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Geothermal energy utilization trends from a technological paradigm perspective

Bobo Zheng [a, b], Jiuping Xu [a, b, *], Ting Ni [a, b], Meihui Li [a, b]

[a] Low Carbon Technology and Economy Research Center, Sichuan University, Chengdu 610064, PR China
[b] Business School, Sichuan University, Chengdu 610064, PR China

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ABSTRACT

The use of geothermal energy and its associated technologies has been increasing worldwide. However, there has been little paradigmatic research conducted in this area. This paper proposes a systematic methodology to research the development trends for the sustainable development of geothermal energy. A novel data analysis system was created to research the geothermal energy utilization trends, and a technological paradigm theory was adopted to explain the technological changes. A diffusion velocity model was used to simulate and forecast the geothermal power generation development in the diffusion phase. Simulation results showed that the development of installed capacity for geothermal generation had a strong inertia force along with the S-curve. Power generation from geothermal power sources reached a peak in 2008 and is estimated to be saturated by 2030. Geothermal energy technologies in hybrid power systems based on other renewable energy sources look to be more promising in the future.

1. Introduction

The fourth assessment report of the United Nations Intergovernmental Panel on Climate Change has revealed that increased CO_2 concentrations in the atmosphere could lead to an increase in the greenhouse effects which in turn could adversely affect climate change [1]. Forced by the need to protect the environment and promote the sustainable development of energy resources, pressure is growing to accelerate the adoption of renewable energy resources worldwide. Geothermal resources offer energy that is constant, and available on demand, providing an important alternative to fossil fuels [2]. The energy savings from using geothermal resources are shown in Table 1 [3]. The case study reported by the Geothermal Energy Association compared geothermal energy with a coal plant that had been updated with scrubbers and other emissions control technologies. It was found that regardless of the emissions improvements, the coal plant emitted 24 times more carbon dioxide, 10,837 times more sulfur-dioxide, and 3865 times more nitrous oxides per megawatt hour than a geothermal steam plant.

However, due to the lack of a systematic analytical framework, much of the research in geothermal energy utilization has had little integrity or universality. In addition, there have been few studies which have specifically examined low-carbon technological paradigms, or, in particular, the geothermal energy utilization technological paradigm (GEUTP). As a result, progress in this area has been slow with previous achievements partially overlapping and therefore adding little to the area. Thus, there is a need to study the paradigm in terms of the technological evolution of geothermal energy utilization. If a geothermal energy technological paradigm is established, it could be used to investigate renewable energy solutions to reduce future carbon emissions.

When seeking to describe technological change and innovative research, the technological paradigm provides a sound method for the investigation of past trends as well as being able to predict future possibilities. In a broad analogy with the definition of the scientific paradigm [4], the technological paradigm is defined as "model for the solution of selected technological problems, based on highly selective principles derived from the natural sciences, together with the specific rules designed to acquire new knowledge, and to safeguard them as far as possible against rapid dissemination to competitors" [5]. An important concept in the above model is the technological trajectory, which is defined as the technological progress restrained by economic and technological trade-offs defined by a paradigm [6]. In other words, the trajectory

* Corresponding author. Business School, Sichuan University, Chengdu 610064, PR China. Tel.: +86 028 85418191; fax: +86 028 85415143.
E-mail address: xujiuping@scu.edu.cn (J. Xu).

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Table 1
Worldwide savings in energy, carbon and greenhouse gases using geothermal energy.

	Fuel oil		Carbon	CO_2	SO_x	NO_x
	bbl	TOE	TOE	TOE	TOE	TOE
As electricity	250.0	37.5	33.2	106.9	0.74	0.022
As direct heat	125.0	18.8	16.6	53.4	0.37	0.011

Including geothermal heat pump cooling (figures in millions) in terms of fuel oil (TOE = tonnes of oil equivalent).

is the external form of the paradigm. For example, when targeting technologies, the trajectory may develop along the technological life cycle, which is presented in S-curves. However, the existence of a paradigm does not guarantee that its associated trajectory will develop, but it does mean that there is a complex process of selection within firms to determine the economic viability of the paradigm [7].

The technological paradigm is mainly applied to analyze technological change and innovation in engineering fields [7–9]. By demonstrating how the various factors interact, such as scientific advancement, economic development, and organizational structural change, blocks that are unable to be solved using existing technologies are exposed and future technological trajectories identified. With respect to how technological change occurs, demand-pull and technology-push have been identified as the two main driving forces [6], with supply and demand, namely push and pull, affecting the development of technological paradigms [10].

Thousands of research papers have been presented which focus on the use and benefits of geothermal energy. A novel data analysis system is created to summarize the trends to support the technological paradigm to elucidate the development of geothermal energy utilization. The data analysis system (DAS) is made up of the Web of Science database (WoS), NoteExpress and NodeXL, which is used to determine the internal relationship between the keywords. Compared with more simple statistical tools, this method has the ability to show the mutual relationships between the keywords over time. A diffusion velocity model is used to simulate and forecast the dominance geothermal power generation development in the diffusion phase of the GEUTP. This model is derived from a classic logistics model, combined with physics-based field theory.

The remainder of this paper is structured as follows. Section 2 uses the data analysis system (DAS) to identify the main technological trajectories and uncover trends of geothermal energy utilization. The geothermal energy utilization technological paradigm is given in three stages in Section 3. In Section 4, geothermal power generation in the diffusion phase is illustrated as a case study and discussed based on the diffusion velocity model. Section 5 discusses the proposed framework. Conclusions are provided in Section 6.

2. Literature mining

With the explosive growth in geothermal energy research, it is difficult to screen for the most useful research foci and development directions. Literature mining, therefore, is indispensable in determining the most pertinent scientific research, especially in areas of particular interest such as geothermal utilization [11]. Literature mining is a powerful method for discovering the major trends across the years in the published scientific literature so that topic maps can be built [12]. Our primary goal for literature mining is to discover the relationships between the published years and the article keywords for geothermal utilization technologies.

2.1. The data analysis system buildup

Garfield, the “father of academic literature citation indexing”, believed that citations were the formal, explicit linkages between papers that have a commonly specific field [13]. A citation index is built on the fact that citations in science served as linkages between similar research items, and can lead to matching related scientific literature, such as journal articles, keywords, years, and abstracts. Moreover, research which has the greatest impact in a specific field, or not less than one discipline, can be easily located using a citation index. For example, a paper's influence can be determined by its links to all the papers in which it has been cited. In this way, current developments, technologies, trends and potential fields of research emerge.

Based on the importance of the scientific research prime resources for observation and review can be identified. Peer-reviewed scientific research is extremely important, as these researchers are required to have considered the latest worldwide progress in their areas and to have ascertained the future in their respective research fields [14]. With this in mind, literature mining plays a pivotal role in the determination of the extent of geothermal utilization. To discover the keywords trends, the DAS is made up of the Web of Science database (WoS), NoteExpress and NodeXL. The WoS is chosen as the primary database, then NoteExpress is applied to review the general characteristics, and NodeXL is used to analyze the bibliographies. Therefore, the DAS, as a comprehensive integrated approach, can guide our research into the potential GEUTP development trajectories as shown in Fig. 1.

The Web of Science is the world's most trusted citation index as it covers all the leading scholarly research. The WoS is an online subscription-based scientific citation indexing service maintained by Thomson Reuters that provides a comprehensive citation search. It gives access to multiple databases that reference cross-disciplinary research, which allows for an in-depth exploration of specialized sub-fields within an academic or scientific discipline. Therefore, the WoS provides researchers, governments, and faculty with prompt and effective access to the world's leading citation databases. The network analysis using the WoS was conducted by Ridley et al. [15].

NoteExpress, which is similar to EndNote, is the most professional literature retrieval and management system in China. NoteExpress efficiently and automatically searches, downloads and manages research papers in a variety of ways. The core function of NoteExpress covers all aspects of knowledge management including knowledge acquisition, management, application, and mining, all of which are essential tools for academic research and knowledge management. Some scholars in China have achieved important research results by making use of NoteExpress in different fields [16–18].

NodeXL, a free analysis tool, was designed to facilitate the learning of the concepts and methods of social network analysis using visualization as a key component [19]. It is a powerful and easy-to-use interactive network visualization tool that leverages the widely available Microsoft Excel application as a platform for representing generic graphical data, performing advanced network analyses and providing a visual exploration of the networks. NodeXL generally supports multiple social network data providers that import graphical data (nodes and edge lists) into an Excel sheet and has been used widely by many researchers [20,21]. NodeXL, therefore, plays a vital role in the analysis of the keyword trends in our research.

2.2. Filtering criteria

Since the WoS is rich with knowledge, it is difficult to select useful articles if the appropriate filtering criterion is not specified. Under this circumstance, and to avoid important documents being