Predicting the Potential of China’s Geothermal Energy in Industrial Development and Carbon Emission Reduction

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Abstract: The goal of carbon peaking and carbon neutrality requires major systemic changes in the energy supply sector. As one of the major non-carbon-based energy sources, geothermal energy is characterized by large reserves, stability, and reliability. This paper summarizes the current situation of geothermal resource endowment and industrial development in China. Based on this, a system dynamics model of geothermal industrialization is established, and the potential of geothermal industrialization and carbon emission reduction in China is predicted. The prediction results show that the growth rate of geothermal heating and cooling areas in the next 40 years will follow a trend of acceleration followed by deceleration. China’s geothermal energy heating and cooling area will reach 11.32–14.68 billion m² by 2060, an increase of about 9–12 times compared to 2020. The proportion of geothermal heating and cooling area to the total building area in China will reach 13.77–17.85%. The installed capacity of geothermal power generation will reach 14,452.80–20,963.20 MW by 2060 under the scenario with electricity subsidies. The proportion of geothermal energy in China’s primary energy consumption structure will reach 3.67–5.64%. The annual carbon emission reduction potential of the geothermal industry will reach 436–632 million tons, equivalent to 4.41–6.39% of China’s carbon emissions in 2020. The results of this study can provide a reference for the healthy and high-quality development of China’s geothermal industry and help to achieve carbon peaking and carbon neutrality goals.

Keywords: carbon emission reduction; carbon neutrality; geothermal energy; system dynamics

1. Introduction

The burning of large amounts of fossil energy has led to rising levels of greenhouse gases. Humanity faces the problem of balancing economic development with ecological conservation. The Paris agreement signed in 2016 proposed to limit the rise in global average temperature to 2 °C compared to the pre-industrial period [1]. On 22 September 2020, President Xi Jinping announced that “China will increase its autonomous national contribution, adopt more vigorous policies and measures, and strive to peak carbon emissions by 2030 and achieve carbon neutrality by 2060”. Since then, President Xi Jinping has made dozens of important speeches on carbon peaking and carbon neutrality, continuously deepening the strategic deployment [2–4]. This series of new goals and deployments demonstrate China’s responsible role as a great power and is also an objective requirement to achieve China’s high-quality development. The proposal of “carbon peaking and carbon neutrality” has pointed out the direction for China to accelerate the change in energy production and consumption and build a “clean, low-carbon, safe, and efficient” energy system [5,6].

Geothermal energy is a new energy source with abundant reserves, wide distribution, stability, and reliability. Vigorously promoting the development and utilization of...
geothermal energy is an important means to achieve carbon neutralization and help build a green, low-carbon, safe, and efficient energy system [7]. China has abundant geothermal resources, accounting for about 1/6 of global geothermal resources, mainly at low and medium temperatures, with great potential for development. Developing the geothermal industry is meaningful to China in optimizing energy structure, energy saving, emission reduction, and improving environment [8]. China’s geothermal resources are exploited in a variety of ways and widely used in power generation, heating, industry, planting, breeding, recreation, and many other areas [9]. In recent years, driven by policy guidance and market demands, the development and utilization of geothermal resources in China have grown at a relatively fast pace, with heating being the main mode of utilization. As one of the earliest countries to develop and utilize geothermal resources, China’s direct utilization of geothermal resources has ranked first in the world for many years [10].

As an emerging and future energy source, geothermal resources can play a significant role in the implementation of carbon peaking and carbon neutrality goals, and the geothermal industry has a broad development prospect [11]. The implementation of the concept of green development and the rational development and scientific management of geothermal resources will play a positive role in greenhouse gas emission reduction. The “Opinions on Promoting the Development and Utilization of Geothermal Energy” issued in 2021 put forward the development goals of geothermal energy. The goal proposed is that by 2025, China’s geothermal energy heating (cooling) area will increase by 50% compared to 2020, and the installed capacity of geothermal energy generation will double compared to 2020. By 2035, the geothermal energy heating (cooling) area and installed geothermal energy generation capacity will strive to double compared to 2025. This paper analyzes the history and current situation of geothermal industry development in China and establishes a system dynamics model to predict the development trend in the next decades. The research results can provide a reference for China to promote geothermal development in an orderly manner and help achieve the carbon peaking and carbon neutrality goals.

2. Geothermal Background

2.1. Overview of Geothermal Resources in China

According to the geological structure characteristics, heat transfer method, temperature range, and development and utilization methods, geothermal resources can be divided into three types: shallow geothermal energy, hydrothermal geothermal energy, and hot dry rock. The national geothermal resource survey and evaluation study shows that China’s geothermal resources are well endowed but are unevenly distributed due to the control of factors such as tectonics, magmatic activity, stratigraphic lithology, hydrogeological conditions, etc. [8]. Shallow geothermal energy resources are commonly distributed throughout the country. The annual recoverable amount of shallow geothermal energy resources within the planning areas of 336 cities in China is equivalent to 700 million tons of standard coal (Figure 1), which can realize an area of 32 billion m² for heating and cooling buildings [12,13].

The total amount of hydrothermal geothermal resources in China is equivalent to 1.25 trillion tons of standard coal, and the annual recoverable amount is equivalent to 1.9 billion tons of standard coal, which is equivalent to 38% of China’s total energy consumption in 2020. Controlled by factors such as tectonics, magmatic activity, stratigraphic lithology, and hydrogeological conditions, the distribution of hydrothermal geothermal resources has obvious regularity and regionality. Geothermal resources can be classified into the sedimentary basin type and the uplift mountain type according to the tectonic genesis. The uplift mountain-type high-temperature geothermal resources are mainly distributed in Taiwan and southern Tibet, western Yunnan, and western Sichuan in China (Figure 2), with a power generation potential of 7.12 million kW. Uplifted mountain-type medium- and low-temperature geothermal resources are mainly distributed in the southeast coastal areas, Jiaodong, the Liaodong Peninsula, and other mountainous and hilly areas. Sedimentary basin type geothermal resources are mainly distributed in the Meso-cenozoic plain basins.
Figure 1. Amount of shallow geothermal energy with the planning area of provinces and cities.

Figure 2. Geothermal resource distribution map in China.

Hot, dry rocks are widespread in the interior of the earth, but those with development potential are mainly found at the edges of plates or tectonic bodies, such as areas of new volcanic activity and regions with thin crust [16,17]. Based on the crustal structure and diagenetic mechanism, hot dry rock resources in China can be divided into four categories: the high radioactive heat production type, the sedimentary basin type, the volcanic region type, and the intraplate active tectonic zone type high temperature geothermal resources. Geothermal resources can be classified into three kinds: the high temperature geothermal resources are mainly distributed in Taiwan and southern Tibet, western Yunnan, and other mountainous regions. Sedimentary basin type geothermal resources are mainly distributed in the Mesozoic and Cenozoic plain basins. In China, the development and utilization of hot spring resources have a history dating back thousands of years, but the large-scale implementation of geothermal exploration and development has been mainly in recent decades. Vigorous development of clean energy, new industries, and high technology enterprises have driven the development of related equipment manufacturing and engineering businesses, and increasing employment. It is an important measure to promote economic development and sustainable development, to achieve clean energy transformation, and to optimize energy structure. It can drive the development of related equipment manufacturing and engineering businesses, and increase employment. It is an important measure to promote economic development and sustainable development, to achieve clean energy transformation, and to optimize energy structure. It can drive the development of related equipment manufacturing and engineering businesses, and increase employment.
categories: the high radioactive heat production type, the sedimentary basin type, the modern volcano type, and the intraplate active tectonic zone type [18–20]. The amount of hot dry rock resources within 3–10 km underground in China’s terrestrial area is equivalent to 856 trillion tons of standard coal [21]. Based on 2% of the recoverable resources, it is about 3400 times the total national energy consumption in 2020. At present, hot dry rock resources in China are still at the stage of exploration, evaluation, and testing [22]. A series of scientific and technical problems still need to be solved to achieve large-scale utilization, and the forecast in this paper does not include the development and carbon reduction potential of hot, dry rock resources.

2.2. Current Development of China’s Geothermal Industry

In China, the development and utilization of hot spring resources have a history dating back thousands of years, but the large-scale implementation of geothermal exploration and development has been mainly in recent decades. Vigorous development of clean energy is one of the themes of our time. The development of the geothermal industry is of great significance for optimizing energy structure, energy savings, and carbon emission reduction. At the same time, it also has a significant pulling effect on the country’s cultivation of new industries, driving the development of related equipment manufacturing and engineering businesses, and increasing employment. It is an important measure to build ecological civilization and achieve green development.

After the 1970s, the development and utilization of geothermal resources in China entered a stage of rapid development. Since entering the 21st century, geothermal resource development and utilization have been developing faster under the guidance of policies and market demands. With China’s increasing demand for clean energy, the advantages of developing and utilizing geothermal energy to optimize the energy structure and improve environmental quality are becoming more and more prominent. At present, the utilization of geothermal resources in China is mainly the direct utilization of medium and low temperature geothermal energy and high temperature geothermal energy power generation [23]. In the past 20 years, China has been at the forefront of the world on the scale of direct geothermal energy utilization. By the end of 2020, China’s geothermal energy heating and cooling areas reached a total of 1.39 billion m$^2$ (Table 1). Among them, the building areas heated by water-heated geothermal energy amounted to 580 million m$^2$, and the building areas heated and cooled by shallow geothermal energy amounted to 810 million m$^2$ [24].

<table>
<thead>
<tr>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Shallow geothermal energy</td>
<td>Installed capacity (MW)</td>
<td>9.7</td>
<td>631</td>
<td>5210</td>
<td>11,781</td>
<td>26,450</td>
<td></td>
</tr>
<tr>
<td>for heating and cooling</td>
<td>Heating and cooling area</td>
<td>0.16</td>
<td>7.67</td>
<td>100.70</td>
<td>330.00</td>
<td>665.00</td>
<td>810.00</td>
</tr>
<tr>
<td></td>
<td>(million m$^2$)</td>
<td></td>
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<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>Quantity of utilization (TJ/a)</td>
<td>83</td>
<td>6569</td>
<td>29,035</td>
<td>100,311</td>
<td>246,212</td>
<td></td>
</tr>
<tr>
<td>Hydrothermal geothermal</td>
<td>Installed capacity (MW)</td>
<td>248</td>
<td>550</td>
<td>1040</td>
<td>2940</td>
<td>4789</td>
<td></td>
</tr>
<tr>
<td>heating</td>
<td>Heating area (million m$^2$)</td>
<td>4.95</td>
<td>9.60</td>
<td>30.20</td>
<td>60.32</td>
<td>478.00</td>
<td>580.00</td>
</tr>
<tr>
<td></td>
<td>Quantity of utilization (TJ/a)</td>
<td>2889</td>
<td>6391</td>
<td>11,992</td>
<td>33,710</td>
<td>74,041</td>
<td></td>
</tr>
<tr>
<td>Geothermal power generation</td>
<td>Installed capacity (MW)</td>
<td>27.78</td>
<td>28.78</td>
<td>24.48</td>
<td>27.78</td>
<td>44.56</td>
<td></td>
</tr>
</tbody>
</table>

Note: The data are collected from the proceedings of previous World Geothermal Congresses and other documents, and the data are statistical values from the previous year’s end.
The development of shallow geothermal energy in China began in the 1990s. Since the 21st century, China’s shallow geothermal energy heating (cooling) building area has increased at an average annual rate of about 30 percent. In 2000, China’s installed shallow geothermal energy capacity was only 9.7 MW; in 2015, the total amount of shallow geothermal energy utilization exceeded 100,000 TJ/a, ranking first in the world [26]. By 2020, the installed capacity of shallow geothermal energy has been about 26,450 MW [23], mainly distributed in Beijing, Tianjin, Hebei, Liaoning, Shandong, Hubei, Jiangsu, Henan, etc. The domestic installed capacity has increased to 34.11% of the global share, and the growth rate continues to accelerate. Shallow geothermal energy will play an increasingly important role in the clean heating and cooling of buildings.

China’s hydrothermal geothermal energy utilization also shows a good development trend. In the past 10 years, China’s direct utilization of hydrothermal geothermal energy has been growing at an average annual rate of 10%, ranking first in the world for many years. According to the statistics of the World Geothermal Congress 2020, among the direct utilization of hydrothermal geothermal energy in China, building heating accounts for about 49.51%, medical bathing accounts for about 40.59%, breeding accounts for 3.40%, planting accounts for 3.71%, and industrial utilization accounts for 2.79%. The proportion used for heating is the highest and is increasing year by year. The area utilized for hydrothermal geothermal energy heating in China was only 60.32 million m$^2$ at the end of 2014, which increased to 102 million m$^2$ in 2016 and exceeded 150 million m$^2$ at the end of 2017. By the end of 2020, China’s hydrothermal geothermal energy heating area had reached 580 million m$^2$, far exceeding the target set in the 13th Five-Year Plan. As the first “smoke-free city” in China, Xiong County, Hebei Province, has a geothermal heating area of 7 million m$^2$ for the benefit of about 70,000 households, creating the “Xiong’an model” of leading geothermal development and utilization [27].

Compared with the brilliant achievements in direct geothermal utilization, China has made relatively slow progress in geothermal power generation in recent years. In 2017, the National Development and Reform Commission and two other departments jointly released the “Thirteenth Five-Year Plan” for the development and utilization of geothermal energy, in which the target for geothermal power generation is to add 500 MW to reach 530 MW. However, during the “Thirteenth Five-Year Plan”, only Hangzhou Jinjiang Group completed the first phase of the Tibetan Yangyi Geothermal Power Plant, adding 16 MW of installed capacity. In addition, three private enterprises realized 0.28 MW of geothermal power generation in Kangding, Sichuan, 0.2 MW in Xianxian, Hebei, and four 0.4 MW units in Ruili, Yunnan. By the end of the 13th Five-Year Plan, the total installed capacity of geothermal power generation in operation nationwide will be only 44.56 MW.

Geothermal power generation in China was once brilliantly developed in the 1970s. In 1970, China’s first geothermal power station, Fengshun Geothermal Power Station, successfully generated electricity, marking China as the eighth country in the world to have achieved geothermal power generation. Since then, geothermal power plants have been built in Tibet, Hebei, Shandong, Hunan, and other places, one after another. Among them, a 1 MW high-temperature geothermal power plant was built in 1977 in the Yangbajing area, which pushed China’s geothermal power generation to a climax. The Yangbajing geothermal power plant was later expanded one after another, eventually reaching an installed capacity of 25.18 MW. According to the World Geothermal Congress, the world’s total installed geothermal power capacity has grown from 7972 MW in 2000 to 15,950 MW in 2020 and is expected to reach 19,361 MW by 2025 (Figure 3) [28,29]. At present, the total installed capacity of geothermal power generation in China has not yet exceeded 50 MW, and the overall growth rate of China’s installed geothermal power generation capacity is slower than the world average. For domestic aspects, the installed capacity of renewable energy power generation in China has exceeded 110,000 MW in 2021, and the annual power generation capacity of renewable energy has reached 2.49 trillion kw·h. The development of the geothermal power generation industry is significantly slower than that of other renewable energies.
It is the one of top priorities for China to achieve carbon neutrality by accelerating the transformation of energy to green and low-carbon and promoting the optimization of energy structure. According to the IEA, China is the world’s largest energy-related emitter of CO₂ in 2020. According to the announcement of the National Bureau of Statistics, in 2021, the consumption of clean energy will account for 25.5% of the total energy consumption in China. The programmatic document of China’s major work on carbon peaking and carbon neutrality was released in September 2021—“Opinions on the complete and accurate implementation of the new development concept to do a good job on carbon peaking and carbon neutrality” and “Action Plan on Carbon Peaking by 2030”. The documents focus on vigorously implementing renewable energy alternatives and accelerating the construction of a clean, low-carbon, safe, and efficient energy system, and put forward the development goal of reaching more than 80% of non-fossil energy consumption by 2060. From now to 2060, clean renewable energy sources face unprecedented opportunities for development. Geothermal power generation is one of the power generation methods with the best emission reduction effect. Academician Dorji of the Chinese Academy of Engineering predicted that by 2030, the installed power generation capacity of major high-temperature geothermal fields in Tibet will reach 630 MW, among which the installed capacity of Yangbajing geothermal field will reach 100 MW [30].

The 14th Five-Year Renewable Energy Development Plan released in 2022 clearly promoted the development of shallow geothermal energy, comprehensively focusing on areas such as the North China Plain and the Yangtze River Economic Zone with dual demand for heating and cooling. The plan sets a development target of more than 60 million tons of standard coal for geothermal energy heating, biomass heating, biomass fuels, solar thermal utilization, and other non-electricity utilization by 2025. Meanwhile, China will orderly promote the development of geothermal energy power generation and support the demonstration of advanced technologies such as hot dry rock and enhanced geothermal energy generation. In the central east and other areas rich in medium and low temperature geothermal resources, promoting medium and low temperature geothermal energy power generation according to local conditions [31–33].

3. Method
3.1. System Dynamics Model

System dynamics was originally proposed by Professor Forrester, using the systems science idea that “all systems have a structure, and the structure of a system determines
the function of the system”. According to the feedback characteristics of the internal components of the system as a result of each other, highlighting the system, the whole, linkage, development, and movement, with the advantages of visually appealing models and fast analysis [34–36]. The system dynamics model consists of three elements: variables, parameters, and functional relationships, and mainly studies the time-varying problems of complex systems [37]. In recent years, system dynamics methods have been widely used in forecasting the development and carbon emission reduction potential of energy and other industries. Mohamd developed a system dynamics model for the assessment of renewable energy systems and energy efficiency in Australia and predicted the impact of energy efficiency improvements on energy productivity and their contribution to carbon reduction in the region [36]. Jiang Yong had simulated the fiscal and taxation policies for geothermal industry development based on system dynamics and proposed a combination of fiscal and taxation policies at the national level and regional level [38]. Based on the analysis of carbon emissions and the relationship between influencing factors, Han Nan designed a variety of scenarios to predict the carbon peak time in Beijing, Tianjin, and Hebei through the system dynamics method and proposed a suitable development model for the actual situation of each place [39].

System dynamics methods have rich arithmetic methods and flexible structural control, which can effectively help us solve complex nonlinear problems involving interactions between multiple systems. The development of the geothermal industry has a close correlation with various influencing factors such as the economy and society, and different influencing factors interact with each other and influence each other. For example, with the growth of GDP per capita, the living area per capita will increase, and the growth of living area per capita and population will also drive the increase in residential heating demands. The increase in R&D capital investment will accelerate the progress of science and technology to further improve the efficiency of geothermal resource utilization and reduce the cost. The development of the geothermal industry will reduce carbon emissions, while the carbon emission reduction benefit will also promote the accelerated development of the geothermal industry. The impact of policy support on the geothermal industry is also significant, with clean heating subsidies/electricity subsidies further boosting market investment in the geothermal industry. Geothermal resource reserves are the upper limit of development and utilization. When the ratio of resource exploitation is low, increasing the exploitation ratio will form a scale effect, which will promote the development of the industry. When the exploitation ratio is too high, the increased difficulty of exploitation will inhibit the development of the geothermal industry. For such a complex system involving the interaction of multiple elements, it is difficult to be portrayed by a single mathematical model, so the system dynamics approach is needed for the study.

In this paper, a system dynamics model of geothermal industry development, including a population subsystem, an economic subsystem, a technology subsystem, a policy subsystem, and a carbon emission subsystem, is constructed to predict the future development prospect of geothermal industry and its contribution to carbon emission reduction (Figure 4). The population subsystem uses a birth mortality model, and it is related to the total building area and GDP per capita. The total population each year is equal to the previous year’s population plus the net increase in population. The economic subsystem is based on a GDP growth rate model and is correlated with, for example, government financial investment and science and technology growth rates. The key parameter in the technology subsystem is the technology level growth rate, which will determine the unit cost of geothermal development. The policy subsystem determines the intensity of investments in geothermal development, including government investments and market revenue inputs. The carbon emissions subsystem deals with emission reductions and emission reduction benefits, which are related to the scale of geothermal development and the price of carbon emission market transactions. The subsystems together form the geothermal industry development system, and the model is identified based on historical statistics and validated using the results of relevant forecasting studies. The simulation period is
2000–2060, with 2000 as the historical base year, 2000–2020 as the model testing phase, and 2021–2060 as the forecasting phase, and the model calculation step is set to 1 year.

Figure 4. The relationship between subsystems.

Based on analyzing the current situation of geothermal industry development and the interaction relationships among the main influencing factors, system dynamics modeling is carried out using Vensim code. The cause-effect diagram of the geothermal industry development system is drawn, the nature of the variables and their interrelationships are further set, and the stock flow diagram of the geothermal industry development system is drawn (Figure 5).

3.2. Parameter Setting and Model Testing

Data sources: The historical data on population and GDP in the model is obtained from the National Bureau of Statistics, and the future population growth rate and GDP growth rate are set with reference to the expectations of official institutions such as the China Population and Development Research Center and the Organization for Economic Cooperation and Development. The volume of building area and future growth trends refer to statistical data and predictions in related field studies [40]. Data on geothermal resource reserves and the current status of development and utilization is obtained from statistical data in the proceedings of the World Geothermal Congress, the China Geothermal Energy Industry Development Report, the China Geothermal Resource Potential Evaluation, and other publications. The energy savings (standard coal that can be replaced) that can be achieved with different types of geothermal development methods are estimated based on data obtained in previous experimental or theoretical studies. Among them, shallow geothermal energy is mainly used for heating and cooling through heat pump technology. According to the energy efficiency test report data of the actual operating projects, the energy saving capacity of the ground source heat pump unit area is about $12 \text{ kgce/(m}^2\text{·a)}$ [41]. According to statistics, the energy consumption of heating per unit
of construction area is about 25 kgce/(m²·a). The main energy consumption of using hydrothermal geothermal energy for heating is the electrical energy of the pump, and the power consumption of the pump per unit heating area does not exceed 10 kw·h, which is equivalent to 3.27 kg of standard coal [42], so the amount of energy that can be saved by using hydrothermal geothermal energy for heating is about 21.73 kgce/(m²·a). The energy savings achieved by geothermal power generation are converted according to the electricity conversion factor of 0.327 kgce/(kw·h) [42]. The CO₂ reduction potential is estimated based on the standard coal emission factor (mass of CO₂ released per kg of standard coal burned), which is taken as 2.386 in the model based on previous research [43].

Figure 5. Geothermal industry development system stock flow diagram.

The functional relationships between the main parameters involved in the model are shown in Table 2.

Model reliability testing: In the model, four indicators are selected as the criteria for testing the model: population amount, GDP, shallow geothermal energy heating and cooling area, and hydrothermal geothermal energy heating area. The reliability of the system dynamics model is evaluated by comparing the simulated values with the actual data. If the simulated values are tested to fit well with the actual values (Table 3), and none of the relative errors exceed 10%, the simulated prediction results are considered credible [44–46].

For the future prediction data, we also compared the model-calculated values with other research results. Wu’s study predicted that China’s population would reach 1.48 billion by 2030 [47], and the model prediction in this paper range from 1.39 to 1.54 billion. The International Monetary Fund forecasts that China’s GDP will grow by 164.3% from 2020 to 2060, with predicted values of 153.20–168.5% in the model. Qi’s study predicted that the total building area in China would reach 66.5–82.8 billion m² by 2060 [40], with the model prediction in this paper being 78.7–82.2 billion m². These data further support the credibility of the model.
Table 2. The functional relationships in the model.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Functional Relationship Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total population</td>
<td>INTEG (birth population − death population + immigrant population, population base)</td>
</tr>
<tr>
<td>GDP</td>
<td>INTEG (GDP increase, GDP base)</td>
</tr>
<tr>
<td>Technology growth rate</td>
<td>Current year science and technology output/total science and technology output in the previous year</td>
</tr>
<tr>
<td>Total building area</td>
<td>Building area per capita × total population</td>
</tr>
<tr>
<td>Investments in geothermal utilization</td>
<td>Government investments + market revenue inputs + carbon emission reduction benefits</td>
</tr>
<tr>
<td>Unit cost reduction</td>
<td>Unit cost × technology growth rate</td>
</tr>
<tr>
<td>Increased heating/heating and cooling area</td>
<td>Geothermal utilization investment/(unit area construction cost − policy subsidy) × extraction difficulty factor</td>
</tr>
<tr>
<td>Shallow geothermal energy heating and cooling/hydrothermal heating area</td>
<td>INTEG (additional heating and cooling area, the heating and cooling area base)</td>
</tr>
<tr>
<td>Installed capacity of geothermal power generation</td>
<td>INTEG (new installed capacity, installed capacity base)</td>
</tr>
<tr>
<td>Annual geothermal power generation</td>
<td>Installed capacity of geothermal power generation × annual utilization hours</td>
</tr>
<tr>
<td>Energy saving amount</td>
<td>Geothermal heating and cooling area × coal conversion factor + annual power generation × electricity conversion factor</td>
</tr>
<tr>
<td>Carbon emission reduction</td>
<td>Energy savings × carbon emission factor</td>
</tr>
<tr>
<td>Carbon reduction benefits</td>
<td>Carbon emission reduction × carbon market trading price</td>
</tr>
</tbody>
</table>

Table 3. Validity test results of the model.

<table>
<thead>
<tr>
<th>Year</th>
<th>Population amount</th>
<th>GDP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Actual value</td>
<td>Forecast value</td>
</tr>
<tr>
<td>2000</td>
<td>126,743 × 10^4</td>
<td>126,743 × 10^4</td>
</tr>
<tr>
<td>2005</td>
<td>130,756 × 10^4</td>
<td>131,448 × 10^4</td>
</tr>
<tr>
<td>2010</td>
<td>134,091 × 10^4</td>
<td>135,179 × 10^4</td>
</tr>
<tr>
<td>2015</td>
<td>138,326 × 10^4</td>
<td>138,873 × 10^4</td>
</tr>
<tr>
<td>2020</td>
<td>141,212 × 10^4</td>
<td>143,185 × 10^4</td>
</tr>
<tr>
<td>2021</td>
<td>141,260 × 10^4</td>
<td>143,925 × 10^4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Year</th>
<th>Shallow geothermal heating and cooling area</th>
<th>Hydrothermal heating area</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Actual value</td>
<td>Forecast value</td>
</tr>
<tr>
<td>2000</td>
<td>16 × 10^4 m^2</td>
<td>16 × 10^4 m^2</td>
</tr>
<tr>
<td>2005</td>
<td>767</td>
<td>765.7</td>
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<tr>
<td>2010</td>
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<td>2015</td>
<td>33,000</td>
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<td>2020</td>
<td>66,500</td>
<td>71,399.9</td>
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<td>2021</td>
<td>81,000</td>
<td>80,973</td>
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</table>


The developed system dynamics model of geothermal industry development is used to predict the future development and carbon reduction potential of the geothermal industry. The current development scenario, the medium-high speed development scenario, and the high speed development scenario were designed to simulate and forecast influencing factors such as policy support, technology level growth rate, geothermal power price, carbon market trading price, etc. The principles of setting each influencing factor in different scenarios are shown in Table 4.

The system dynamics simulation results show that the shallow geothermal heating and cooling area will continue to maintain a fast growth trend in the future, facing growing heating and cooling demand (Figure 6). Taking the current development scenario as an example, the shallow geothermal energy heating and cooling area under this scenario...
will reach 1.27 billion m$^2$ by 2025, an increase of about 91% compared to 2020; by 2035, it will reach 2.89 billion m$^2$, an increase of about 1.28 times compared to 2025. Around 2040, the total building area in China will reach its peak [40], and the growth rate of shallow geothermal energy heating and cooling areas will slow down to some extent. The faster growth of shallow geothermal heating and cooling areas is predicted in the medium-high-speed development scenario and the high-speed development scenario. By 2060, the shallow geothermal heating and cooling area will reach 6.52 billion m$^2$, 8.07 billion m$^2$, and 8.86 billion m$^2$, respectively, under the three scenarios.

Table 4. Development scenario setting of the geothermal industry in China.

<table>
<thead>
<tr>
<th>Influencing Factors</th>
<th>Current Development Scenario</th>
<th>Medium-High Speed Development Scenario</th>
<th>High Speed Development Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>Policy Support</td>
<td>Not changed</td>
<td>×150%</td>
<td>×150%</td>
</tr>
<tr>
<td>Technology growth rate</td>
<td>Not changed</td>
<td>Not changed</td>
<td>1.05 CNY</td>
</tr>
<tr>
<td>Geothermal power price</td>
<td>Not changed</td>
<td>Not changed</td>
<td>1.05 CNY</td>
</tr>
<tr>
<td>Carbon market trading price</td>
<td>Not changed</td>
<td>Not changed</td>
<td>×150%</td>
</tr>
</tbody>
</table>

Figure 6. Prediction of shallow geothermal energy heating and cooling areas.

The predicted results for the area heated by hydrothermal and geothermal energy also show a faster growth trend (Figure 7). Taking the current development scenario as an example, the hydrothermal geothermal energy heating area will reach 0.87 billion m$^2$ by 2025, an increase of about 83% compared to 2020; in addition, the heating area will reach 2.01 billion m$^2$ by 2035, an increase of about 1.30 times compared to 2025. Under the three development scenarios, the hydrothermal geothermal energy heating area will reach 4.80 billion m$^2$, 5.48 billion m$^2$, and 5.82 billion m$^2$ by 2060, respectively.

According to the forecast results, the total area of geothermal energy heating and cooling will reach 11.32 billion m$^2$, 13.55 billion m$^2$, and 14.68 billion m$^2$, respectively, by 2060. Compared to 2020, the growth is about 9–12 times. The proportion of geothermal heating and cooling area to the total building area in China will reach 13.77%, 16.48%, and 17.85%. Geothermal energy will make an important contribution to the clean and high-quality development of the building heating and cooling industry.

One important reason for the slow development of China’s geothermal power industry in recent decades is the high cost and risk of geothermal power generation, which cannot at-
tract commercial investment. According to statistics, the initial cost of site development and power plant construction for a geothermal power plant is about 20–30 million CNY/MW, and the full investment for each MW of installed capacity of the Tibetan Longyuang power plant is approximately 23–24 million CNY. Although Tibet is the region with the most geothermal power generation in China, the feed-in tariff in Tibet is only 0.25 CNY/(kw·h), the revenue is very limited, and a geothermal resource tax has to be paid, so it is difficult to attract enterprises to invest. Chinese People’s Political Consultative Conference member Li Ziyiing had proposed to reference wind energy, solar energy, and other renewable energy early tariff policies and set the geothermal power feed-in tariff at 1.05 CNY/(kw·h). In view of this, we set the geothermal power feed-in price at 1.05 CNY/(kw·h) under the medium-high speed development scenario and the high speed development scenario in this paper to predict the development trend of the geothermal power industry.

![Graph showing predicted geothermal energy heating and cooling areas](image)

Figure 6. Prediction of shallow geothermal energy heating and cooling area.

According to the forecast results, the total area of geothermal energy heating and cooling will reach 11.32 billion m², 13.55 billion m², and 14.68 billion m², respectively, by 2060. Compared to 2020, the growth is about 9–12 times. The proportion of geothermal heating and cooling area to the total building area in China will reach 13.77%, 16.48%, and 17.85%. Geothermal energy will make an important contribution to the clean and high-quality development of the building heating and cooling industry.

![Graph showing predicted geothermal energy heating areas](image)

Figure 7. Prediction of the heating area of hydrothermal geothermal energy.

Compared to the predicted results for geothermal energy heating and cooling areas, the predicted results for installed geothermal power capacity under different scenarios show more significant differences (Figure 8). Under the three scenarios, the installed geothermal power generation capacity will reach 119.88 MW, 172.78 MW, and 177.72 MW by 2025, an increase of 1.6–2.9 times compared with 2020. The installed geothermal power generation capacity will reach 316.51 MW, 852.37 MW and 955.78 MW by 2035, an increase of 1.6–3.9 times compared with 2025. By 2060, the installed capacity of geothermal power generation will reach 1172.94 MW, 14,452.80 MW, and 20,963.20 MW, respectively. The forecast values of the medium-high speed development scenario and the high speed development scenario with tariff subsidies are about 12–18 times the forecast values of the scenario without tariff subsidies.

The carbon reduction potential of geothermal energy development is based on the carbon dioxide produced by standard coal combustion that it can replace. This mainly includes the standard coal replaced by geothermal for heating and cooling and the use of geothermal for power generation [48,49]. According to the model prediction results (Figure 9), the amount of standard coal that can be replaced by geothermal resources will reach 54 million tons, 69 million tons, and 72 million tons, respectively, by 2030. By 2060, this value will increase to 183 million tons, 238 million tons, and 265 million tons, respectively. According to the forecast of energy consumption of 4.7–5 billion tons of standard coal by 2060 [50], the share of geothermal energy in the primary energy
consumption structure will reach 3.67–5.64%. The carbon emission reduction potential of geothermal resource development under the three development scenarios will reach 129 million tons, 165 million tons, and 174 million tons by 2030 and increase to 436 million tons, 567 million tons, and 632 million tons by 2060, which is equivalent to 4.41%, 5.73%, and 6.39% of China’s carbon emissions (9.894 billion tons) in 2020, respectively. The rapid development of the geothermal industry will provide strong support for China to achieve carbon peaking and carbon neutrality goals.

In the scenario setting of the prediction model, policy support, technology growth rate, geothermal power price, and carbon emission trading price are used as variables. Among them, policy support and geothermal power prices are mainly influenced by policies, while technology level growth rates and carbon emission prices are mainly influenced by society and the market. From the predicted results, the improvement of policy support and geothermal power prices will have a more significant impact on the development of
the geothermal industry. This is consistent with previous forecasts for shorter periods. Jiang built a model to predict the development prospects of the geothermal industry by 2030 and recommended strengthening the financial subsidies and tax incentive system for the development and utilization of geothermal resources [38]. This paper provides a longer-term forecast of the development of the geothermal industry. We found that the development rate of geothermal heating and cooling areas tends to grow first and then slow down, which is mainly due to the impact of receiving the peak of China’s building area. However, the growth rate of installed geothermal power capacity has gradually increased over a 40-year period, which is closely related to the clean and stable properties of geothermal energy and the advancement of technology.

5. Conclusions and Suggestions

Based on fully summarizing the geothermal resource endowment and the current situation of geothermal industrial development in China, this paper establishes a system dynamics model containing population, economic, policy, technology, and carbon emission subsystems. The coupling relationship between each subsystem is fully considered, and the model is identified and validated using historical statistics. The validated model is used to predict the development trend and carbon emission reduction potential of the geothermal industry under different scenario conditions. The following conclusions are obtained from the paper:

(1) China has abundant geothermal resources, and the scale of direct geothermal utilization has maintained a high growth rate in recent decades. The amount of geothermal direct utilization has ranked first in the world for many years, but geothermal power generation has failed to achieve greater development in recent decades. The geothermal industry, significantly influenced by policy support and driven by the double carbon target, geothermal, as a stable, efficient, and clean renewable energy source, is facing unprecedented development opportunities.

(2) The growth rate of geothermal heating and cooling areas in the next 40 years will appear to be accelerating first and then slowing down. According to the prediction results, China’s geothermal energy heating and cooling area will reach 11.32–14.68 billion m$^2$ by 2060, an increase of about 9–12 times compared to 2020. The proportion of geothermal heating and cooling areas to the total building area in China will reach 13.77–17.85%.

(3) The influence of the electricity price subsidy policy on the geothermal power industry is significant. The installed capacity of geothermal power generation will reach 14,452.80 MW–20,963.20 MW by 2060 under the scenario with electricity subsidies. It is about 12–18 times the forecasted value of the scenario without electricity subsidies. It is recommended to speed up the introduction of geothermal power generation electricity price support policies to promote the development of the geothermal power generation industry.

(4) Actively promoting the exploration and exploitation of geothermal energy is of great significance to the construction of a clean, low-carbon, safe, and efficient modern energy system. By 2060, China’s utilization of geothermal energy will reach 183–265 million tons of standard coal, which will account for 3.67–5.64% of the primary energy consumption structure. The CO$_2$ emission reduction potential of the geothermal industry will reach 436–632 million tons, equivalent to 4.41–6.39% of China’s carbon emissions in 2020. The large-scale development and utilization of geothermal energy will effectively help achieve the goal of “carbon peaking and carbon neutrality”.

Author Contributions: Conceptualization, G.W.; methodology, H.S.; data collation, W.Z., F.M. and W.L.; validation, formal analysis, H.S.; writing—original manuscript preparation, H.S.; writing—review and editing, M.J. All authors have read and agreed to the published version of the manuscript.

Funding: This paper is financially supported by the Geological Survey Project of the China Geological Survey (Grant No. DD20221676) and the National Key R&D Program of China (Grant No. 2021YFB1507401).

Data Availability Statement: Data and materials are available from the authors upon request.
Acknowledgments: All authors gratefully acknowledge the comments of reviewers and editors of this article.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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