is believed to have potential for reducing the energy a building consumes [4,5,7]. Specifically, GSHP technology utilizes shallow-ground heat to supply buildings with heat and cool air, as well as support the domestic hot water system [2]. Relative to other types of HVAC systems, GSHP systems are widely considered to be more energy-efficient [3–8].

1.1. Inefficient promotion of GSHP in China

To promote the utilization of renewable energy based various “green” technologies, the Chinese government implemented wide-ranging legislation, including the Renewable Energy Law (2006) and the Recyclable Economy Law (2008), through a series of federal and local policies and standards. Among these policies and standards were some related to GSHP. By the end of 2012, over 100 policies geared towards promoting GSHP had been issued by the Chinese government [9]. In addition to these policies, the Chinese government also legislated various standards to guide the design, installation, and testing of GSHP systems. Some of these standards include the Technical Code of Ground Source Heat Pump System (GB 50366-2005) and Design Code of Water Source Heat Pump (GB-T 19409-2013).

Despite the implementation of numerous standards and regulations designed to guide development of and/or promote the GSHP, Chinses use of the GSHP remains limited. This is largely attributable to low return rates and lengthy payback periods to consumers/developers [10–13]. Practitioners have attempted to determine how to circumvent these disincentives to GSHP dissemination, but two major obstacles remain, thus jeopardizing the promotion of GSHP in China. First, product specifications do not reflect installation practices, raising significant concern about quality. Second, there is a marked lack of understanding about the technical terms associated with GSHP. We elaborate on these problematic issues in Sections 1.1.1 and 1.1.2, respectively.

1.1.1. Specifications do not echo practices and thus quality is of a significant concern

The Chinese government has proposed several standards to facilitate the implementation of GSHP. Issued in 2005 and revised in 2009, technical specifications for the ground source pump system (GB 50366-2005) are characterized by unified terminologies and installation approaches for GSHP systems. These approaches include inspection, design requirements of the heat exchanger, installation, and start-up procedures. GB 50366-2005 describes GSHP systems in a broader sense, focusing on ground coupling and water source systems. Because of its prevalent use in China, GB-T 19409-2013 focuses on the testing, inspection, transportation, and storage of water source heat pump (WSHP) systems. However, the current design and installation specifications for the GSHP do not guarantee system quality, as its current practical experience is quite limited [15]. For example, engineers have asserted that the requirements associated with pipe pressure are too strict, and are thus not economically tenable in practice. Backfill specifications represent another example. Compaction of backfill material is the key factor related to the heat exchange rate. Although installation standards indicate that one can use a mixture of cement and sand, the borehole is too small for this mixture in practice. As a result of using the cement–sand mixture, gaps are created in the backfill material, affecting heat exchange efficiency [16].

1.1.2. A lack of common understanding of GSHP technical terms

Contractors and consumers are often hesitant to utilize GSHP because of a lack of a common understanding of its technical terms. As a result of this widespread caution, nationwide investment in GSHP projects is limited [12]. In addition to this, insufficient government subsidies for GSHP makes it an unattractive option [16–18]. Some scholars have asserted that widespread dissemination of a specific technology can incentivize the use of alternatives; however, this does not seem to be the case for GSHP in practice [12,18]. For instance, although GB 50366-2005 discusses the WSHP in detail, including direct/indirect heat exchange systems and open/closed ground water systems loops, severe government restrictions on the use of underground water make these terms largely obsolete [14]. In addition, parts for the ground coupled heat pump (GCHP) are rarely mentioned in the technical specifications. In this regard, government subsidies do not support the installation cost of various GSHP systems. Therefore, the incentive of government subsidies have a limited effect on their promotion [9]. In practice, many developers purchase traditional HVAC systems (that lack GSHP), thereby negating any possibility of achieving economies of scale [9]. This vicious circle impedes dissemination of GSHP in China [12].

1.2. A lack of consensus on the classification of GSHP

Previous studies have attempted to clarify the nature of GSHP systems and identify trends that explicate their development. However, the results of these studies have been based on the subjective classification of GSHP, thereby failing to provide an objective basis for the development of a policy roadmap. Past researchers in this domain have classified GSHP systems in terms of their components (e.g., the primary circular, the heat pump, and the secondary circular), their ground heat sources (e.g., soil, ground water, underground water), and circulation or buried pipes (i.e., open or closed, horizontal or vertical) [2,7,16,19–22]. Trends in the development of GSHP systems have been approached differently. In a review of the development of GSHP in China, Yang et al. [23] summarized the most prevalent topics related to research and development, as well as the nature of GSHP's distribution, scales, and investments. Through this review, they concluded that although GSHP development in China is rapid technological innovations, economic incentives, and industry standards were still in need of governmental instructions. Xu [24] claimed that GSHP technology in China was in the start-up phase between the 1980s and 2000, followed by a four-year period of technology promotion, and a rapid increase in the use of GSHP after 2005. Similarly, Xu and Liu [17] reported on the development and potential of GSHP use in China. Qi et al. [25] argued that hybrid energy systems would become an important approach for utilizing renewable energy. They also demonstrated that corresponding technological issues, including parameters for system design, energy extraction, and system control strategies, should be prioritized. In summary, extant studies have discussed the ground coupled heat pump (GCHP), the ground water heat pump (GWHP), the surface water heat pump (SWHP), and the hybrid ground source heat pump (HGSHP) systems. The authors of these studies have argued that (a) research related to the applicability and efficiency of GSHP systems was insufficient, (b) a determination of the financial tenability of GSHP systems required further study, and (c) the integration of a heat pump station and heat exchangers required further improvement for more energy-saving.

Taken together, the results of these studies offer some insight into the development of GSHP systems. Although these studies collectively provide a number of findings, there are two principal observations that can be derived from their results. First, empirical analyses of GSHP development trends remained broad in nature, but are without strategic alignment. Technology forecasting is of critical importance for planning the promotion of a given technology, and specific domains or specialized skills related to the technologies are the most integral tenets of forecasting [19]. That said, GSHP systems consist of various components that past researchers have differentially categorized. Given the diversity of these components, incentivizing the application of the GSHP system in a broad sense (without a comprehensive understanding of the relationships between their components) may not be effective. Second, although systematic investigations of the developmental trends of different sub-technologies and technological themes are available, the classifications of GSHP sub-technologies are often derived by expert opinion. Thus, incentive policies have largely been derived on the basis of subjective information. Xu and Liu [18] argued that an understanding of system efficiency requires more research, but failed to identify which components of the GSHP should be investigated further. Qi et al. [25] may provide a framework for future analysis, but argue that the "hybrid system" should not serve as the unit of analysis for future research because the term is vague. Therefore, we argue that sub-technologies that underpin GSHP systems should be triangulated with large public datasets to more comprehensively observe trends in their development, support enterprises' R&D strategies, propose promotion policies, and guide government legislation geared towards popularizing the use of GSHP systems. Fortunately, Zhang and Liao [53] used patent information to propose a GSHP ontology that systematically outlines terms related to GSHP systems based on the physical components. This ontology helps guide this (and other) research that will help address the issues outlined above.

However, descriptions based on physical components (i.e. GSHP ontology) without understanding their dependent relationships and foresee their potential development, the abovementioned obstacles remain. Thus, it is imperative that we develop a more thorough understanding of the technology [13]. How many sub-technologies comprise GSHP, consisting of which physical components (ontology terms)? Which GSHP sub-technology has the greatest potential for development? How can the Chinese government establish reasonable standards and policies to effectively promote the development of GSHP? To answer these questions, we use a bibliometric approach to highlight the potential for the development of GSHP sub-technologies. For the sake of clarity, we offer definitions for key terms in Appendix A for reference.

2. Methodology

As a part of a larger research project, the first step in this research was to create a "dictionary" to be used to facilitate data transformation. Zhang and Liao referred to academic studies that featured several key terms, "ground source heat pump," "water source heat pump," "soil source heat pump," and "ground-coupled heat pump." The authors then summarized these keywords in a list. Using the brute-force method, these keywords (ontology terms) were further expanded to form the basis of a "dictionary" [53]. As outlined in Fig. 1, this dictionary includes both specific ontology terms and generic technical terms, was structured schematically, and published by Zhang and Liao [53].

Fig. 2 summarizes the methodology we employ in this study.

Step 1: To collect quantitative data from qualitative patents, we searched the database of the State Intellectual Property Office of the P.R.C. In doing so, we searched for: "ground source heat pump," "water source heat pump," and "soil source heat pump/ground-coupled heat pump". We then downloaded each resulting patent in the form of a plain text file. This resulted in a list of 1380 patents (ground source heat pump=721, water source heat pump=600, soil source heat pump/ground-coupled heat pump=58) between 2000 and 2013. Each file included the patent's number, application date, issued date, IPC number, intellectual property owner, illustrative graph(s), and an abstract to describe the nature of the product. Fig. 3 provides an example of one of the patent files. Second, we transformed all qualitative

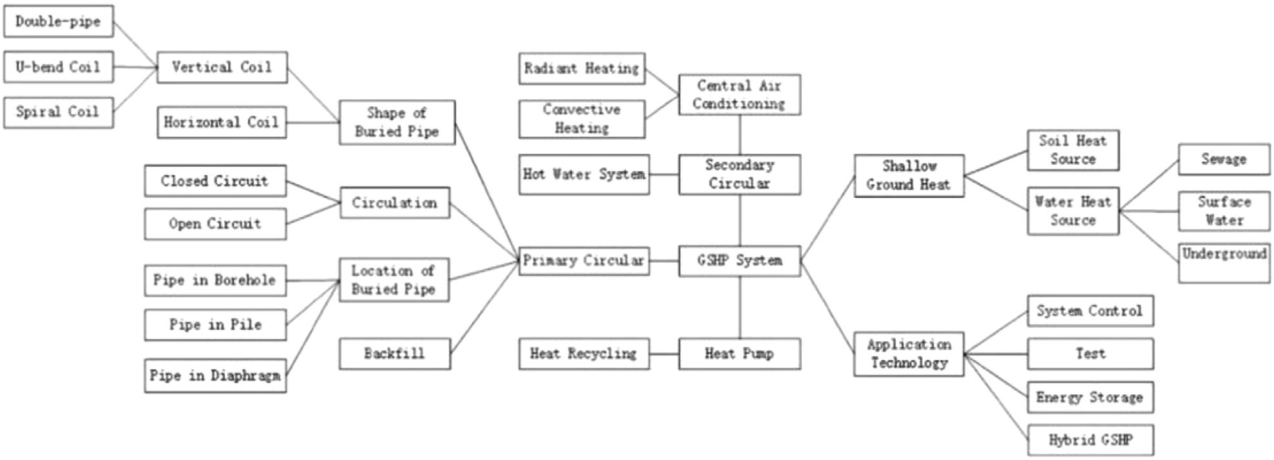

Fig. 1. GSHP Ontology (Zhang and Liao 2015).

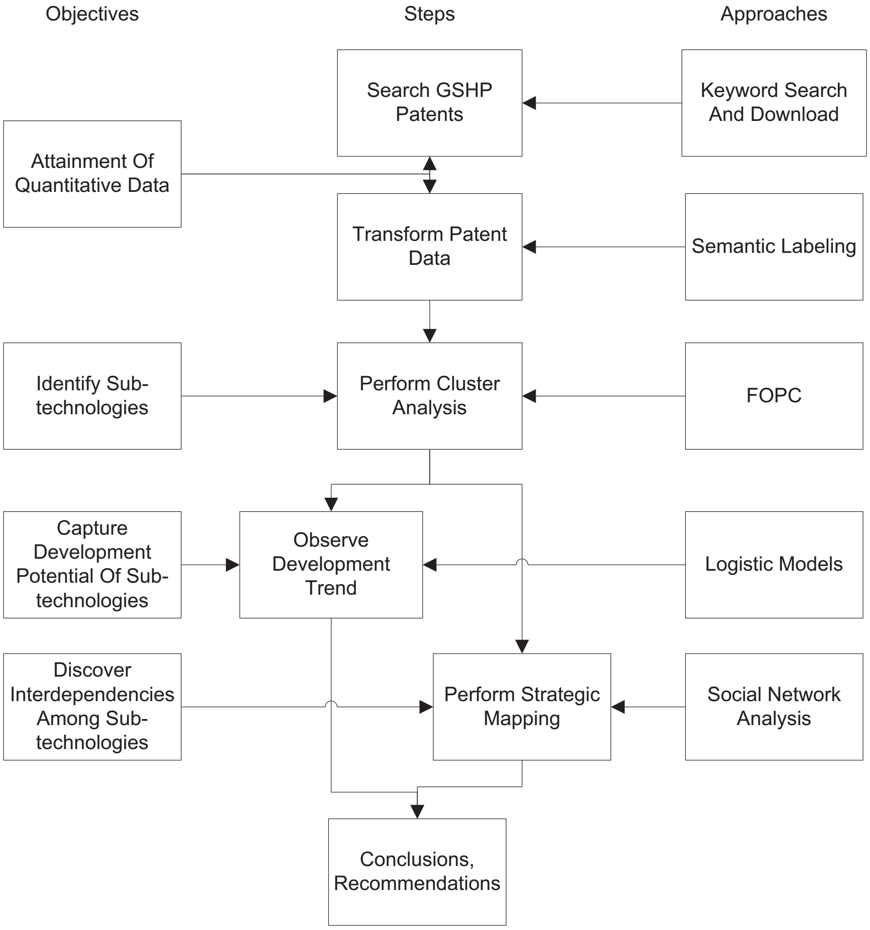

Fig. 2. Methodology.

patent information into quantitative data. Specifically, we used the dictionary of the GSHP ontology to label terms in the patent files. This allowed for the determination of the frequency with which ontology terms co-occurred in the patent data. These frequencies were recorded in a spreadsheet.

Step 2: To glean GSHP sub-technologies from the patent information, we calculated the degree of crowding among the ontology terms by defining the association between any paired ontology terms. For the purposes of our research, we defined the strength of term co-occurrence as the strength of the association between the pair of terms. Based on the strength of the association, we applied the Fuzzy Overlapping Cluster (FOPC) algorithm (described in Section 2.1) to perform a cluster analysis on the ontology terms. We then compared our results with those produced by previous studies, and solicited feedback on these comparisons from a systems engineer, a procurement engineer, a construction project manager, a GSHP vendor, and a GSHP subcontractor. Each of these individuals had more than five years of experience in the design, procurement, and installation of GSHP systems on construction projects. The results were further presented commented in a ten-people focus group including government officers, real-estate representatives, and representatives of GSHP suppliers. We then augmented the names of clusters on the basis of their feedbacks.

Step 3: We used the dictionary to label the patent and record accumulative numbers by year for each sub-technology cluster in a spreadsheet. We then performed logistic curve fitting with OriginPro8® to capture the potential for each sub-technology's development, including descriptions of fast-development period, inflexion point and mature time period of each sub-technology.

Step 4: We used the co-occurrence frequencies of all ontology terms to calculate network metrics, including network density and centrality. These metrics were determined via social network analysis (SNA), normalized, and used to develop a strategic map that illustrates the interdependence among the various sub-technologies pairings. The details of Steps 3 and 4 are illustrated in Section 2.2.

Finally, we integrated the results of the logistics models (Step 3) and the strategic map (Step 4) to suggest strategies for promoting GSHP systems and offer directions for future research. The results and suggestions were then again demonstrated in the focus group and feedbacks were also collected as the foundation for revisions of the suggestions.

2.1. Clustering method: The FOPC algorithm

Cluster analysis is a quantitative methodological approach that categorizes elements on the basis of their similarity. Different types of cluster analysis include Partitioning Clustering, Hierarchical Clustering, and Density-based Clustering [26–29]. Cluster analysis is widely used in literature searches, image processing, model identification, as well as the classification of patent data and innovation of technologies [26,30,31]. The results of cluster analyses that use technological innovations as data serve as the foundation for identifying sub-technologies. Given its import to this end, it is critical that the algorithm used to perform the cluster analysis is appropriate. To develop the FOPC algorithm, we reviewed several other typical, widely used algorithms.

发明名称 — Ground-source heat pump system

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IPC分类号	C02F9/02; F25B49/00; F25B30/06
申请（专利权）人	JIANGSU HAILEI DEMENG ENVIRONMENTAL ENGINEERING CO LTD;
发明人	ZHENG HAIQING;
优先权号	CN201420235881
优先权日	2014.05.09

摘要

Abstract:

The utility model relates to a ground-source heat pump system. The ground-source heat pump system comprises a tap water inlet pipeline, an underground water inlet pipeline, water inlet pipe switching valves, water purifying devices, a water storage tank, a use water device, a ground-source heat pump host and a buried pipeline device, wherein the water inlet pipe switching valves are arranged at the lower end of the tap water inlet pipeline and the lower end of the underground water inlet pipeline; the water purifying devices are respectively arranged at a water inlet of the tap water inlet pipeline, and a water inlet of the underground water inlet pipeline; the water storage tank is respectively connected with the water purifying devices, the user water device and the ground-source heat pump host; the ground-source heat pump host is connected with the buried pipeline device. The ground-source heat pump system is simple in structure and adopts tap water and underground water as a cold source and a heat source; the ground-source heat pump system has the advantages of remarkable environment-friendly benefit, high efficiency, energy conservation and stable and reliable operation.

摘要附图

Fig. 3. An Example of GSHP Patent.

K-means, a typical form of cluster analysis, categorizes each element in the analysis into a group of other elements with which it is most similar. This algorithm assumes that each sub-cluster should be independent, but this is often not possible practically. Specifically elements related to sub-technologies are often categorized in more than one group, though the groups should be related [32]. Many scholars have developed algorithms meant to optimize the K-means approach, including the Fuzzy c-means (FCM) [33–36] and Overlapping Cluster (OPC) algorithms proposed by Chen and Hu [37]. These algorithms are based on the concept of fuzzy clustering and dictate that subordinate principles and objective functions can address the problems intrinsic to the K-means approach.

FCM identifies the subordinate scale as [0, 1], an approach for which Dunn and Bezdek provided evidence for its mathematical feasibility [33]. The advantage of this algorithm hinges on the polarized categorization approach, which allows each element to be categorized in different clusters, thereby moving from “local optimization" to "global optimization." In spite of its flexibility, there are still some barriers that limit the analysis. First, the elements are continuously distributed in various clusters without threshold limitations. Second, the objective function only considers the minimized distance within the clusters but does not consider other factors, including the number of elements or the distance between the clusters [36]. Subordinate distribution does not establish thresholds to exclude elements. Therefore, results of the categorization may be biased by including the remote elements. Therefore, one should consider other factors as the objective function rather than simply focus on the distance within the clusters.

The Overlapping Cluster (OPC) algorithm was proposed by Chen and Hu [37]. For elements *i* and *j* (a total of n elements) with *p* characteristics, the OPC algorithm calculates Euclidean distance d_{ij} and similarity $s_{ij} = 1 - \min\{d_{ij}, d_{if}\}/d_{if}$, where d_{if} is the top 5% of distances between all element-pairs. The non-center elements x_i with higher CRF(x_i), the weighted average of the Crowding value $Cv(x_i) = nx_i/\max(nx_i)$, and the second criterion value $Mdv(x_i) = ndx_i/\max(dx_i)$ will be recommended as the initial clustering center. With more than 5000 iterations, the algorithm will continuously adjust the clusters by maximizing each included element and minimizing the distance between the clusters. In this approach, elements can be categorized in more than one cluster, or remain uncategorized. We used several simulation and real world datasets to demonstrate the effectiveness and efficiency of this algorithm. Furthermore, this algorithm was demonstrated to be adaptive to patent clustering [27]. Not only revising subordinate rules of the elements, the OPC algorithm resets the objective function given the number of elements within clusters is maximized and the similarity of the centers of clusters is minimized. This algorithm requires manual inputs to weight these two metrics and the threshold of similarity, thereby overcoming the limitations of the FCM's categorization rules. Still, the OPC does suffer some limitations. First, the polarized subordinate relationship does not depict the distance between the element and the center of the cluster. Second, the inner distance reveals the density of a specific cluster and is thus an important metric for evaluating clustering results. Therefore, ignoring this criterion seems inadvisable.

Based on the critiques above, two main revisions were made to be FOPC. First, distinct from the OPC approach, the FOPC algorithm does not report the n-dimension subordinate matrix, but instead directly calculates C_v and subordinate distribution. Second, in addition to the objective functions of OPC approach (the number of elements within clusters is maximized and the similarity of the centers of clusters is minimized), we added two objective functions to FOPC: the maximum value of the relative distance of all the ontology terms (categorized by fuzzy relationships), and the maximum value of a pair of ontology terms within a category. Users should weight the metrics within the objective function. Smaller values of these metrics ensures more accurate results for the cluster analysis. In this study, we defined the distance of the centers as 0.4, the numbers of the elements within one cluster as 0.1, the average distance of the elements from the center of from their respective clusters as 0.4, and the distance of the most remote element from the center as 0.1.

With proposed FOPC algorithm, we used the dictionary to capture the co-occurrence of ontology terms (x_i) in each patent's abstract. For instance, in Table 1, if "WSHP System" and "Sea" co-occur in a paragraph within a patent file, we counted this as an association between "Water Heat Source" and "Surface Water Source" (terms from the ontology). The association between any ontology-term pairing will be triggered for at least one generic term found in the patent's abstract. We then calculated all metrics (d_{ij}, S_{ij}, d_{if}, $C_v(X_i)$, and $\mathrm{Mdv}(X_i)$) accordingly. As mentioned, this algorithm was run for 5000 iterations considering the four objective functions. Final clusters obtained after these iterations are illustrated in Section 3.1.

Table 1
Ontology terms and their generic counterparts (Zhang and Liao, [53]).

Ontology terms	Generic terms				
GSHP system	Ground source heat pump				
Shallow ground heat	Shallow ground heat		Low-temperature ground heat		
Water heat source	WSHP system		WSHP air conditioning		WSHP central air conditioning
Sewage source	Sewage	Polluted water	Reclaimed water		
Underground water source	Underground water				
Surface water source	River	Lake	Sea	Surface water	
Soil heat source	Soil source heat pump		Ground-coupled heat pump		

In our application of the FOPC algorithm on 1380 patents, we utilized five various sets of weightings and three clustering numbers, resulting in 15 clustering combinations. However, we obtained only six different classification results. We then used Yoon and Park's [40] principle for determining the best classification. This principle dictates that the classification with the lowest ratio of inter-cluster distance over to intra-cluster distance is the most optimal. As a result, we chose Cluster 6 to be the best classification. As an aside, there was substantial overlap between Clusters 2 and 3, so we combined these into one large sub-technology cluster.

2.2. S-curve fitting and strategic mapping

The use of logistic models is prevalent within the practice of technology management. Various scholars have used logistic models to predict the life cycles of various technologies. One can observe the results of logistic (s-curve fitting) models to evaluate sub-technologies, thereby allowing for an understanding of competition among these technologies.

Function of S-curve:

$$y = a/(1 + e^{-k \times (x - Xc)}) \tag{1}$$

Eq. (1) illustrates the logistic model where y represents the year; a indicates the predicted total number of patents when the sub-technology is the mature phase; parameter *k* is derived from the fitting of data; and *Xc* depicts the inflection point (year) of the s-curve.

Various scholars, including Callon [38], Ding et al. [39], and Yoon and Park [40] proposed various approaches for determining the values of the two metrics. For a paired ontology terms *i* and *j*, we utilized the normalized distance index $E_{ij} = (C_{ij})^2/(C_i \times C_j)(i, j = 1, \ldots, n)$ to represent their associations, where *Ci*, *Cj*, and *Cij* are the crowding values of ontology term *i*, ontology term *j*, and their joint (as introduced in Section 2.1). For a ontology term *i*, "outer E_{ij}" refers to its association with a ontology term *j* that is not clustered in the same group with ontology term *i*. In contrast, "inner E_{ij}" refers to ontology term *i*'s association with a ontology term *j* in the same group. We normalized the associations (depicted via centrality and density metrics) by dividing the respective number of links, as depicted in Eqs. (2) and (4). Based on the associations E_{ij} of each ontology term pair, each cluster's relative centrality (Cen_Rel) and density (Den_Rel) is calculated by dividing the average centrality of all paired ontology terms (see Eqs. (3) and (5)).

$$\mathrm{Cen.} = \mathrm{sum}(\mathrm{outer}E_{ij})/\mathrm{number(outerlinks)} \tag{2}$$

$$\mathrm{Cen\_Rel} = \mathrm{Cen}/\mathrm{aveCen} \tag{3}$$

$$\mathrm{Den.} = \mathrm{sum}(\mathrm{inner}E_{ij})/\mathrm{number(innerlinks)} \tag{4}$$

Table 2
Sub-technologies and keyword elements of GSHP

GSHP ontology level 1	A WSHP	B GCHP		C central air-conditioning system	D heat pump/system operation technique
		B1 buried pipe system	B2 vertical coil and relevant technology		
Primary circular	Open circuit	Primary circular Backfill Vertical coil Horizontal coil Double-pipe Spiral coil Pipe in pile Closed circuit Pipe in diaphragms	Primary circular Backfill Vertical coil U-pipe Spiral coil Pipe in pile Pipe in borehole	Double-pipe Closed circuit Pipe in diaphragms	Closed circuit
Secondary circular	Secondary circular central air-conditioning	–	–	Central air-conditioning Convective heating Radiant heating	Secondary circular hot water system Radiant Heating
Heat pump	Heat pump	–	–	–	Heat pump Heat recycling
Shallow ground heat	Water heat source surface water underground water sewage	Shallow ground heat Soil heat source	Soil heat source	Underground water	–
Application tech.	–	–	Testing	Heat storage System control	Heat storage system control Hybrid GSHP

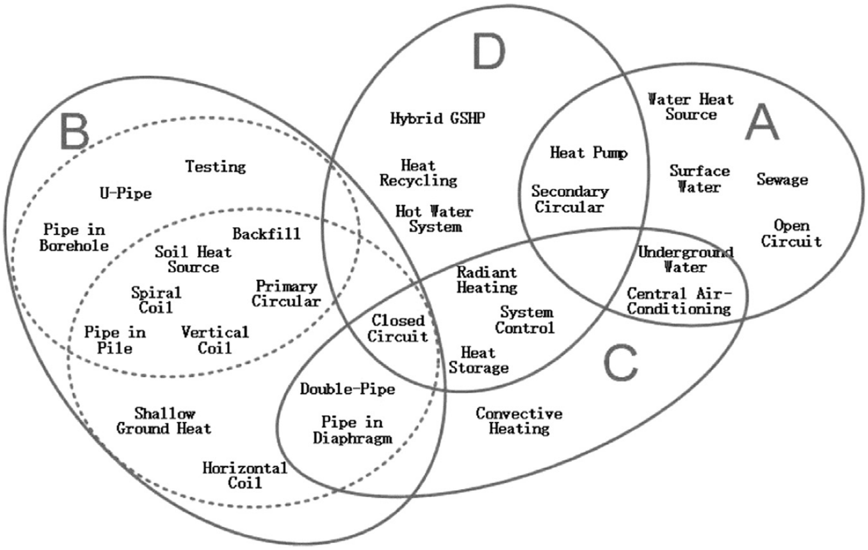

Fig. 4. GSHP sub-technologies and their correlations.

$$\mathrm{Den\_Rel} = \mathrm{Den}/\mathrm{aveDen} \tag{5}$$

Strategic mapping is another prevalent approach that facilitates the interpretation of s-curve fitting. One can employ social network analysis using the co-occurrences of elements categorized in different groups[1].

3. Findings

Our findings are presented in terms of the technological context, sub-technologies, and GSHP systems (Section 3.1), as well as via forecasts of their development (Section 3.2). Section 3.1 refers to the outputs produced by Step 2 in the methodology outlined above, and Section 3.2 concerns Steps 3 and 4.

3.1. *GSHP sub-technologies*

We identified four clusters as sub-technologies of GSHP (see Table 2, Fig. 4). After considering input from the focus group, we specified these respective sub-technologies as WSHP, GCHP, central airconditioning systems, and heat pump and system operation techniques. All ontology terms were mapped with the GSHP sub-technologies and level 1 ontology category proposed by Zhang and Liao [53].

The WSHP cluster (A) features the term "open circuit" in relation to the primary circular, outlining its key feature—heat exchange. The heat source of such a sub-technology was featured with water including surface water and sewage. The GCHP cluster (B) features various lower level ontology terms including vertical coil, spiral coil, and others. We identify "buried pipe systems" (B1) and "vertical coil and relevant technology" (B2) as two distinct sub-technologies, but given that they are relatively similar, we combined them under the GCHP cluster in response to feedback from practitioners. "Buried pipe systems" are

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[1] Because this analysis is a component of a larger study, details regarding the methods of strategic mapping are available in a report produced by Zhang [41].

featured with “horizontal coil”, “double-pipe” and “pipe in diaphragms,” which illustrate the variability of such a sub-technology. “Vertical coil and relevant technology” consists of distinctive ontology terms “testing” and “U-pipe.” This category shows that testing is critical to the quality of U-pipe installation. “Central air-conditioning system” (C) is featured with the term “conceive heating,” suggesting it is the central feature of air-conditioning systems. “Heat pump/system operation technique” (D) is featured with the terms “hybrid GSHP,” “heat recycling,” and “hot water system.” Whereas the first two of these terms are justifiable given their relation to economic or geological issues during design or installation, the inclusion of “hot water system” may be because this type of sub-technology has been wildly used for water heating such as bath in China.

The FOPC algorithm allows for one ontology term to be simultaneously categorized into different clusters. For instance, the ontology term “spiral coil” was categorized in both the B1 and B2 clusters, indicating that the spiral coil is a key component in both sub-technologies. The cluster “central air-conditioning system” overlapped with all other clusters except “convective heating,” suggesting that the promotion of the central air-conditioning system is restricted by the development of other GSHP sub-technologies. In contrast, the GCHP and WSHP clusters do not overlap with any ontology term. In reality, these clusters are competitive technologies in the green building market. As previous researchers have shown, WSHP is superior to GCHP in terms of heat exchange intensity, covers less area, and is cheaper; GCHP is superior to WSHP in terms of operational stability and has a longer life span [18].

Because of the substantial amount of ground heat resources available in China, GCHP and heat pump/system operation techniques should be treated as an independent sub-technology. We compared the results of our cluster analysis with past work in this domain and discussed them with workshop participants; both these steps validated our findings. Classified by Chinese Intellectual Property Development and Research Center State Intellectual Property Office, GSHP systems consist of water source heat pump, heat pumps, system operation techniques, system applications, and hybrid ground source heat pumps. However, the GCHP has not been evaluated by the Chinese government. This is notable, given that ground heat resources are abundant in China. Given the amount of resources in the top 5 km of the earth's surface, GCHP could generate about 140×10^6 EJ of heat. Even 1% of this energy could be utilized to save on costs associated with providing energy with the world's inhabitants [19]. Consider, for example, that 70% of the building area in China requires air-conditioning in both summer and winter [18,46]. This substantial demand, coupled with the potential for energy output, suggests that the potential of GCHP should not be ignored.

Although we were able to identify four sub-technology clusters from the patent data, the authors should note that the ontology of GSHP proposed by Zhang and Liao [53] focus on the systematic structure of physical components of GSHP; on the other hand, the results of this research identified the interdependencies of these components based on practices (patent information) for further analysis to explicate their potential for development.

3.2. Development trends of GSHP sub-technologies

We recorded the frequency (by year) with which the ontology terms appeared in the patents. This means that if at least one keyword within a specific cluster is found, that specific sub-technology is counted once. Using S-curve fitting (as shown in Fig. 5), we have found an acceptable fit to the data in Table 3 ($r^2=0.99$. This means all the sub-technologies will surpass a “turning point” in 2012 (X_c) and become “mature” after that year. According to the patent data, one may expect all four sub-technologies to be fully developed around 2020. Readers should note that the logistic model only provides a preview of development trends for each sub-technology rather than offer exact predictions related to the number of patents in a given time frame.

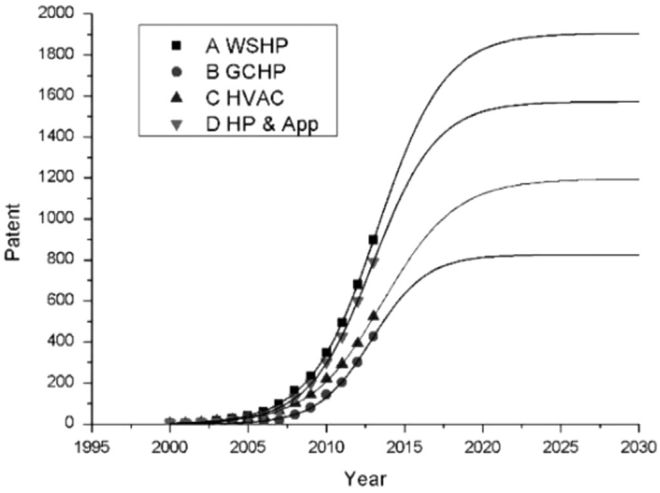

Fig. 5. Sub-technology development trends.

Table 3
Results of S-curve fitting of sub-technologies

Sub-tech	Max. of patent # (a)	Turning point (Xc)	Increasing coeff. (k)	N (10′–13′)	Adj. R^2
WSHP	1906.84	2013.25	0.46	898	0.99
GCHP	825.79	2012.90	0.57	427	0.99
Central air-conditioning system	1193.87	2013.60	0.43	523	0.99
Heat pump/system operation technique	1572.70	2012.98	0.48	792	0.99

As shown in Table 3 and Fig. 5, the four sub-technologies identified above have very different developmental trends. One should note that simply adding these numbers will not replicate the entire dataset, as these sub-technologies overlapped with their ontology terms. According to the models, the WSHP and heat pump systems/applications have greater potential for development than air-conditioning systems (HVAC) or the GCHP.

The curve-fitting model considers the existing number of patents and assumes the sub-technologies to be independent. In reality, however, the sub-technologies can be competitive during development. As a result, findings based on the curve-fitting procedures require supplementation to provide a more comprehensive analysis of the patent data. We utilized strategic maps to further analyze the four sub-technologies. First, we used the frequency with which keywords co-occurred to determine the strength of each tie (a connection between any pair of ontology terms) to perform social network analysis. The “distance” between any pair of sub-technologies in the network can be determined by the rate at which any pair of ontology terms categorized in different sub-technology clusters co-occurred. The centrality and density of each sub-technology cluster was derived with co-occurrence rates within patents to represent the relationships among these sub-technologies. Centrality depicts the degree to which a given technology is associated with other technologies. Nodes with greater centrality have a greater number of associations with other technologies. This can serve as a proxy measure for a sub-technology's development. A high density measure indicates stable development of a sub-technology.

As shown in Table 4 and Fig. 6, the water source heat pump system has a high relative centrality compared to other sub-technologies (Cen._Rel = 0.43), indicating that this system is more highly associated with

Table 4
Centrality and density of sub-technologies

Sub-tech.	Centrality	Cen._Rel.	Density	Den._Rel
WSHP	2.16	0.43	3.97	1.43
GCHP	0.59	−1.15	2.69	0.14
Central air-conditioning system	2.54	0.81	1.27	−1.27
Heat pump/system operation technique	1.64	−0.09	2.25	−0.30
Mean	1.73		2.54	

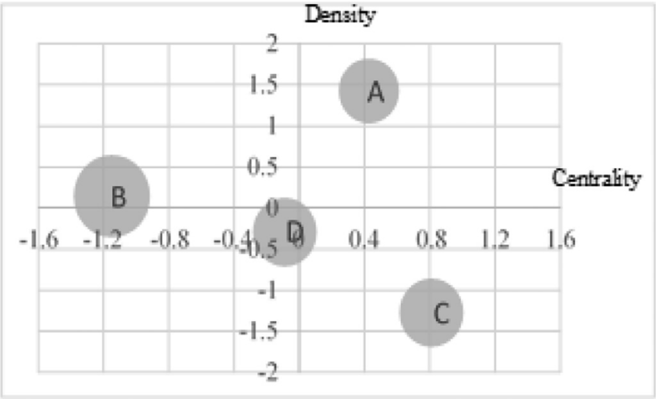

Fig. 6. Sub-technology strategic map.

(and thus playing a critical role with) other technologies (the scale of the following metrics are normalized with a center of zero, and therefore all judgments of "high," "medium," and "low" centrality are made using the other clusters as reference points). Its relative density (Den._Rel = 1.43) demonstrates the stability of its development relative to other sub-technologies. As indicated by the logistic curve (see Fig. 5), WSHP has the greatest potential for development among the various sub-technologies. However, the Chinese government has set various restrictions, including the management of ground water resources. For example, the Nanjing Municipal Government has specifically restricted the use of WSHP systems. The application of WSHP is widely prohibited in China for a number of reasons. First, despite wide dissemination of water source heat pumps in China, its application has been limited by policies enforced by the central or local governments, as WSHP-led settlement was significant in many urban areas. Second, the benefits afforded by the GSHP have been misunderstood by industry officials. As a result, many researchers have predicted reductions in the application of WSHP systems in China; these predictions contradict results produced by patent data [17,48,49]. Therefore, and despite its potential for development, we argue that the application of WSHP will be more limited than other sub-technologies.

Low relative centrality (Cen._Rel = −1.15) and low relative density (Den._Rel = 0.14) values indicate that the development of the GCHP remains limited. This probably results from problems that emerged during the development of GCHP systems, particularly in relation to the ground heat exchanger. First, the design of the ground heat exchanger is normally limited by the heat exchange models because they fail to account for the effect of groundwater advection [54]. Second, there are few reliable instruments available for measuring the thermal properties of undisturbed soil in real-time (which is critical for decision-making related to pipe materials). Typically, decisions concerning pipe procurement are experience-based, and thus ultimately reduce heat exchange efficiency [17]. Finally, the implementation of GCHP requires substantial investment and large amounts of space for installation, thereby increasing expenses associated with its application [47]. As illustrated above, it seems that the development of the GCHP systems requires a more thorough scientific understanding and an improvement in construction techniques.

The high relative centrality of the central air-conditioning cluster indicates a close association among technologies related to it. This means that GSHP systems are designed to be compatible with this sub-technology. However, the low relative density associated with this cluster (Den._Rel = −1.27) signifies the slacked development of this technology. Strategic development of this technology may be useful for improving the interfaces between central air-conditioning systems and GCHP or WSHP. However, the logistic curve indicates that the turning point lags behind 2012, thereby inhibiting the development of this sub-technology. This suggests the investment of more resources is required to effectively develop this sub-technology. As such, we argue that emergent investment in this sub-technology may not be ideal.

According to the results presented in Section 3.1, the heat pump and system operation techniques are closely related to WSHP and GCHP, as they focus on heat exchange efficiency and the control of various parts and sub-systems. Moderate relative centrality (Cen._Rel = −0.09) and relative density (Den._Rel = −0.30) values compared to WSHP and GCHP suggest that this sub-technology is neither central among the subsystems, nor is it highly developed. This result is consistent with results produced by past research that has shown that the development of the heat pump system and operation techniques will continue to be the focus of GSHP in the coming years [48–51]. Moreover, GSHP sub-technologies (i.e., heat pump/system operation techniques and central air-conditioning) overlap with the WSHP and GCHP clusters, indicating that their development may affect the development of other sub-technologies. Given these results, we assert that investment in the heat pump system (as well as the technology needed to implement it) can be an efficient means of promoting GSHP. This is consistent with Liu's assertion that the heat pump system is the core technology of the GSHP; the design of the heat exchanger (the key component of heat pump systems) directly affects heat exchange efficiency and total expenses associated with the system. However, there remain difficulties associated with heat exchanger design, which jeopardizes the distribution of closed-loop GSHP [47].

4. Discussion and conclusions

Insufficient understanding related to the development of GSHP technology in China has limited the degree to which effective policies regarding its dissemination have been developed. This study has proposed a new bibliometrics-centered methodology that integrates semantic labeling, the FOPC algorithm, logistic models, and social network analysis to observe and explain the development of GSHP systems. The results of this study provide a data-driven categorization of GSHP technologies, thereby laying the foundation for fruitful discussions concerning future investments. Furthermore, we also outlined the development of each technology in terms of their associations with other technologies, providing more nuance for policy makers.

According to research results outlined above, the government should undertake several measures to encourage the dissemination of GSHP in the building sector. First, incentives concerning the R&D of GSHP should focus on GCHP and heat pump/system operation techniques. More specifically, backfill and different types of primary circulars still face problems in relation to GCHP installation. More extensive research geared towards improving installation quality and enhancing the heat exchange rate, as well as increasing the potential for applying GCHP systems would be useful. Second, the Chinese government should revise building codes and standards to synthesize with GCHP systems, thereby facilitating their installation.

Although this study provides significant insights, its results should be interpreted cautiously given a few limitations. First, we exclusively utilized patent data from mainland China. According to the World Intellectual Property Organization (WIPO), a patent is a recognition of the right to the inventors, and can thus be considered a valid indicator of the nature of the innovation, and core techniques associated with it [24]. In other words, patents protect the rights of the inventors in a specific location, and thus illustrate the innovation's maturity and local development [29,31,44,45]. Because mainland China establishes its own standards related to the dissemination of GSHP technology, the local development of such a technology is a crucial precursor for its distribution. Second, patent data is currently the only indicator of the GSHP's development. Although many studies support this point of view [31,42–45], to provide a more nuanced understanding of GSHP's developmental trends, future researchers should employ other types of data. For example, the language inherent to relevant legislation would make a useful data source for bibliometric analysis.

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Appendix A

GSHP = Ground Source Heat Pump
GCHP = Ground Coupled Heat Pump
WSHP = Water Source Heat Pump
FCM = Fuzzy C-Means
FOPC = Fuzzy Overlapping Clustering

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