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The Socioeconomic and Environmental Assessment of Using geothermal Heat Pumps in Buildings: An EIO-LCA Analysis for China

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ABSTRACT

As China's rapid urbanization continues, and the growing demand for carbon emission reduction increases, integration of renewable energy technologies with buildings has become an efficient solution. Geothermal heat pumps (GHP) are being widely applied in China due to being both safe and clean. In this paper, GHP is regarded as an independent industry sector, and the economic relationship with other industries and environmental influence was also studied in greater depth. The life cycle inventory was used to calculate the raw material input and energy consumption of GHP Sector at each stage. A new Input-Output (I–O) table was developed based on actual data on GHP life cycle inventory analysis. Taking a project in a northern China city as an example, this study calculated the linkage and spread relationship between the GHP sector and other industries in China and quantized and calculated the energy consumption and carbon emission of GHP during the whole life cycle. It is shown that the GHP sector has a high industrial consumption for the power supply sector, mining and processing of metal ores sector, manufacture of chemical products sector, and it has a significant pulling effect on the economy. The life-cycle energy of the GHP system was 47.59 TJ, and the CO_2 emission was 11,877 tons. If the GHP is further widely used, it will have greater emission reduction potential.

1. INTRODUCTION

Greenhouse gas (GHG) emissions influence climate change directly. Thus, it is imperative to reduce carbon emission, adjust the energy structure, and promote energy transaction. The Paris Agreement (UNFCCC, 2015) has reached a consensus that greenhouse gas emissions should be urgently reduced globally. China has pledged to peak carbon dioxide emissions around 2030 and has planned to make non-fossil fuels account for about 20% of primary energy consumption by the same year. Carbon emissions from the construction industry are an important part of China's total carbon emissions and have a significant impact on China's ability to successfully achieve its 2030 carbon peak target. The main reasons for the gradual increase of building energy consumption include the acceleration of urbanization and the improvement of living standards (Self S J, 2013). Building energy consumption mainly concentrates on the heating and cooling system energy consumption which improves the indoor environment (Allouhi A, 2015).

In recent years, renewable energy has been encouraged in many countries in response to the problems caused by global warming, environmental pollution, resource depletion, and energy security. Renewable energy includes solar, wind, biomass energy and geothermal energy. Renewable energy has the advantages of wide distribution of resources, great potential for development and utilization, a small impact on environmental pollution and sustainable utilization (Panwar N L, 2011). Shallow geothermal resources are an important part of the earth's thermal energy, with the advantages of sustainable utilization, convenient access, high efficiency and energy saving, low operating costs, and is an important local, renewable and pollution-free resource. Shallow geothermal resources use geothermal heat pump technology, with a small amount of electrical energy can be used to solve building heating, cooling and supply of domestic hot water as well as other problems. It has advantages over conventional heating and cooling methods such as coal, gas and oil (Zhu, 2015). Geothermal (ground-source) heat pumps (GHP) are one of the fastest growing applications of renewable energy in the world. Its main advantage is that it uses normal ground or groundwater temperatures (between about 5 and 30℃), which are available in all countries of the world (Lund J, 2004).

John W. Lund (2016) reviewed the worldwide application of geothermal energy for direct utilization, in particular the thermal energy used in the year 2015 is 592,638 TJ/year (164,635 GWh/year). GHP accounts for about 55.2% of thermal energy. China is relatively rich in geothermal energy resources, accounting for about 8% of global geothermal energy resources, equivalent to more than 400 billion tons of coal (Yin, 2018). Direct utilization of geothermal energy in China mainly comes from the requirements of building energy saving and carbon dioxide emission reduction. Compared with Europe and the United States, GHP started late in China. GHP started in China at the end of 1990s under the impact of the world, and then gradually formed and developed. With the support of policies, GHP has developed at a higher speed over the past decade and entered the era of rising GHP industry in China (Zheng, 2010). As of 2015, the direct utilization of geothermal resources in China reached 17,870.00MWt (Lund, 2016), the annual utilization of GHP in China accounted for 30.86% of the total energy utilized, ranking first in the world. The fastest growing part is the utilization of geothermal heat pumps (Xu,2018). According to geological survey of China, in 2015, the installed capacity of geothermal heat pumps was 11,781 MWt, and the heating/cooling area of Geothermal heat pumps in China reached 392 million square meters.

Since GHP was first widely adopted, its investment cost and its impact on soil, temperature and water have been the focus of research. At present, the academic community has conducted much research into both economic assessments and environmental performance. Some scholars have studied whether the GHP industry is economical and environmentally friendly based on the monitoring and comparison of technical indicators. Esen and Inall (2007) made a techno-economic comparison between a ground-coupled heat pump (GCHP) system and an air-coupled heat pump (ACHP) system. The results indicated the GCHP is more energy efficient and environmentally friendly than ACHP. Oliver and David (2012) employed thermo-economic analysis to establish a valuation method of renewable energy technologies which including the ground-source heat pumps. Badescu (2007) explored the economic feasibility of different active space heating systems based on ground thermal energy utilization. The results show that GHP configuration is the most economical solution for medium and long-term operation (i.e. over 3-10 years). Lu (2017) assessed some economic indicators for residential vertical ground source heat pump (GSHP) systems in Australia. It is found that throughout its the design life of 20 years, the economic benefit of air source heat pump (ASHP) system is slightly higher than that of GSHP system. However, for a 40-year design life, the GSHP system offers significant savings over other alternatives, including the ASHP system. Climate change was also factored into the economic analyses, with only minor effects observed.

Predecessors in the economic and environmental impact of the use of GHP made for comparatively abundant research. However, there has a lot of micro researches undertaken, which stay within parameter evaluation and impact research into various projects, but do not rise to the industrial level and study the actual impact of the development and utilization status of the overall industrial regional economy and environment. Most of the economic and environmental impact assessments in a limited number of regions are based on the prediction of economic and environmental impact from the perspective of resource potential, which is of little significance to the research on industrial development policies. Studies on the correlation and influence between GHP and other industries and between regional economies have not been carried out. In addition, there are few studies into the carbon emission reduction potential of the GHP sector compared with other fossil fuels.

In order to make up for the above defects, this study focuses on the impact of GHP application on socioeconomic and environment. The LCI method was used to analyze the input and output of GHP in each production stages. Using the collected LCI data, a hybrid I-O table is constructed to measure the direct and indirect impacts of the GHP sector on other industries. Finally, the energy consumption and carbon emission of GHP Sector are calculated. The part 2 of this paper presents the methods, the part 3 presents the data, the part 4 is the results and discussion, the part 5 is the conclusions and recommendations.

2. METHODOLOGY

2.1 Life Cycle Assessment Methodology

Life cycle inventory analysis (LCI) forms a part of life cycle assessment (LCA), which includes compiling and quantifying the inputs and outputs of a given product system of every stage. (Suh and Huppes, 2002). The LCI model is used to calculate the energy use and environmental emissions of buildings equipped with GHP, and we can obtain the specific results of each stage through this model. A distinguished distribution of cost and impacts can be found in chronologic terms for specific energy saving measures in Figure1.

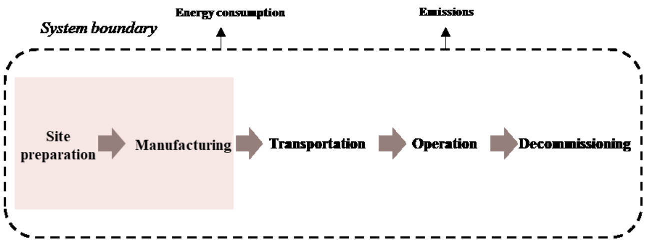

Figure 1: System boundary of the geothermal heat pump (GHP).

Below are details of the main processes involved in the construction and operation of the example project in Henan province, China, and the assumptions made about these processes. Table 1 summarizes the key parameters adopted to inform the life cycle assessment, the underpinning assumption and the information source. Each of the steps in Table 1 is explained further in the subsections that follow.

Table 1: Key parameters and assumptions of the geothermal heat pump (GHP).

Parameter	Aspect	Assumption	Source
Construction	Site preparation		Greening et al. (2012)
	Raw material and manufacturing	900kwh	Example project and Greening et al. (2012)
Transportation		78tkm	Greening et al. (2012)
Operation	Heating(annual)	750,503.7kwh	Example project
	Cooling(annual)	254,469.6kwh	Example project
	Project lifetime	15 years	Example project
Decommissioning		Not concerned	

2.2 Hybrid Input Output analysis

Economic input–output (I-O) analysis is a well-established model, which was first theorized and developed by Wassily Leontief in 1970s, based on his earlier work in the late 1930s, for which he received the Nobel Prize (Leontief,1970). In its simple and basic form, an input–output model is very comprehensive and detailed in describing national economic systems with many e relationships, including supply and demand information between industrial sectors (Xing and Dong,2017).

Industrial correlation refers to the direct and indirect economic relation of mutual dependence and restriction by industries of national economy in the process of social reproduction. Industrial correlation includes forward correlation and backward correlation. Forward correlation refers to the influence of an industry on those industries that directly or indirectly use the products of the industry as inputs, while backward correlation refers to the influence of an industry on those industries that directly or indirectly supply products to the industry.

The direct consumption coefficient is generally used in the analysis of the direct backward related industry. The direct consumption coefficient, a_{ij}, refers to the value of goods or services of the *i* product industry directly consumed by the unit total output of the j product or industry in the process of production and operation, as represented by Eq. (1). The larger the direct consumption coefficient is, the closer the technical and economic relationship between the two industries is.

$$a_{ij} = X_{ij} / X_j \quad \text{with i, j = 1, 2…n} \qquad (1)$$

The direct consumption coefficient of each industry is expressed as the direct consumption coefficient matrix A. The complete consumption coefficient is generally used in the analysis of the complete backward. The larger consumption coefficient is, the closer the direct and indirect technical and economic relations between the two industries are. The complete consumption coefficient matrix can be defined in Eq. (2) based on the direct consumption coefficient matrix.

$$B=(I-A)^{-1}-I \qquad (2)$$

In Eq. (2), A is the direct consumption coefficient matrix, *I* is the unit matrix, and B is the complete consumption coefficient matrix.

The direct distribution coefficient rij, which is used as an indicator to analyze the direct technical-economic relationship between industries from the perspective of output, refers to the proportion of the value of an industry or a product allocated to another industry or an industry for direct use as an intermediate product in the total output value, as represented by Eq. (3).

$$r_{ij} = X_{ij} / X_i \quad \text{with i, j = 1, 2…n} \qquad (3)$$

The complete distribution coefficient is generally used in the analysis of the complete forward associated industries. The greater the perfect distribution coefficient, the greater the forward perfect correlation between industries, indicating that the industry has played an obvious role in promoting other industries. The complete distribution coefficient matrix is represented by Eq. (4).

$$D=(I-R)^{-1}-I \qquad (4)$$

In Eq. (4), D is the complete distribution coefficient matrix, and R is the direct distribution coefficient matrix.

Industrial spread refers to that the change of an industry will cause the change of industries directly related to it in the national economy industry. It then leads to changes in other industries directly and indirectly related to the latter, which in turn are transmitted. Industrial spread effect can be quantitatively analyzed by the index of inductance coefficient and influence coefficient.

Industry induction reflects the ability of an industry to be influenced by other industries. Induction coefficient is the ratio of inductance of one industry to that of other industries. Induction coefficient greater than or less than 1 indicates that the induction of the industry is above or below the average level in all industries. Induction coefficient can be represented by Eq. (5).

$$f_j = \sum_{i=1}^{n} C_{ij} / (\sum_{i=1}^{n}\sum_{j=1}^{n} C_{ij} / n) \quad \text{with j = 1, 2…n} \qquad (5)$$

On the other hand, industrial influence reflects the ability of the change of the final product of an industry to affect the change of the total output of the entire national economy. The influence coefficient is the average ratio between the influence of an industry and the influence of each industry in the national economy. The influence coefficient is greater than or less than 1, indicating that the influence of the industry is above or below the average level in all industries. Influence coefficient can be represented by Eq. (6).

$$e_i = \sum_{j=1}^{n} C_{ij} / (\sum_{i=1}^{n}\sum_{j=1}^{n} C_{ij} / n) \quad \text{with i = 1, 2…n} \qquad (6)$$

In Eqs. (5) and (6), n is the number of industries. C_{ij} is an element of the Leontief inverse matrix.

However, in the existing input-output table, the technical characteristics of the GHP Sector are not reflected. The data in the input-output table also does not reflect the process of the department or product. To solve these problems, some scholars have developed hybrid I-O methods. Bullard and Herendeen (1975) developed a hybrid I-O method. Hendrickson (1998) proposed economic input-output models for environmental life-cycle assessment (EIO-LCA). After that many researchers developed the method to deal with environmental performance of economy production. Ji and Liu (2011) built a sectoral GHG emissions matrix to investigate GHG emissions of the Chinese economy by producing sectors. Igos and Rugani (2015) used hybrid life cycle-input–output method to predict environmental impacts of energy policy scenarios. Nagashima and Uchiyama (2017) proposes Eq. (7) to analyze environmental performance of a wind power generation system.

$$O^{\text{hybrid}} = \begin{pmatrix} O^{*} & H^{d} \\ H^{u} & O \end{pmatrix} \tag{7}$$

In this equation, matrix Ohybrid is a newly constructed I-O table that can reflect the situation of all departments. The matrix Hu represents upstream cut-off to process data flows of new developed sector associated with the relevant industrial sectors. The matrix Hd captures the cut-off stream downstream to the I-O table from the process data. The matrix O is mostly an existing I-O table. According to the selected sector, the matrix Hu, Hd, O may need to be adjusted accordingly. Fig. 2 is a graphical representation of Eq. (7).

<table>
<tr><td colspan="2" rowspan="2"></td><td colspan="5">Intermediate output</td></tr>
<tr><td>New sectors</td><td>Industrial sector 1</td><td>2</td><td>......</td><td>n</td></tr>
<tr><td rowspan="7">Intermediate input</td><td>New sectors</td><td>O*</td><td colspan="4">H^d</td></tr>
<tr><td>Industrial sector 1</td><td rowspan="6">H^u</td><td>x₁₁</td><td>x₁₂</td><td>......</td><td>x_{1n}</td></tr>
<tr><td>2</td><td>x₂₁</td><td>x₂₂</td><td>......</td><td>x_{2n}</td></tr>
<tr><td>......</td><td>......</td><td>......</td><td>O</td><td>......</td></tr>
<tr><td>Conventional heat utility</td><td>x_{k1}</td><td>x_{k2}</td><td>......</td><td>x_{kn}</td></tr>
<tr><td>......</td><td>......</td><td>......</td><td>......</td><td>......</td></tr>
<tr><td>n</td><td>x_{n1}</td><td>x_{n2}</td><td>......</td><td>x_{nn}</td></tr>
</table>

Figure 2: I–O table for hybrid I–O analysis

3. DATA

3.1 Inventory Analysis

The LCA methodology used in this study follows the ISO 14040 and 14,044 guidelines (ISO, 2006). The goal of this study is to estimate the life cycle environmental impacts of geothermal heat pumps. According to China Geological Survey, in 2015, the installed capacity of geothermal heat pumps was 11,781 megawatts, and the heating/cooling area of geothermal heat pumps in China reached 392 million square meters. A typical design capacity of the heat pumps of 10 kW is assumed (Greening and Azapagic, 2012). The functional unit is defined as 'generation of 1 kWh of thermal energy for domestic space heating'. The scope of the study is from 'cradle to grave'; the details for the heat pump of construction and transportation is summarized in Table 2.

The data relating to site preparation and operation for GHP is from an example project undertaken in Henan Province, China in Table 3. The project needs 900kW heat pump and heating or cooling for 30,179m^2.

Table 2: Construction and transportation inventory of a 10 kW GHP systems.

Component, system or life cycle stage	Ground-source heat pump	Weight	Cost (CNY)
Site preparation			26.67
Evaporator and condenser	Low-alloyed steel	1,800.00 kg	42.96
Housing and compressor	Reinforced steel	6,750.00 kg	138.59
Wiring, piping and expansion valve	Copper	1,980.00 kg	658.01
Pipework insulation	Elastomere:	900.00 kg	8.04

Wiring insulation	Polyvinylchloride	90.00 kg	4.81
Lubricating oil	Polyolester oil	153.00 kg	184.42
Refrigerant	R-134a	278.10 kg	3.09
Assembly of pump units	Medium-voltage electricity	30,330.00 MJ	74.14
	Natural gas	78,750.00 MJ	58.45
Under-floor heating system	Sand	418,500.00 kg	358.05
	Cement	81,000.00 kg	288
	Aluminum	11,340.00 kg	1216.32
	LDPE	9,090.00 kg	984.75
	Polystyrene	5,940.00 kg	587.4
Heat collector pipework	HDPE (horizontal heat collector, HHC)	27,108.00 kg	2981.88
	HDPE (vertical heat collector, VHC)	16,479.00 kg	1812.69
Heat collector pipework insulation	LDPE	423.00 kg	45.83
Heat carrier liquid	Ethylene glycol (HHC)	15,030.00 kg	778.22
	Ethylene glycol (VHC)	9,018.00 kg	466.93
Manifold	Brass	594.00 kg	205.59
Back-fill	Cement (VHC only)	1,719.00 kg	6.11
	Bentonite (VHC only)	342.00 kg	6.02
Scaffolding, rods, supports	Reinforcing steel	2,970.00 kg	60.98
Installation	Diesel (VHC)	72,900.00 MJ	97.04
	Diesel (HHC)	874,800.00 MJ	1164.46
	Electricity	23.04 kWh	0.1536
Transportation		78tkm	39
Total			12259.6036

Table 3: Operation inventory for the example GHP project.

Items	Annual service days	Daily operation hours	Electricity use (kWh)	Cost (CNY)	Corresponding sector in IO table
cooling	90	16	254,469.6	152,700	Production and distribution of electric power and heat power
heating	120	24	750,703.7	450,500	Production and distribution of electric power and heat power
Compensation of employees				72,000	Compensation of employees
Total				747,200	

3.2 The Compiled Input and Output Matrix in the Hybrid Model

In this study, Matrix Hhybrid has 43 rows and 43 columns synthesized from four submatrices: O*, Hu, Hd, and O. O* is assumed zero, O is a basic I–O table for China in 2015 compiled by relevant government ministries and agencies (National Bureau of Statistics of China). The table integrates a variety of Chinese industries comprising 42 sectors. Based on the available data, the I-O table of the GHP Sector is compiled on the basis of China's 2015 I-O table. According to industry division, the GHP sector should belong to the electricity, heat production and supply department. However, it was confirmed that due to the small size of the industry, the sample survey was not included. In this paper, GHP Sector is added to the existing input-output table. It should be noted that the GHP manufacturing and construction sectors are based on single-year analyses, the conditions are therefore reflected in the results of this study. Hu includes calculations for sectors related to construction, transportation and operation. The depreciation method of GHP adopts the straight-line method, and the net residual value rate of machine equipment is 5%. The calculated total domestic GHP value is 893.7198 (unit: 10,000 CNY), see Table 4.

Table 4: Input data of GHP department.

Department	value	proportion
Extraction of petroleum and natural gas	9.848498	1.10%
Mining and processing of metal ores	16.29438	1.82%
Mining and processing of nonmetal and other ores	0.104958	6.55%
Manufacture of chemical products	58.5713	0.12%
Smelting and processing of metals	1.03408	0.12%
Production and distribution of electric power and heat power	790.1429	88.41%
Construction	4.865976	0.54%
Transport, storage, and postal services	0.290991	0.03%
Scientific research and polytechnic services	3.141993	0.35%
Compensation of employees	9.4248	1.05%
Total	893.7198	100%

Input-output analysis assumes that the total input and output are the same, so the total output of the Hd is equal to the total input, that is 893.7198 (unit: 10,000 CNY). Output data can be divided into "intermediate use" and "final use", "export", "domestic outflow from outside the province", "import", "domestic inflow from outside the province" and "other". Processing of "intermediate use" data: the intermediate output of the GHP sector is only in the "production and supply of electricity and heat" sector. "Resident consumption expenditure" and "government consumption expenditure" have not been formed. As a regional resource development and utilization industry, GHP department has low development and utilization cost of local materials, but it is not suitable for "export" or "outflow of domestic provinces", nor for "import" or "inflow of domestic provinces". The direct intermediate output of the GHP sector only exists in the "production and supply of electricity and heat" sector. But industry between input and output is mutual, continuous, thus producing the conduction effect, the GHP sector increases "electricity, heat production and supply" industry output to the many other departments, in order to improve computing, a similar "electric heat production and supply department" output structure is analyzed, according to the proportion of transverse data calculation GHP departments.

4. RESULTS AND DISCUSSION

4.1 Economic Effects

4.1.1 Analysis of Industrial Correlation of the GHP Sector

The analysis of industrial correlation mainly reflects the breadth and depth of inter-industry connection through the analysis of the direct consumption coefficient and the complete consumption coefficient. According to the calculations for both the direct backward related industry and complete backward related industry within the GHP sector, the results are as follows (Fig. 3): From the specific industries backward related to GHP sector, the backward relation of industries related to the "Power and heat supply department" is significantly higher than that of other industries. In 2015, the top three GHP Sector departments consumed the most directly were production and distribution of electric power and heat power, manufacture of chemical products, mining and processing of metal ores, with the direct consumption coefficients of 0.8841, 0.0655 and 0.0182, respectively. The top three industries with the largest complete consumption of GHP sector in 2015 were: production and distribution of electric power and heat power, mining and processing of metal ores and manufacture of chemical products, the complete consumption coefficients are 1.5373, 0.2508 and 0.02353, respectively. That is, GHP sector produce products and services per 10,000CNY, production and distribution of electric power and heat power, mining and processing of metal ores and manufacture of chemical products were consumed 15,373, 2,508 and 2,353CNY by direct and indirect means respectively.

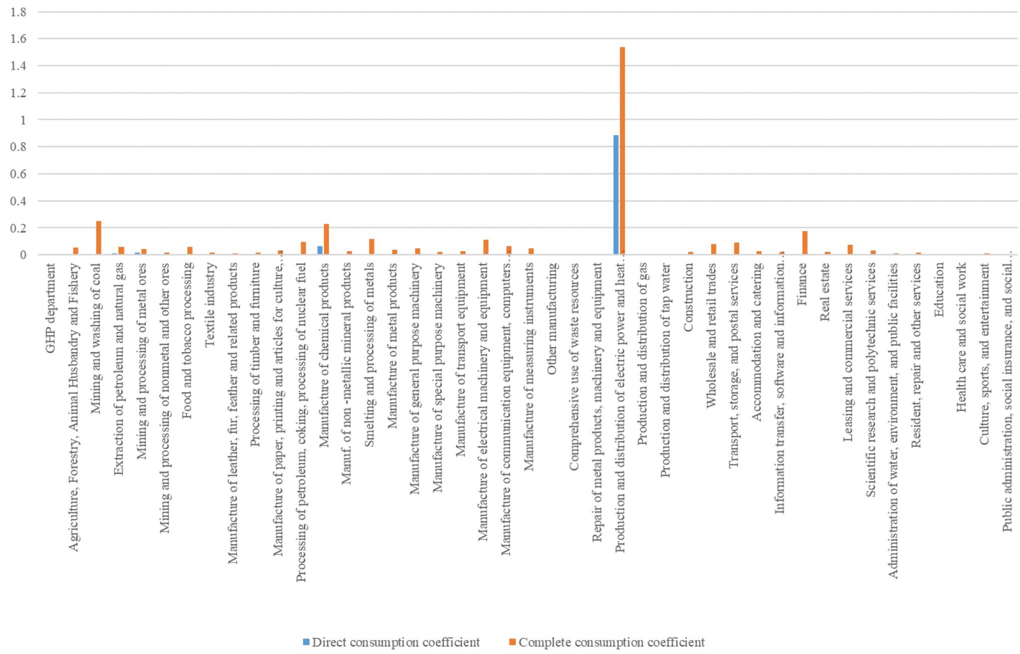

Figure 3: The direct and complete coefficient of the geothermal heat pump (GHP) sector.

Compared with the direct and complete backward correlation between GHP sector and other industries, the GHP sector is more closely related to the complete backward correlation with other industries. For example, the GHP sector's direct backward correlation with production and distribution of electric power and heat power was 0.8841, while the complete backward correlation was 1. 5373. As another example, the direct backward correlation degree of the GHP sector to mining and processing of metal ores is 0.0182, while the complete backward correlation degree is 0.4308. It shows that GHP sector not only has a direct demand pulling effect on the development of other industries in the national economy, but also has an obvious indirect demand pulling effect.

According to the calculations of the GHP sector's direct and complete forward related industries, the results are as follows (Fig. 4): From the specific industries backward related to GHP sector, GHP sector has significant direct forward correlation with the production and distribution of electric power and heat power, smelting and processing of metals, the manufacture of chemical products, and manufacture of non -metallic mineral products. The direct forward correlation between the GHP sector and these industries is above 0.04, that is, the 10,000CNY products or services produced by the GHP sector are directly placed into these industries as intermediate inputs and the production is above 400CNY. It indicates that the production demand of these industries directly affects the sales of GHP sector, and their development has a greater direct pulling effect on the GHP sector, that is, the development of the GHP sector has a more obvious driving effect on the direct supply of these industries.

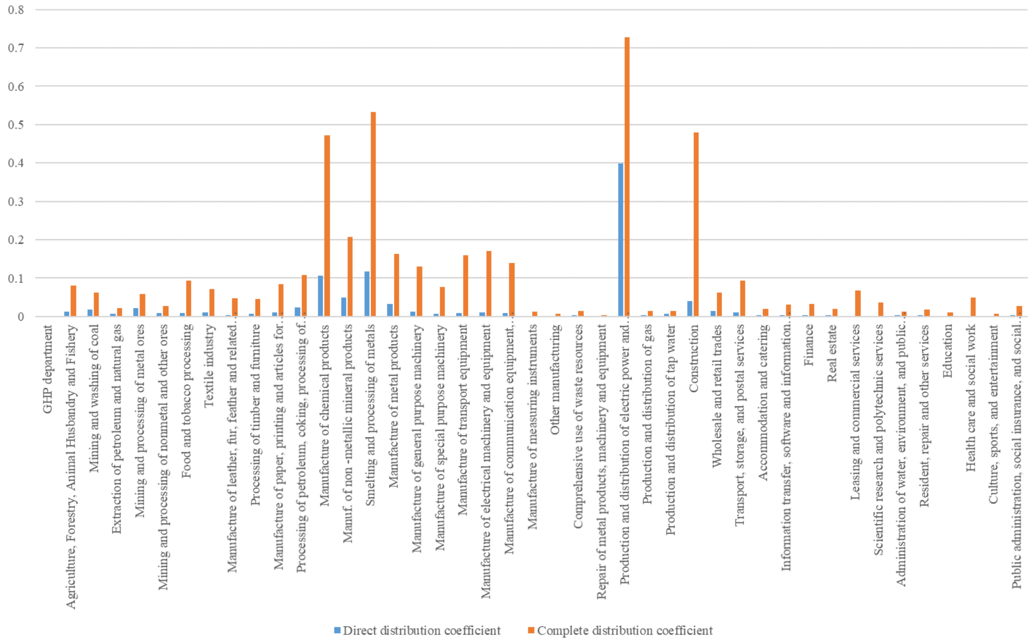

Figure 4: The direct and complete distribution coefficient of the geothermal heat pump (GHP) sector.

Compared with the direct and complete forward correlation between the GHP sector and other industries, the GHP sector is more closely related to complete forward correlation with other industries. For example, the GHP sector's direct forward correlation with smelting and processing of metals was 0.1181, while the complete forward correlation was 0.5328. The GHP sector's direct forward correlation with manufacture of non-metallic mineral products was 0.0487, while the complete forward correlation was 0.2078. It indicates that the industrial development not only has a direct demand pulling effect on the development of the GHP sector, but also has an obvious indirect demand pulling effect.

4.1.2 Analysis of the Industrial Spread of the GHP Sector

Combined with the characteristics of the GHP department, this study selected two indexes, namely, the sensitivity coefficient and influence coefficient, to measure the ripple effect of GHP department. Induction degree refers to the degree of demand induction that a certain department receives when each department within the national economy adds a unit for final use, that is, the output quantity that the department needs to provide other departments with. The sensitivity coefficient is greater than 1, indicating that the industry's sensitivity is above the average level in all industries; otherwise, it is below. The higher the induction degree coefficient, the greater the pulling effect of national economic development on the department, the stronger the demand induction degree of the department to economic development, on the contrary, it indicates a weak demand induction degree to economic development. The economic meaning of influence is the extent to which the production demand of each sector of the national economy is affected when a product sector adds a unit of final product. The larger the influence coefficient of a department is, the stronger the pulling effect of the expansion of its final product demand on the national economy is. When the coefficient of influence is less than 1, it means that the products or services produced by this sector have less impact on the production activities of other sectors than the average level of social influence. When its coefficient is greater than l, it indicates that the products or services produced by this sector have a greater impact on the activities of other sectors than the average social impact level.

In 2015, the induction coefficient of the GHP department was 0.3094, far lower than the average level within society, indicating that when all departments of national economy increase 10,000 CNY for final use, the total output of the GHP department will be increased by 3,094 yuan (see Fig.5). As a new energy industry, the GHP department has a very low restraint on other departments, and is only slightly affected by other industrial departments, meaning that the supply promotion effect on economic development is not obvious. Therefore, so as to ensure the development of the GHP department at the present stage, the government's promotion and corresponding policy support are particularly important.

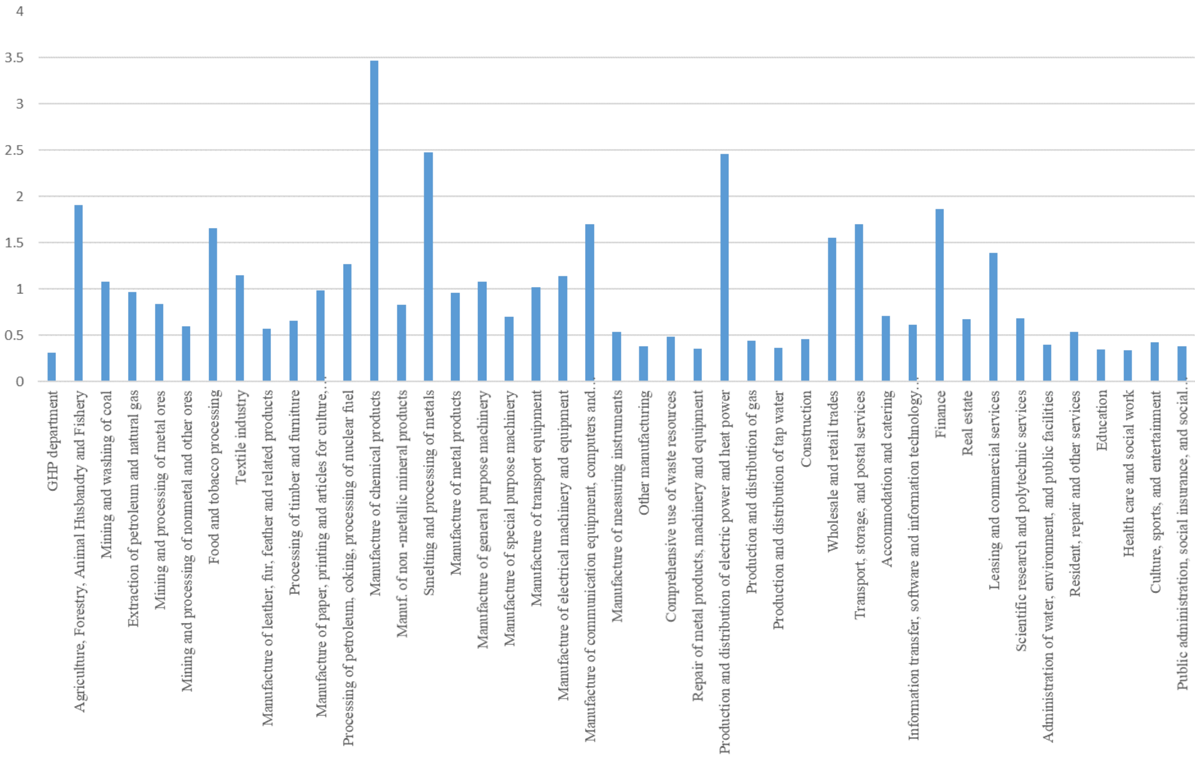

Figure 5: The induction coefficient of the geothermal heat pump (GHP) sector.

In 2015, the influence coefficient of the GHP department was 1.4219, higher than the average level within society, indicating that the GHP department has a significant pulling effect on the city's economy when it adds one unit of final product (see Fig.6). Through the analysis of inductance and influence, it is shown that the utilization of the geothermal heat pump has causal and linkage relationship with national economic development.

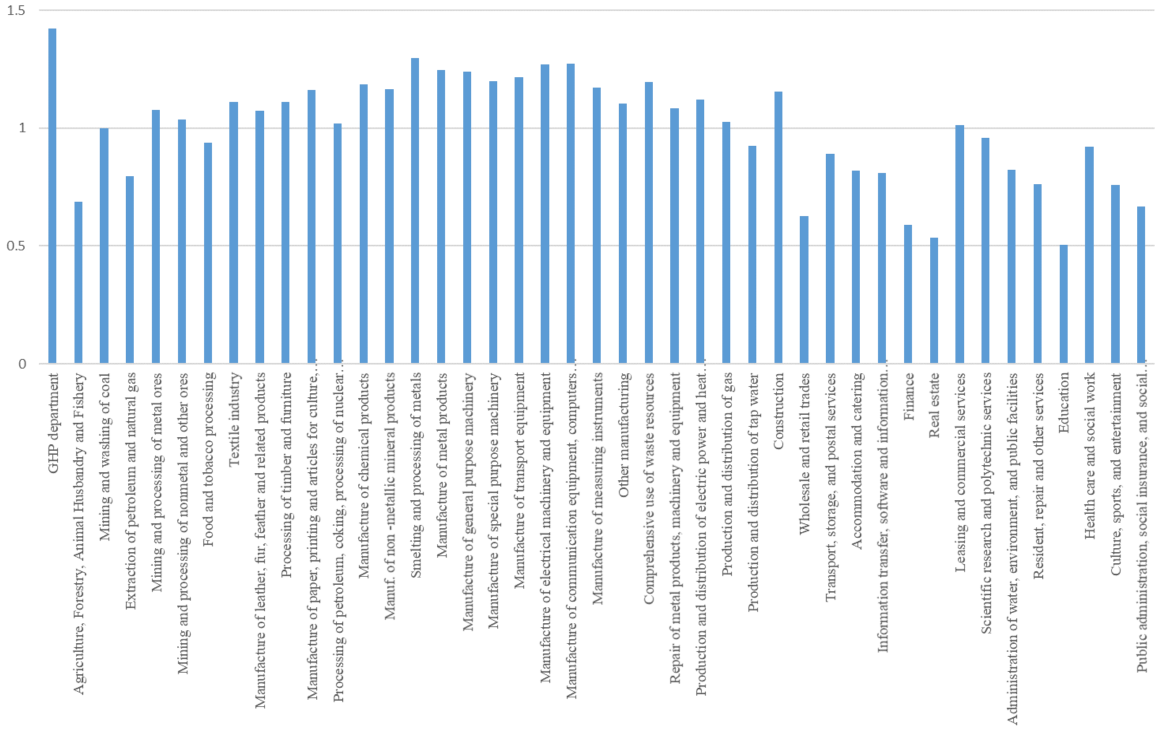

Figure 6: The influence coefficient of the geothermal heat pump (GHP) sector.

4.2 Energy and Environmental Effects

In 2015, the installed capacity of geothermal heat pumps was 11,781 MWt, and the heating/cooling area of geothermal heat pumps in China reached 392 million square meters. The amount of energy consumption and CO2 emissions induced from construction, transportation and operations of the GHP department have been estimated to be 47.59 TJ and 11877 tCO_2, mostly from operation. These burdens are concentrated in specific sectors, such as the "production and distribution of electric power and heat power", which account for 98% of total CO_2 emissions. Most energy consumption and carbon emissions are from the operation stage. This confirms that the transition to green energy is helping to reduce the associated energy and environmental costs associated with renewable energy efficiency. The metals and metal products sectors are the second largest source of emissions. This is mainly due to the high consumption of structural steel and steel tubes in GHP.

In 2015, China's total construction energy consumption was 857 million tons of standard coal, accounting for 20% of China's total energy consumption. The country's total construction area reached 61.3 billion square meters. As a part of this total, the heating area and energy consumption of northern towns are 12.9 billion square meters and 193 million tons of standard coal, and the heating energy intensity is 14.9 kilograms of standard coal per square meters. If GHP is used instead of traditional heating methods, 505.26 million tons of CO_2, 1.64 million tons of SO_2 and 1.42 million tons of carbon oxides can be saved. In general, using GHP in buildings can effectively save coal consumption, as well as reducing the emission of carbon dioxide and other pollutants.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

With increasing energy and environmental pressures associated with economic development and urbanization in China, the need to construct efficient buildings is urgent. Based on EIO-LCA method, the socioeconomic and environment assessment of the GHP sector in 2015 were examined. Concerning the economic aspect, the establishment of hybrid input-output table studied the industrial correlation and industrial spread of GHP sector. In the aspect of the environment, the energy consumption and emission of the GHP sector are calculated by the input of energy and raw materials. Several valuable conclusions have been reached through these analyses.

First, from the perspective of the direct consumption coefficient and complete consumption coefficient, the correlation between the GHP sector and other industries is different. The GHP sector has a high industrial consumption for the power supply sector, mining and processing of metal ores sector, and the manufacture of chemical products sector. Therefore, the development of these sectors is of great significance to the development of the GHP sector. In addition, there is no obvious direct link between the GHP sector and the numerous other industries, but the indirect link between them is quite common. Although the GHP sector is closely related to almost all industries, its impact on other industries is not deep. It suggests that we should continue to vigorously develop the GHP sector and encourage its driving effect on other sectors. Also, we should accelerate GHP innovation and improve the interrelation between GHP and other sectors.

Second, the induction coefficient and influence coefficient of GHP sector was compared, the latter was greater than the former, indicating that GHP sector's pulling effect on economic development was significantly greater than that of economic development. Therefore, it is necessary to further clarify the status and role of the GHP sector in China's economic development. Only through adopting a more proactive development strategy can the GHP sector play a more relevant, radiating and stimulating role within the economy. At the same time, the efficiency and technological level of the GHP sector must be promoted to ensure the fast growth of GHP sector demand alongside economic growth.

Lastly, GHP sector's performance in energy consumption and emissions was measured. The energy consumption and carbon emission of the GHP sector are also mostly related to the consumption of power sector in the operation stage. If GHP is used to completely replace traditional heating methods in China, it will have a great potential for emission reduction.

5.2 Policy implications

With the acceleration of economic development, the demand for energy will increase. Due to the gradual depletion of petroleum, coal and other fossil resources, the development and utilization of renewable energy has attracted much attention. GHP has great advantages in using renewable energy and plays an important role in promoting energy saving and emission reduction. Therefore, it is necessary to continuously increase policy support for the application of GHP. For example, the decision of “coal to electricity” policy for clean winter heating in northern China, and the implementation of an electricity price preference for GHP. Furthermore, scientifically implementing renewable energy utilization technology and guiding healthy and rapid development of the renewable energy industry should be the main goal of renewable energy research in the future.

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REFERENCES

Allouhi A, El Fouih Y, Kousksou T, et al. Energy consumption and efficiency in buildings: current status and future trends[J]. *Journal of Cleaner Production*, 2015, 109: 118-130.

Badescu V. Economic aspects of using ground thermal energy for passive house heating[J]. *Renewable Energy*, 2007, 32(6): 895-903.

Bullard III C W, Herendeen R A. The energy cost of goods and services[J]. *Energy Policy*, 1975, 3(4): 268-278.

Cabeza L F, Rincón L, Vilariño V, et al. Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review. *Renewable and sustainable energy reviews*, 29, (2014), 394-416.

Esen H, Inalli M, Esen M. A techno-economic comparison of ground-coupled and air-coupled heat pump system for space cooling[J]. *Building and environment*, 2007, 42(5): 1955-1965.

Greening B, Azapagic A. Domestic heat pumps: Life cycle environmental impacts and potential implications for the UK[J]. *Energy*, 39(1), 2012, 205-217.

Hendrickson C, Horvath A, Joshi S, et al. Peer reviewed: economic input–output models for environmental life-cycle assessment[J]. *Environmental science & technology*, 1998, 32(7): 184A-191A.

Igos E, Rugani B, Rege S, et al. Combination of equilibrium models and hybrid life cycle-input–output analysis to predict the environmental impacts of energy policy scenarios[J]. *Applied energy*, 2015, 145: 234-245.

ISO. ISO 14040-environmental management e life cycle assessment eprinciples and framework. Geneva; 2006.

ISO. ISO 14044-environmental management e life cycle assessment erequirements and guidelines; 2006. Geneva.

Ji J P, Liu L, Ma X M. Greenhouse gas emissions by Chinese economy: An assessment based on EIO-LCA model[J]. Acta Scientiarum Naturalium Universitatis Pekinensis, 2011, 47(4): 741-749.

Leontief, W. Environmental repercussions and the economic structure: An input–output approach. *The Review of Economics and Statistics* 52(3),1970, 262–71.

Lu Q, Narsilio G A, Aditya G R, et al. Economic analysis of vertical ground source heat pump systems in Melbourne[J]. *Energy*, 2017, 125: 107-117.

Lund J W, Boyd T L. Direct utilization of geothermal energy 2015 worldwide review[J]. *Geothermics*, 2016, 60: 66-93.

Lund J, Sanner B, Rybach L, et al. Geothermal (ground-source) heat pumps: a world overview[J]. Geo-Heat Center Quarterly Bulletin, 2004, 25(3).

NBSC (National Bureau of Statistics of China), 2016a. China Statistical Yearbook. China Statistics Press, Beijing.

NBSC (National Bureau of Statistics of China), 2017b. China Input-output Table 2015. China Statistics Press, Beijing.

Oliver D, Groulx D. Thermo-economic assessment of end user value in home and community scale renewable energy systems[J]. *Journal of Renewable and Sustainable Energy*, 2012, 4(2): 023117.

Panwar N L, Kaushik S C, Kothari S. Role of renewable energy sources in environmental protection: A review[J]. *Renewable and Sustainable Energy Reviews*, 2011, 15(3): 1513-1524.

Self S J, Reddy B V, Rosen M A. Geothermal heat pump systems: Status review and comparison with other heating options[J]. *Applied energy*, 2013, 101: 341-348.

Suh S, Huppes G. Methods for life cycle inventory of a product. *J Clean Prod*. 13, 2005, 687–97.

United Nations Framework Convention on Climate Change, 2015. Adoption of the Paris Agreement, 21st Conference of the Parties. United Nations, Paris Available at. https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement, Accessed date: 2 September 2018.

Xing L, Dong X, Guan J. Global industrial impact coefficient based on random walk process and inter-country input–output table[J]. *Physica A: Statistical Mechanics and its Applications*, 2017, 471: 576-591.

Xu Wei. China ground source heat pump development research report. 2018

Yin Yulong. Assessment of China's geothermal resources and potential. *Technology and innovation*, 05, 2018, 57-58.

Zheng K, Han Z, Zhang Z. Steady industrialized development of geothermal energy in China Country Update Report 2005-2009[C]//Proceedings World Geothermal Congress. 2010, 136: 1-11.

Zhu J, Hu K, Lu X, et al. A review of geothermal energy resources, development, and applications in China: Current status and prospects[J]. *Energy*, 2015, 93: 466-483.