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Case Report

Supply Assurance, Affordable Prices, Energy Conservation, and Zero-Carbon Heating: Promising Directions for Social Welfare and Industrial Development

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Abstract

I had the privilege of conducting the field visits to several notable projects: the Inner Mongolia heating project, the Intelligent Thermal Energy Metering and Monitoring Platform of Menghua Technology, Tsinghua University's Building Energy Saving and Rural Heating solutions, Newenergy's air source heat pump, SPIC's Shandong nuclear heating project, and the Xiangtan's solar heat pump demonstration project. Based on my analysis of the current status and future trends of clean heating, and drawing insights from the rapid advancement of clean energy in China's electric power sector, this paper evaluates the challenges and opportunities within the heating industry. Elevated coal prices, in conjunction with limited price tolerance among residents, have led to industry-wide financial deficits and a reduction in both the motivation and available funding for energy-saving and carbon-reduction upgrades of heating systems. Moreover, the path to achieving efficient heating in small towns and rural areas remains challenging, while zero-carbon heating technologies are only beginning to demonstrate potential. In this context, it is crucial to implement policies that foster energy conservation and emission reduction while attracting investments, including long-term special bonds, to execute national strategies and bolster safety capabilities in critical sectors. Effective interactions among stakeholders can be achieved through the utilization of direct financing tools such as equity financing, bond financing, and REITs, thereby attracting more entrepreneurs and social capital into the heating industry. This will facilitate a synergistic relationship among the government, enterprises, and residents. Under government guidance, strategic directions and solutions for building energy conservation, emission reduction, and zero-carbon heating—such as heat pumps, medium and deep geothermal energy, nuclear energy, and distributed renewable energy power generation and heating—can be established. Simultaneously, the government can balance the triad of supply security, affordable prices, and environmental sustainability. By fostering technological, model, and institutional innovations, we can expedite the development of energy-saving, intelligent, clean, and zero-carbon heating technologies and industries. This industry holds promising prospects, offers robust cash flow, and has significant potential for energy conservation and emission reduction.

Keywords

Building Energy Conservation, Heat Pumps, Geothermal Heating, Nuclear Heating, Solar Heat Pump Heating, Thermal Energy Storage, Zero-carbon Heating, Development Reform and Innovation

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1. Current Situation and Main Problems of Heating in China

According to the incomplete statistics of the China Clean Heating Industry Committee, by the end of 2023, the total area of heating in northern China will be 24.5 billion square meters (17.5 billion square meters for urban heating and 7 billion square meters for rural heating). About 2.5 billion square meters of heating metering devices have been installed (less than 15% of the urban heating area), and about 1 billion square meters of metering charges have been realized (less than 6% of the urban heating area). China's building operation consumes 1.15 billion tons of standard coal, accounting for 21.09 percent of the country's total energy consumption. Carbon emissions during building operation totaled 2.3 billion tons, accounting for 21.6 percent of China's energy-related carbon emissions. The total output value of the heating industry reached nearly one trillion yuan, accelerating the transformation and upgrading of the new smart and clean heating industry.

I had the honor to participate in the annual meeting of China's clean heating industry for two years, and carefully read the Development report of China's clean heating industry 24 [1] and the Annual Development Research Report of China's Building Energy Efficiency 2024 [2]. The prominent contradictions in China's heating industry mainly include: There is a big difference between cities, especially between urban and rural areas, high coal prices lead to thermal losses in the industry, residents' price psychological expectations and affordability are limited, central heating energy saving transformation and low-carbon heating lack of power and funds, zero carbon heating technology has just emerged in the background of the government subsidies in place in the northern big cities to clean heating transformation is still insufficient. Metering and charging popularization is not in place, heat supply and demand balance control means are not intelligent, insufficient resulting in waste, hot and cold uneven phenomenon is relatively common, the scale effect of central heating in small and medium-sized towns in the north is not obvious, especially in less developed areas there are still difficulties in heating supply assurance, many central heating in the middle and lower reaches of the Yangtze River has not been put on the agenda. Clean zero carbon heating and rural heating outside the economically developed areas is a long way to go.

"China's heating industry is generally still in the power industry to raise funds to run electricity to the grid plant separate stage" expert judgment, let me try to seek a brief history of energy and power reform and development for clean zero carbon heating reference significance. The reason why this article takes such a long length to quote the brief history of the reform and development of the power industry is to hope that the relatively complete quotation will help resonate with people in the non-power industry and form a consensus. The brief history of the development of China's electric power industry is a history of reform, development history and innovation.

2. A Brief History of China's Electric Power Industry Development

2.1. The History of China's Power Industry Is One of Reform, Development, and Innovation

According to Wang Xinmao's article commemorating the 140th anniversary of China's power industry [3]: The development history of electricity development in China can be divided into two distinct periods: 67 years in old China and 75 years in New China.

The development of the power industry in the old China was extremely slow. On the eve of liberation in 1949, the installed power generation capacity was only 1.8486 million kW, generating capacity 4.361 billion kw.h (excluding Taiwan, the same below), and the per capita power consumption was less than 8kW.h / person. The installed power generation capacity and generating capacity ranked 21st and 25th in the world respectively, lagging behind in the world.

New China's electric power industry achieved rapid development.

By the end of 1978, China's installed power generation capacity had reached 57.1221 million kW, generating capacity reached 256.55 billion kWh, and per capita electricity consumption had risen to 260kWh/person, 30.9, 59.5 and 32.7 times that of 1949, respectively. The installed power generation capacity and power generation rank eighth and seventh in the world respectively. The power grid has also begun to take shape, with 23,207 km of 220kV and above transmission lines built and a capacity of 25.28 million kVA of power transformation equipment. An independent and complete power industry system has been initially established, playing a significant role in the development of the national economy and the improvement of people's living standards.

Since 1978, the electric power industry has persisted in reform and innovation and achieved leapfrog development.

In the first ten years of reform and opening up, the focus of the power reform is to solve the problem of "power shortage" that has plagued the power industry for many years, as well as the problem of safe and reliable power supply under the environment of power shortage. The Party Central Committee deployed the implementation of various forms of fund-raising power investment and financing system reform, multiple rounds of electricity price reform and power system reform, to raise construction funds as the guidance, through fund-raising power, the use of foreign funds to generate electricity, the imposition of 2 cents per KWH of electricity construction funds, the implementation of a variety of electricity prices and other measures, as well as to adapt to fund-raising power and electricity conservation of power legal construction, Solved the problem of serious power shortage in the country caused by insufficient electricity funds, and effectively promoted the rapid development of the power industry. In 1987, China's installed capacity of power generation exceeded 100 million kW.

With the development and growth of the power industry, the Party and the state carried out reforms on the transformation of government functions, the separation of government from enterprises, and the establishment of a modern enterprise system, which improved the production and operation efficiency of enterprises. During the "Seventh Five-Year Plan" and "Eighth Five-Year Plan" period, China's installed power generation capacity increased by an average of 10% per year. In 1991, Qinshan Nuclear Power Plant in Zhejiang Province and Daya Bay Nuclear Power Plant in Guangdong Province were completed and put into commercial operation in 1994. Since 1996, China has ranked second in the world in terms of installed power generation capacity and power generation. In the same year, China began to achieve a preliminary balance between supply and demand of electricity nationwide, which had long plagued China's economic development and people's livelihood, and has been basically reversed. At the end of 1996, The State Council decided to set up the National Power Company. The Ministry of Electric Power Industry and the State electric power Company operate with two brands, two sets of teams and one set of people. In 1998, The State Council institutional reform plan decided to abolish the Ministry of Electric Power Industry, the implementation of the separation of government and enterprise, the Ministry of Electric power industry power administration functions to the State Economic and Trade Commission, industry management and coordination functions to the CEU, smoothly realized the separation of government and enterprise power.

From the "tenth Five-Year Plan" to the "Twelfth Five-Year Plan", the power industry, in accordance with the deployment of the Party Central Committee and The State Council, further implemented the power system reform with the goal of "breaking monopoly, introducing competition, improving efficiency, reducing costs, improving the electricity price mechanism, and building a fair and orderly power market system under government supervision", and split and reorganized the national power company. Set up five power generation groups, two major power grid companies and four major power auxiliary industry groups, set up the State Electricity Regulatory Commission, realized the separation of plant network, broke the vertical integration monopoly model of the power industry, and strengthened the dominant position of enterprises in the market. The power industry has initially formed a new pattern of the power system of "government macro-control, supervision by regulatory agencies according to law, enterprise independent management, and industry association self-regulatory management services", further enhancing and playing the role of the market mechanism, the competition situation on the power generation side has initially taken shape, and the power construction has leap-forward development. China's grid-connected installed capacity of hydropower and wind power surpassed that of the United States in 2004 and 2010 respectively, ranking first in the world. In 2012, the Sanxia Hydropower Station, the world's largest hydropower station with a total installed capacity of 22.5 million kW, was put into operation. The power supply structure is gradually tilted toward green power generation, and by the end of 2012, the proportion of installed power generation capacity from non-fossil energy sources reached 28.5 percent. In accordance with the unified requirements and deployment of the state, the power industry has actively implemented the policies of "replacing small power with large power" and "putting pressure on small power" in coal power generation, and stepped up efforts to control sulfur dioxide and manage energy conservation and emission reduction. In 2009, the scale of China's power grid surpassed that of the United States and ranked first in the world. 500kV has become the main grid of regional power grids and provincial power grids, and 750kV has become the main grid of the Northwest power grid, and basically completed the three major channels of "West-East power transmission" in the north, central and south. The Three Gorges power transmission and transformation Project has been fully put into operation, contributing to the national network pattern with the Three Gorges power system as the core. The 1000kV UHV AC and ±800kV UHV DC power transmission projects developed and operated by China on its own have been put into commercial operation, marking that China's power grid construction level and scientific research and innovation capability are now in the world's leading level. In 2011, with the commissioning of the Qinghai-Tibet ±400kV interconnection project, the whole country has been connected to the grid except Taiwan. In the same year, China ranked first in the world in power generation. Through two rounds of construction and renovation of rural power grids, we rationalized the rural power management system. In 2012, every village in China was electrified, and some households were electrified in some grid areas. We achieved the goal of charging the same price for all types of electricity in urban and rural areas on a provincial basis, and basically built a new rural power grid featuring safety, reliability, energy conservation, environmental protection, advanced technology and standardized management.

From the middle of the 12th Five-Year Plan period to the present, China's economic development has entered a new normal, and China's power industry has transformed from high-speed growth to high-quality development. In 2015, the "Several Opinions on Further Deepening the Reform of the Electric Power System" clarified the institutional framework of "controlling the middle and letting go of both ends" in accordance with the reform idea of "giving play to the decisive role of the market in resource allocation and better giving play to the role of the government". In September 2020, at the 75th session of the United Nations General Assembly, China solemnly pledged to "strive to reach the peak of carbon dioxide emissions before 2030, and strive to achieve carbon neutrality before 2060". The Fifth Plenary Session of the 19th

Central Committee of the Communist Party of China set "peaking carbon" and "carbon neutrality" as the goals of the country's 14th Five-Year Plan and the construction of ecological civilization by 2035. Through this round of reform, an independent electricity transmission and distribution price system has been basically established, power trading institutions have been fully established, and their management and operation are relatively independent from market entities. Steady progress has been made in the liberalization of electricity sales, and a market competition pattern of more buying and more selling has initially taken shape. Progress has been made in the construction of the electricity market, and a power market dominated by medium - and long-term transactions and supplemented by spot transactions is taking shape. In 2021, market-based transactions accounted for 45.5 percent of total electricity consumption.

The power industry has actively implemented the new development concept, focused on high-quality development, formed a strong production capacity, and displayed a new outlook for development. In 2013, China's installed power generation capacity surpassed that of the United States, ranking first in the world. In 2015, the total installed photovoltaic capacity of China surpassed Germany and ranked first in the world. In the same year, the problem of electricity consumption for people without electricity was fully solved. In 2016, China surpassed the United States to become the world's largest producer of renewable energy. In 2017, the Three Gorges Hydropower Station became the first hydropower station in China to exceed 1 trillion kWh in cumulative power generation. By the end of 2021, China's installed power generation capacity had reached 2.38 billion kW, with annual generating capacity of 8,376.8 billion kWh and per capita electricity consumption of 5,885kWh, 41.6, 32.7 and 22.6 times of 1978 respectively. The length of 220kV and above transmission circuits in the national grid is 826,000 km, and the capacity of power transformation equipment is 4.77 billion kVA, 35.6 and 188.7 times of that in 1978, respectively. As of April 10, 2024, a total of 38 Ultra High Voltage (UHV) projects have been successfully commissioned nationwide, comprising 18 AC and 20 DC projects. By the end of 2023, China's installed power generation capacity had reached 2.9 billion kW, and grid-connected wind power capacity had reached 441.34 million kW, an increase of 20.7 percent. Grid-connected solar power capacity had reached 609.49 million kW, an increase of 55.2 percent. China's power industry has achieved leapfrog development and now ranks among the world's most advanced in terms of scale, capacity, and equipment, providing strong support for building a moderately prosperous society in all respects.

2.2. The Resplendent Accomplishments Attained

Since the founding of the People's Republic of China 75 years ago, accompanied by the rapid development of China's economy, China's power industry has undergone tremendous changes from being weak to strong, from backward to advanced, and from local urban power supply to national interconnection. Nowadays, a large-scale, technologically leading and highly efficient management system of China's power industry provides a solid and reliable power guarantee for the rapid development of the country's economy and society.

China has established a comprehensive and self-reliant electric power industry system, forming an integrated industrial chain that encompasses planning, design, construction, generation, transmission, distribution, sales, and consumption of electricity. China holds the top position globally in terms of grid scale, installed power generation capacity, and annual power output. Characterized by advancements in smart grids, ultra-high voltage (UHV) technology, and clean energy, China's power sector has emerged as a global leader in power development. With the exception of Taiwan, China's power grid has connected and electrified every household in the country, becoming the world's largest hybrid AC-DC grid with the strongest transmission capacity, the highest operating voltage, the largest scale of new energy connection, and the longest record of safe operation.

The adjustment of the power structure has accelerated in the direction of green, low-carbon, safe and efficient, making outstanding contributions to ecological progress and addressing climate change.

Although China's installed thermal power capacity stands at 1.3 billion kW, the power sector plays a pivotal role in fulfilling the national emission reduction targets. Nearly 100 percent of coal-fired power plants have implemented dust removal, desulfurization, and denitrification measures, with approximately 970 million kW of coal-fired power units achieving ultra-low emission standards. The control of pollutant emissions and carbon dioxide emissions from coal-fired power plants has reached world-class levels. At the same time, the power structure continues to improve. By 2021, the installed capacity of hydropower, wind power, and solar power had ranked first in the world; the scale of nuclear power under construction also ranked first globally; and the installed capacity of non-fossil energy accounted for 45.4 percent of the total installed power generation capacity, making power supply greener and more efficient.

The rapid development of power science and technology has transformed China from a big power country to a strong power country.

China's electric power industry has implemented innovation projects to tackle key technologies and equipment R&D, continuously enhancing its innovation capabilities. This rapid advancement in power technology has transformed China from a major player into a leader in the field. Ultra supecritical coal power generation technology, air cooling systems, secondary reheating processes, and circulating fluidized bed boiler technology have all reached world-leading standards. The hydropower sector excels globally in planning, design, construction, installation, operation, maintenance, and equipment manufacturing. The wind power and photovoltaic industries boast top-tier technological capabilities and production capacities across their entire value chains. China has successfully completed and operationalized its third generation nuclear power demonstration project, which features full intellectual property rights. Key components such as reactor pressure vessels, steam generators, and reactor internals have been domestically manufactured. The High-Temperature Gas-cooled Reactor (HTGR) demonstration project, independently developed and constructed by China, represents the world's sole commercially operational fourth-generation nuclear power plant. China's power grid has achieved numerous world-leading scientific and technological innovations in Ultra-High Voltage (UHV) transmission, smart grids, safe and stable operation control of large power grids, and new energy integration. It has acquired independent intellectual property rights for UHV core technology and comprehensive equipment manufacturing capabilities. A comprehensive UHV technical standard system has also been established.

The electric power industry has always prioritized meeting the people's electricity needs for a better life, ensuring and improving livelihoods and providing electricity access to impoverished populations as key development goals. It has accelerated the construction of power infrastructure and public services, achieving universal household electrification, a first among developing countries. It provides "high-quality, convenient, standardized, and sincere" services to customers and has made significant achievements in key areas such as air pollution control, rural grid upgrades, urban distribution network construction, photovoltaic poverty alleviation, and epidemic prevention. These developments have benefited people nationwide, enhancing their sense of gain, happiness, and security.

3. The Profound Implications of China's Power Development Journey Towards a Zero-carbon Era of Energy and Heating

3.1. The Implications of a Concise History of China's Power Industry for Future Energy Sector Reform and Development

In the new development stage, it is necessary to adhere to national overall planning, comprehensively deepen reform and continuously expand opening up, and participate in international power cooperation and competition in a broader scope, wider field and higher level.

It is necessary to continue to implement the innovation-driven strategy, give priority to the development of the energy and power industry moderately in advance, accelerate the development of clean energy and renewable energy, and establish an energy framework centered on electricity with clean energy as the primary component.

3.2. The Significance of Reform, Development, and Innovation in China's Power Industry for the Heating Sector

Although the heating industry may not be as prominent as the power industry in driving economic and social development, the requirements for simultaneous production, transmission, and use are not as stringent as those for electricity, it still plays a crucial role in national economic security and energy security. Insufficient supply of heat can impact the national economy, albeit to a lesser extent compared to electricity.

The heating industry is a public welfare and foundational sector that serves both as a means of production and a means of living. It significantly influences the improvement of people's living standards. Particularly, as the energy and power sectors have alleviated supply-demand imbalances, heating has emerged as a critical bottleneck and major concern for the broader energy industry, as well as a key area in achieving the dual carbon goals. The current challenges faced by the heating industry and its potential development opportunities closely resemble those encountered during the early stages of the power industry's reform and development.

People firmly believe that the value and ultimate goal of the existence of an industry or an enterprise is a better life for human beings. As long as it is the actual needs of the people, it can surely be properly solved and developed, and the difficulties brought about by poverty are only temporary.

The heating industry requires clear national-level oversight to manage and supervise the sector, define reform and development objectives and plans, and set energy-saving, consumption reduction, and carbon reduction goals. It is essential to promptly inject capital, support market competitiveness, and foster technological innovation and international competitiveness in heating equipment manufacturing and engineering. Policy and financial support should be provided for universal service.

Development is the absolute principle. We should leverage development, reform, and innovation to first establish robust development momentum, industrial attractiveness, and economic scale while nurturing a number of competitive market entities. We must rely on technological advancement, economies of scale, and particularly market competition following supply-demand equilibrium to reduce costs and prices. Financial support can be obtained through positive interactions among local governments, market entities, end customers, and financial institutions. Universal services can be supported by construction funds, market space, natural resources, government backing, and cross-subsidies. We must consistently adhere to development, reform, innovation, and marketization, and appropriately address and manage the primary contradictions at different stages: addressing shortages, ensuring supply guarantees, promoting energy conservation and emission reduction, maintaining price affordability, managing cross-subsidies and universal services, enhancing market entity competitiveness, increasing marketization levels, stabilizing price levels, and achieving low carbon goals.

From 1979 to 1997, China's power industry successfully introduced new investors into the power generation market. The reform of the power investment and financing system effectively alleviated the power supply shortage. Currently, the heating industry faces a deficit, lacks market appeal, and has insufficient self-development momentum. To address these challenges, it should adopt the capital-raising experience from the power industry, starting in developed regions to benefit both market participants and consumers. This approach would promote industry growth and attract more market players. A comprehensive thermal industrial system, encompassing planning, design, construction, equipment manufacturing, heat source provision, pipeline network development, and sales, should be preliminarily established. Financing for heating, particularly through the issuance of special bonds and special treasury bonds in the new era, will significantly promote China's clean heating initiatives. The initial investment returns and social benefits demonstrated in developed regions will attract increased social capital into the heating sector. Leveraging economies of scale and technological advancements will yield greater cost efficiencies. Furthermore, the social impacts of ensuring supply stability, enhancing energy storage, promoting energy conservation and emission reduction, and advancing low-carbon heating will enhance industry attractiveness. This virtuous cycle will accelerate technological innovation, expand industry scale, and reduce costs and prices.

The development of key players in the heating market can benefit from the experience gained in the power industry. At present, breaking down the integration of source-grid-storage-load is not the immediate priority for the heating sector. Instead, emphasis should be placed on nurturing a number of capable entities within the heating market. Thermal power plants, which currently serve as the primary heat sources for combined heat and power generation and centralized heating, exhibit significant interest in photovoltaic projects, geothermal resources, energy storage, emission reduction, and future market opportunities. Considering that low-carbon and zero-carbon heating is crucial for achieving dual-carbon goals, it is advisable to encourage strategic cooperation and restructuring between power generation groups and local heating enterprises. This would foster the emergence of backbone heating market enterprises capable of providing universal services and fulfilling carbon reduction tasks, as well as cultivate internationally competitive heating equipment manufacturing and engineering firms.

The imbalance between developed and underdeveloped cities, especially between urban and rural areas, is a common problem. The universal service of public utilities for underdeveloped areas and relatively poor groups is also a worldwide challenge. Public utilities must adhere to the principle of universal service. Just like the access to electricity in every village and every household, the heating business in remote and poor villages must be incorporated into the development goals of the entire heating industry. It is necessary to draw on the experiences of the development and reform of rural electricity in China, make good use of the advantages of new energy and land resources in vast rural areas and the broad market development potential, and take advantage of the favorable period when there is insufficient consumption and energy storage capacity in the rapid development stage of distributed new energy. Measures such as construction funds, special treasury bonds, cross-subsidies in heat prices, resource pricing adjustments, and redirecting carbon tax revenues from centralized heating areas towards underdeveloped regions can enhance the investment and financing capabilities and production capacity formed by new energy in rural areas and heating in developed areas, thereby addressing the challenge of clean heating in rural areas.

4. Analysis of Development Trends and Strategic Directions for Clean Heating in China

As early as the 14th meeting of the Central Financial and Economic Leading Group held at the end of 2016, it pointed out the direction for the development of clean heating in China. In accordance with the principle of enterprise first, government promotion and affordable for residents, and clean energy is utilized as much as possible to accelerate the increase of the proportion of clean heating. Specifically, clean heating refers to the use of electricity, geothermal, biomass, solar energy, industrial waste heat, clean coal (ultra-low emission), natural gas, nuclear energy and other clean energy, through efficient energy use system to achieve low emissions, low energy consumption of heating, including to reduce pollutant emissions and energy consumption as the goal of the whole process of heating. It involves clean heat source, efficient transmission and distribution network (heat network), energy-saving building (heat user) and other links. Promoting clean heating is of great significance to reducing heating energy consumption, improving energy efficiency, and winning the battle to protect blue skies and the battle to prevent and control smog pollution.

4.1. Ensuring the Supply of Clean Burning Cogeneration Central Heating Continues to Be a Long-term and Challenging Task

The heating project in the Inner Mongolia Autonomous Region is anticipated to serve as a model for supply security and ultra-low emission of air pollutants during the clean combustion heating phase of fossil energy.

Generalized clean heating is an intricate and comprehensive system encompassing diversified heat sources, efficient transmission and distribution networks, extensive user bases, cost-effectiveness, and intelligent management. Clean heating can be broadly categorized into two primary phases: the initial phase characterized by the clean combustion of fossil fuels aimed at reducing emissions of air pollutants such as particulate matter, sulfur compounds, and nitrogen oxides; and the advanced phase where low-carbon or zero-carbon energy sources serve as the principal means for heating. Presently, we are at a critical juncture transitioning from clean combustion-based heating to zero-carbon heating. Notably, heating in small and medium-sized cities, underdeveloped regions, and particularly rural areas remains inadequately addressed, indicating that ensuring reliable heating services still presents significant challenges.

Clean heating project, is one of urban and rural public municipal facilities, clean heating project belongs to quasi-public goods, central heating pipe network also has a natural monopoly. For residents in cold and severe climates, heating is a subsistence demand; The residents in the climate transition zone use air conditioning to cool down in summer and "warm themselves by fire" in winter, which may still belong to the improvement demand at present, but there is a trend of becoming more and more rigid demand. The winter peak electricity consumption in the middle and lower reaches of the Yangtze River exceeds the summer peak electricity consumption is a strong evidence. To meet the needs of residents to warm in winter and cool in summer is the starting point and landing point of the development of urban and rural clean heating industry. After the central heating in the city is basically guaranteed, it should be extended to the climate transition zone and the vast rural areas in the north. Ensuring safety and security of heating in winter is increasingly becoming an inevitable requirement for governments and enterprises to provide quasi-public goods. In recent years, positive progress has been made in clean heating and loose coal replacement work in the north. It is also necessary to fully realize that heating is just needed, and avoid "one size fits all" promoting coal to gas; Clean heating coal replacement work should adhere to the principle of first standing before breaking, to avoid "good intentions to do bad things". While promoting clean heating and strictly supervising loose coal burning, it is necessary to fully take into account the guarantee of supply and the affordability of the people, so that the happiness of the people is significantly enhanced.

In the winter of 2023, a significant temperature drop in many regions of Inner Mongolia led to strong public reactions concerning heating issues such as "insufficient heating and substandard room temperatures." Even in northern cities with centralized heating systems, challenges remain in ensuring adequate warmth. Wang Lixia, Chairperson of Inner Mongolia, who has been actively promoting comprehensive management of centralized heating and coal-burning for scattered heating since 2020, emphasized that Inner Mongolia is abundant in coal, electricity, and gas resources. Therefore, it is unacceptable for residents to suffer from inadequate heating. She stressed the importance of seizing the opportunity presented by the national promotion of urban pipeline network renovation to increase investment and improve heating infrastructure. Specific measures include focusing on heat source and heat network construction plans for the warmth project, addressing the governance of coal-burning for scattered heating, enhancing the intelligence level of the heating system, and implementing household-based heating renovations based on local conditions. Efforts should also be made to explore and establish new intelligent heating models for precise and on-demand heating, continuously optimizing heating efficiency to ensure sufficient and high-quality heating. The Inner Mongolia Autonomous Region government has significantly increased investment in the warmth project, with all localities submitting their plans. In 2024, the total fiscal investment will reach nearly 20 billion yuan, including over 10 billion yuan for pipeline networks and more than 1 billion yuan for intelligent upgrades. The project encompasses heat source and heating capacity matching, new energy heating, peak shaving and standby heat sources, waste heat utilization, heat network and heating station renovations, measurement, intelligence, and business model innovations. It is believed that the warm project of Inner Mongolia will explore more successful experiences of increasing investment, cultivating main body, technological innovation, price mechanism and system reform for the development of China's heating industry to ensure the safety, energy saving and emission reduction of coal-burning central heating and affordable prices.

4.2. Technical and Economic Comparison of Several Conventional Clean Heating Methods in Typical Northern Cities

The Plan for Clean Heating in Winter in Northern China (2017-2021), issued by China in 2017, has set the tone for improving the level of clean heating in northern regions. The total area of district heating in northern China was 19.1 billion square meters in 2017, rising to 22.5 billion square meters in 2021, with an average annual growth rate of 4.18 percent. From 2017 to 2021, the rate of clean heating in the northern region increased from 43 percent in 2017 to 70 percent in 2021, basically achieving the above goals in the Plan. The heat source cleanliness here refers to the initial formation of a heating pattern [4] mainly dominated by ultra-low emission coal-fired cogeneration, supplemented by natural gas and supplemented by other heat sources.

Overview of heat supply in Hohhot and Beijing:

Hohhot is a city with rapid development of central heating in the northern cold region. The user's indoor heating design temperature is 18 ℃, and the outdoor heating design temperature is -19 ℃. The heating time is from October 15 to April 15 of the following year. After years of development, urban central heating has formed a heat source heating pattern based on cogeneration, supplemented by regional boiler rooms and supplemented by other heat sources. In 2016, the total heating area of the city was 129.116 million square meters. Among them, cogeneration heating area accounted for 29.62%, large coal-fired heat source plant heating area accounted for 25.24%, regional boiler room (more than 10 tons of coal-fired boiler room) heating area accounted for 20.68%, gas heating surface accounted for 20.86%, small coal-fired boiler room (less than 10 tons of coal-fired boiler room) heating area accounted for 3.20%. Other clean energy (heat pump units, electric heating, etc.) accounted for 0.40% of the heating area. At that time, there were 3 thermal power plants, 5 large heat source plants, 61 regional boiler rooms (more than 10 tons of coal-fired boiler rooms), 689 gas boiler rooms, 82 small coal-fired boiler rooms (less than 10 tons of coal-fired boiler rooms), and a small number of heat pump units, wall hanging furnaces, electric heating and so on. In accordance with the national policies at that time, Hohhot City proposed the requirement of "promoting centralized heating in urban areas, advancing the project to introduce heat into Hohhot, and striving to achieve a coal-free main urban area within three years" with the ultimate goal of establishing a heating pattern dominated by cogeneration of heat and power, supplemented by clean energy, and featuring multi-heat source complementation.

According to Wang Zhongmin's Beijing low-carbon heating challenges and countermeasures [5], the heating pattern system of Beijing is different from that of Huh. Through continuous improvement, it has basically formed a multi-component urban heating system dominated by cogeneration and gas heating, and combined with a variety of energy sources and a variety of heating methods. In the heating season from 2021 to 2022, Beijing's urban district heating area will be 919 million square meters, of which 243 million square meters will be cogeneration heating, accounting for 26.44%; Gas heating area is 633 million square meters, accounting for 68.88 percent; New energy and renewable energy coupled heating 0.36 million square meters, accounting for 3.92 percent; Electricity and other heating were 0.07 million square meters, accounting for 0.76 percent. Beijing has built an urban cogeneration heating system with four heat and power centers, eight thermal power plants in Taiyanggong and Zhengchangzhuang as the main heat sources, and seven large gas heating plants as peak heat sources. Regional cogeneration heating systems such as Haidian Shanhou, Tongzhou Canal core area and Changping Future Science City have been built; To introduce heat from other cities into Beijing, and realize that Sanhe thermal power Plant supplies heat to Tongzhou and Zhuozhou thermal power Plant supplies heat to Fangshan. Clean heat supply in rural areas continued to advance. There are 3,921 villages in the rural areas of Beijing, of which 3,386 villages and about 1.3 million households have converted coal to clean energy for heating, accounting for 86.3% of the total number of villages. Among them, 2,111 villages have converted coal to electricity (the main use of electric energy is air source heat pump and ground source heat pump), about 860,000 households; There are 552 coal-to-gas villages, about 220,000 households; And another 723 villages achieved clean heat supply through demolition. The remaining rural areas were all converted to high-quality coal for heating.

Evaluation of Several Heating Methods in Clean Heating in Hohhot by Jie Xiong and Zhang Xiaosong [6], based on the price levels in Hohhot in 2017, a technical and economic comparison was conducted for various heating methods including long-distance pipeline central heating, gas boiler heating, coal-fired boiler heating, and heat pump heating. The primary definitions and conclusions are summarized as follows:

The definition of several heating methods and the investment cost and operating expenses.

Conventional heating pipe network Central heating is generally the farthest heating distance of the pipe network is controlled within 20km, the long distance heating pipe network refers to the heating distance of the pipe network exceeds 20km, and has a relay pump station or pressure isolation station heating system, the heating area is usually more than 15 million m^2 (nominal diameter ≥DN1200). China's Beijing, Jinan, Taiyuan, Hohhot and other cities have built hot water heating long distance pipeline.

This paper takes two long-haul heating projects that have been put into operation and one that is being demonstrated as examples to calculate the initial investment of long-haul heating projects (73, 78, 81 yuan per square meter respectively), and takes one long-haul heating project as an example to calculate the operating cost of long-haul heating heat sources. The operation cost of long-haul heating project includes heat cost, water cost, electricity cost, employee salary, maintenance, management cost, depreciation cost and so on. The total operating cost of the project is 23.71/m^2 a.

Gas boiler central heating uses natural gas as energy for heating/heating, mainly in the following three forms: household gas wall hanging furnace heating, small gas boiler heating, large gas boiler central heating. In the multi-heat source joint heating system of the peak mode, the peak of the central gas boiler room is more common. In the coal-gas combined heating scheme, the gas peak-regulating boiler is set up in the thermal station as the peak-regulating heat source, which is operated jointly with the central heating network.

This paper takes two central heating projects under construction gas boiler room as an example to calculate the initial investment of gas heating project (respectively 51 and 61 yuan per square meter), and takes a gas central heating project that has been put into operation as an example to calculate the operating cost of gas central heating heat source. Gas central heating project operating costs include natural gas fee (natural gas 2 yuan /m^3 ~ 2.2 yuan /m^3), water fee (4.45 yuan /t), electricity fee (0.6 yuan /kWh), employee compensation, maintenance, management costs, depreciation costs, etc., the total operating cost of 46 yuan /m^2 a~ 50 yuan /m^2 a.

Coal fired boiler heating is the traditional heating method in China, which has the characteristics of small investment, short construction period and low technical requirements. The thermal efficiency of large regional boiler room can reach 80%, which is also a mature heating technology. However, the general scale of coal-fired regional boiler room energy consumption, consumption of conventional energy, serious pollution, in developed countries belong to the elimination of technology, currently in China is one of the main heating methods.

This paper takes two coal-burning heating projects that have been put into operation as an example to calculate the initial investment of coal-burning heating projects (respectively 57, 64 yuan per square), and takes a coal-burning central heating project that has been put into operation as an example to calculate the operating cost of coal-burning heating heat sources. The operation cost of coal-fired central heating project includes coal cost (180 yuan /t ~ 420 yuan /t), water cost (4.45 yuan /t), electricity cost (0.6 yuan /kWh), environmental protection standard operation cost, employee salary, maintenance cost, management cost, depreciation cost and so on. The total operating cost is 26 yuan /m^2 a~32.5 yuan /m^2 a.

Heat pump technology Heat pump technology refers to the use of electric energy, the heat from the low temperature heat source into a high temperature heat source of a heating technology. It uses air, industrial wastewater, river water, sea water and other heat sources to recover the energy used for heat supply. It does not limit the geographical location and density of the heat user, and the concentration, stability and balance requirements of the heat load are not too harsh, and it is convenient to use. It is "heat by electricity", which not only saves fuel, makes rational use of energy, and reduces environmental pollution. The initial investment per unit area of the air source heat pump heating system calculated is 136.7 yuan /m^2, and the operation management fee is 31.89 yuan /m^2 a.

Conclusion of comparative analysis:

The annual value of the central heating cost of long-distance pipeline is the lowest and the economy is the best (the annual value of the total cost of long-distance transportation, gas, coal and heat pump is 30, 50, 35 and 43 yuan per square respectively). Although the initial investment of the heat pump is greater than other heating methods, its annual operating cost is lower than that of the gas boiler, and with the increase of economic life, its economy is on the rise. Although the economy of central heating for coal-fired boilers is not bad now, its economy may become worse with the improvement of environmental protection requirements. The economy of gas boiler heating is poor.

4.3. Before Zero-carbon Heat Sources Prevail, Focus on Efficient Heat Pumps, Energy Storage, and Smart Metering Systems

Heat pumps provide heat by extracting thermal energy from the environment and transporting it indoors, or transporting indoor heat to the outside for cooling in the summer. In general, a COP between 3 and 5 for domestic and commercial air source heat pumps is the more common range. This means that for every 1 kilowatt-hour of electricity consumed by the heat pump, the corresponding heat of 3-5 kilowatt-hours can be transported or moved out of the room. Therefore, the heat pump can not only provide an efficient heating solution, but also use the electricity generated by the wind and solar to reduce the dependence on traditional fossil fuels, helping users reduce energy costs and carbon footprint. Air source heat pumps transport heat from the outside air; Ground source heat pumps move heat from underground water. Compared with traditional coal or gas heating systems, heat pumps have obvious advantages in high energy efficiency, low maintenance costs, especially the use of renewable energy for heating, and can significantly reduce carbon emissions.

Compared to heat energy, electric energy represents a higher-quality energy source. While the conversion efficiency of fossil fuels into heat has long surpassed 90%, the efficiency of converting fossil fuels into electricity remains below 50%. To achieve economic viability in transitioning from coal-based electricity to heat, it is imperative to employ heat pumps with a coefficient of performance (COP) exceeding 2, rather than relying on electric boilers or direct electric heating methods. Continuous improvements in the COP of heat pumps are also essential. Until zero-carbon heat sources become predominant, enhancing the COP and reducing the cost of heat pumps remain critical strategies for facilitating the transition from coal to electricity. Once green electricity becomes the primary power source, heat pumps will have significantly broader development prospects.

In fact, heat pumps have been regarded as the key technology to solve global warming, because of their advantages of high energy efficiency and low emissions, have been widely used around the world. According to the International Energy Agency report, there are currently about 190 million heat pumps used for space heating in buildings worldwide, covering 10% of the building sector's heating needs, but the deployment rate of heat pumps is still well below the level needed to achieve the zero carbon target by 2050, and the adoption of heat pumps needs to accelerate. Many countries are developing policy measures to accelerate the roll-out and deployment of low-carbon home heating systems: In the European Union, the RePowerEU plan, published in March 2022, sets out targets to double heat pump sales that year, add 10 million heat pumps over the next five years, and add a total of 30 million heat pumps by 2030; In the United States, the Reduction of Inflation Act signed in August 2022 proposes to encourage residents to purchase heat pumps for heating purposes, with significant rebates and tax incentives.

In northern China, where heating demand is high, low ambient temperature air source heat pumps have been adopted. For example, in rural areas of Beijing, Tianjin and Hebei province, heat pumps are the main equipment installed in the "coal to electricity" national program supported by government subsidies. Government subsidies have been playing a central role in promoting heat pumps in these areas. However, it is precisely the inappropriate use of heat pumps in the process of coal to electricity in the northern countryside, so that China's heat pump industry has not shown the development trend and advantages it should have. Despite their many advantages, heat pumps also face their own challenges. The first is high initial installation costs, especially since ground source heat pumps can be twice as expensive as conventional heating units. In addition, the effectiveness of heat pumps can be compromised in extremely cold climates. Technological advances in recent years have made it possible for heat pumps to operate effectively in temperatures as low as -25 ℃. Putting the heat pump technology, which has the highest initial investment, first in the rural north is a bit of a cart before the horse. The heat pump has not yet formed a scale effect, the initial price is high; The lack of funds in rural areas, low price affordability, the initial cost of high program is not suitable for rural demonstration; The northern winter temperature is low, the heating effect is poor; Rural distributed green electricity has not yet formed rich, the cost of terminal electricity is high. Even if the demonstration is carried out in Beijing and other places, there are concerns about its replicability in the vast poor rural areas. The Ministry of Ecology and Environment issued a document prohibiting law enforcement from being "one-size-fits-all", and the General Department of the National Energy Administration issued a Notice on Solving Problems related to the promotion of clean heating such as "Coal to gas" and "coal to electricity", proposing that local conditions should be adapted, with appropriate electricity for electricity, appropriate gas for gas, appropriate coal for coal and appropriate heat for heat; Can be understood as the implementation of the policy out of shape and demonstration application scenario selection of correction.

The heat pump has not yet formed a positive leading and driving role in the rural areas of northern China, which does not change the promotion trend of China's heat pump industry to clean and low-carbon heating. Perhaps the Yangtze River Delta region can serve as a model for other southern parts of China, such as Hunan, Hubei, Sichuan and Chongqing in the middle and lower reaches of the Yangtze River. Similar to the Yangtze River Delta, these regions have both hot summers and cold winters, and rely on distributed equipment for heating. The promotion of heat pumps for home heating in China's Yangtze River Delta region not only contributes to zero-carbon heating in the region, but also accelerates the adoption of heat pumps worldwide to achieve zero-carbon heating on a larger scale.

As a world manufacturing power that has made significant contributions to the global dual-carbon goal, China is also the world's largest exporter of air source heat pumps. As early as 2021, the export volume reached 4.86 billion yuan. Although China has emerged a number of new heat pump enterprises such as Nuentai and Zhongguang Outers, but compared with the total industrial output value of China's air conditioning industry in 2023 to achieve more than 830 billion yuan, the heat pump sales of about 30 billion yuan and the total output value of 800 billion yuan of air conditioning industry can be described as small. Heat pump is not only a public equipment for coal to electricity, but also a general equipment for geothermal, solar heating, electric vehicle thermal management and other heating methods. Tesla's thermal management system can be said to be enough to put the entire traditional HVAC industry to shame. China is already the world's industrial power, there must be and will be world-class heat pump products and enterprises. It is encouraging that Gree Air conditioning has begun to enter the field of photovoltaic + energy storage + cooling and heating. In summary, heat pump is the key equipment to promote heating electrification, and there must be broad space for development. Heat pumps are not only an efficient solution for home heating, but also an important part of achieving a sustainable lifestyle. With the continuous development of technology and the encouragement of policies, the popularity and development prospects of heat pumps will be broader. Therefore, traditional air conditioning enterprises and emerging heat pump enterprises should cooperate with energy storage heating, HVAC engineering design and electric vehicle industry to continuously improve the competitiveness of the heat pump industry and the contribution of the heat pump industry to clean and low-carbon heating.

Heating and cooling have now become the largest energy consumption that fluctuates with the change of ambient temperature. In the coming period, fluctuating wind power and photovoltaic will become the main incremental primary energy sources. Heat storage and cold storage have become an important way of energy storage in themselves. Landscape plus energy storage (heat) will increasingly become an important mode of integrated operation of source network storage and load.

4.4. Building Energy Conservation and Emission Reduction Are Global Priorities, Zero-carbon Heating Is Essential to Meet These Targets

According to the accounting results of the International Energy Agency for the terminal energy use and CO_2 emissions in the global construction sector, the implied energy consumption and building operation energy consumption of the global construction industry (including housing construction and infrastructure construction) in 2021 accounted for 37% of global energy consumption, of which the implied energy consumption of building infrastructure construction accounted for 7% of global energy consumption. The proportion of building operation in global energy consumption is 30%. In 2021, global CO_2 emissions (including emissions from energy and industrial processes) will be 36.3 billion t CO_2, of which the implied CO_2 emissions from construction (including house construction and infrastructure construction) will account for 12% of the global total CO_2 emissions, and the CO_2 emissions related to building operation will account for 28% of the global total CO_2 emissions.

According to the calculation results of Building Energy

Efficiency Research Center of Tsinghua University for energy use and emissions in China's construction sector, the implied energy consumption and operation energy consumption of China's building construction in 2022 will account for 30% of the total energy consumption of the whole society. In China, the implied energy consumption of building construction accounts for 9% of the total energy consumption of the whole society. Large-scale construction activities brought about by the continuous promotion of urbanization in China require the use of a large number of building materials, and the production of building materials leads to a large amount of energy consumption and carbon emissions. Is an important reason for the continuous growth of energy consumption and carbon emissions in China and the proportion of implied energy consumption in building infrastructure construction is slightly higher than the global average. Construction operation accounts for 21% of China's total social energy consumption, which is lower than the global average level. People's living standards and energy consumption intensity still need and space to further improve. In 2022, China's per capita building operation carbon emission index will be 1.52t CO_2/ person, equivalent to the average building operation carbon emission index per unit area of 31kg CO_2/m^2.

In order to achieve about 2.2 billion tons of carbon related to building operation in China (plus the increment brought by the current heating and cooling groups that have not been covered), in addition to energy saving and consumption reduction to reduce the carbon emission intensity per unit area, it is necessary to continuously increase the proportion of zero carbon heat sources. Being able to use zero carbon or low carbon heat sources in one step to heat small and medium-sized cities, rural towns and farmers in underdeveloped areas that have not yet been covered is an ideal solution.

According to Elon Musk's plan to achieve a sustainable civilization, key steps include: replacing fossil fuels with renewable energy as the main energy source of the grid, which can reduce carbon emissions by 35%; Switching from conventional vehicles to electric vehicles could reduce carbon emissions by 21 percent; The adoption of heat pump technology to heat (cool) residential and commercial buildings will reduce carbon emissions by 22%; The adoption of high-temperature heat storage technology for industrial processes will reduce carbon emissions by 17%; Renewable fuels for aircraft and ships would cut emissions by 5%.

Although cogeneration will also assume the role of heating ballast and backstop guarantee for a period of time, burning fossil energy will also be the main heat source for guaranteed supply, every household needs heating and cooling, extensive central heating and charging by area, and the lack of accurate heating capacity of the heating system on demand, so that the potential for energy saving and cost reduction in the heating industry is still great. However, clean heating will eventually transition from clean combustion heating to zero carbon heating, and the demand and space for innovation in low-carbon and zero-carbon heating technology will be greater. The key ultimately depends on the source of heat. The current clean and low-carbon heat source, that is, low-carbon primary energy, has no exhaled nuclear, geothermal, wind and solar energy.

4.5. Near Nuclear Power Plants, Nuclear Energy Heating Is the Leading Choice for Zero-carbon Heating

The Warm Nuclear No. 1 Project of Haiyang Nuclear Power Plant in Shandong has conducted valuable explorations and demonstrations for the safe, long-distance, large-scale, zero-carbon, and cost-effective heating capabilities of third-generation nuclear power plants.

Nuclear heating is a clean heating method using the thermal energy generated by nuclear fission as a heat source. Nuclear cogeneration includes the production mode of nuclear thermal power plant and the combined production mode of heating transformation of nuclear power plant to make nuclear power plant have additional heating capacity. From the 1950s to the 1970s, the first batch of nuclear reactors have begun to try to heat the surrounding towns by nuclear cogeneration. In addition to nuclear cogeneration, low-temperature nuclear heating reactor heating and nuclear waste heat heating are also one of the comprehensive utilization ways of nuclear heating. Nuclear cogeneration is a beneficial exploration of nuclear energy as a clean and low-carbon heat source, and an effective way to alleviate the contradiction between the shortage of fossil energy and the shortage of clean heat source supply, and improve the effective utilization efficiency of clean energy.

The "Winter Clean Heating Plan in Northern China (2017-2021)" mentions nuclear heating for the first time, and clearly states that "research and explore nuclear heating, and promote the existing nuclear power units to supply heat to the surrounding areas", that is, promote the development of nuclear cogeneration; The "Guiding Opinions on Energy Work in 2022" of the National Energy Administration proposed to organize the implementation of the "Pilot program for central heating and comprehensive Utilization of Nuclear Energy"; The "14th Five-Year Plan" Modern Energy System Planning clearly proposes to promote the comprehensive utilization of nuclear energy in clean heating and other fields, as well as the implementation of key technologies and demonstration applications of three generations of nuclear power, including low-temperature heating reactors. In 2019 and 2021, Shandong Haiyang Nuclear Power Plant and Zhejiang Qinshan Nuclear Power Plant will respectively carry out nuclear cogeneration of different scales to supply heat to Haiyang City of Shandong Province and Haiyan County of Jiaxing City of Zhejiang province. Nuclear cogeneration provides a stable and clean heating solution for China's coastal district heating areas. In the future, with the advancement of inland nuclear power projects, nuclear cogeneration will have a wider range of application scenarios.

At present, due to the relatively short development time of nuclear cogeneration technology in China, the relevant research and practice of nuclear cogeneration system is at the demonstration stage, and there are still many problems to be solved in the evaluation, planning, design, operation, regulation and standardization of nuclear cogeneration. Among them, the comprehensive evaluation of the nuclear cogeneration system and the comparison of the nuclear cogeneration long-run heating scheme will provide a theoretical basis for the feasibility study of nuclear cogeneration, the design of planning schemes and the establishment of relevant technical standards, and is of great significance for promoting the development and application of nuclear clean heating in China.

According to a report by CCTV Finance's "World Finance" [7] on November 25, 2023, China has launched its first intercity nuclear heating project, State Power Investment's "Warm Nuclear No.1". This project initiates cross-regional nuclear heating from Yantai to Weihai in Shandong Province. The heat source for "Warm Nuclear No.1" is derived from the exhaust steam of the high-pressure cylinder of the nuclear power unit. Through physical isolation, multiple heat exchanges and radiation detection measures are implemented, ensuring that the heat is safely delivered to residential areas via the municipal heating network. Additionally, multiple isolation circuits and continuous radiation monitoring are employed to guarantee the safety and reliability of the nuclear heating system. This newly operational cross-regional nuclear heating project, enabled by technological upgrades including cogeneration and steam extraction, delivers nuclear heating over long distances to Rushan City, Weihai, marking the first instance of intercity nuclear heating.

The third phase of the "inter-regional" nuclear energy heating project of "Warm Nuclear No. 1" has improved the nuclear heating capacity of nuclear power units under the premise of ensuring safety, once again breaking the record of the largest residential heating area of a single nuclear power unit. As a key project of the national "14th Five-Year Plan", "Warm core No. 1" has stabilized the heating of Yantai Haiyang City for 5 complete heating seasons, and is the first cross-prefecture level city nuclear energy heating project in China. State power Investment nuclear energy development chief engineer, Shandong nuclear Power Party secretary, chairman Wu Fang told reporters: "Nuclear heating is from the nuclear power unit second loop extraction steam as a heat source, through the heat exchange station for multi-channel isolation, multistage heat exchange, and finally the heat transfer to the user through the municipal heating pipe network, this process only heat transfer, no water and other media exchange, to ensure that the user heating clean and safe." The "Warm core No. 1" project covers 6.3 million square meters in Rushan's main urban area, meeting the clean heating needs of about 200,000 local residents. This heating season, the heating area of "Warm Core No. 1" has reached 13 million square meters, benefiting nearly 400,000 residents in Haiyang and Rushan cities. Compared with traditional fossil energy and other heating methods, nuclear energy heating is characterized by cleanliness, economy and stability. Compared with the past, the residential heating fee in Haiyang City has been reduced by 1 yuan per square meter, the PM2.5 concentration in the air in the heating season has decreased by 16%, the air quality rate has increased by 17%, and the air quality in the heating season has significantly improved."

In the view of Zhao Xin, chairman of Haiyang Haiyuan Energy Co., LTD., compared with traditional boiler heating, nuclear heating has three major advantages: first, the environmental protection effect is significant, and the heating capacity is greatly improved; Second, the energy saving effect is obvious; The third is scientific and standardized management -- according to reports, the local nuclear energy heating first station control system into the smart heat network dispatching and control platform, nuclear heat sources, transmission and distribution systems and end users of the heating process parameter monitoring, data analysis and intelligent control, while according to weather changes, timely temperature control, to achieve smart heating, scientific heating and stable heating. The Shandong Provincial Energy Bureau has given the evaluation of "clean, safe, stable and efficient" for nuclear energy heating in Haiyang City, and Haiyang City has also been awarded the "Demonstration City of Comprehensive development and utilization of Nuclear energy in Shandong Province". [8]

Unit 1 and Unit 2 of the first phase of the Haiyang Nuclear Power Plant Project were put into commercial operation in October 2018 and January 2019 respectively. According to reports, while ensuring the "zero carbon" heating of the entire urban area of Haiyang, the two nuclear power units can also generate 58 million KWH per day, which can meet the domestic electricity demand of all residents in Qingdao, Yantai and Weihai, and effectively guarantee the regional power supply. In the future, the Haiyang nuclear power Plant will have a heating capacity of 200 million square meters, providing a strong clean energy guarantee for the integration of Jiaodong economic circle.

The third phase of the "warm core No. 1" nuclear energy heating project of the State Power Investment is put into operation in Shandong, which has three significant meanings: First, the safety and economy of the generation and heating of the third-generation nuclear power units have gradually been accepted and recognized by the public; Second, based on the low primary energy cost and high energy density of nuclear power generation and heating, the heating radius has been greatly expanded, and the technical maturity and economy of nuclear heating have been verified; Third, zero-carbon large-scale heating technology based on nuclear energy heating has been demonstrated. With public acceptance and the expansion of the heating radius, nuclear energy heating will play a great role in zero-carbon heating around safe and economical third-generation nuclear power plants. Coupled with the further maturity of high-temperature gas-cooled reactor technology and its essential safety advantages, especially the maturing of nuclear fusion technology, nuclear energy is likely to have its development space in the field of zero-carbon heating.

Qinshan Nuclear Power Base is located in Haiyan County, Jiaxing City, Zhejiang Province, in the load center area of East China Power grid. It started construction in 1985 and was connected to the grid in 1991. There are 9 operating units with a total installed capacity of 6.62 million kW and an annual generating capacity of about 52 billion KWH. It is the nuclear power base with the largest number of nuclear power units, the most abundant type of reactors and the largest installed capacity in China, and is honored as "the glory of the country". Under the premise of ensuring the safe and stable operation of nuclear power units, Qinshan Nuclear Power Plant actively promotes the construction of nuclear heating demonstration projects, and provides the "Qinshan solution" for solving the "bottleneck" of central heating in southern China. Qinshan Nuclear power supply project through the technical transformation of cogeneration of nuclear power units, the use of Qinshan nuclear power units in winter surplus thermal power to achieve external heating. On the premise of maintaining the unit's power generation capacity, the outlet water temperature is 130 ℃, while the return water temperature is set at 70 ℃, to achieve the Haiyan County public facilities, residential communities and industrial parks nuclear heating. After the completion of the project, it will have 150MW of nuclear energy heat supply capacity and a heating area of 4 million square meters. On December 3, 2021, the first stage demonstration project of Qinshan Nuclear Power Heating Project has been officially put into operation, with a heating area of 464,000 square meters, and three living quarters in Haiyan County has taken the lead in realizing nuclear central heating. The project has set a precedent for nuclear central heating in southern China, and has played a good demonstration role in the construction of large-scale central heating projects in southern China. The first-stage demonstration project of Qinshan nuclear power heating is running well. While realizing the clean replacement of natural gas boilers, the heating quality has been significantly improved compared with previous years, which has been widely recognized and fully affirmed by the residents of the heating district. On December 3, 2021, Yu Bing, a member of the Party group and deputy director of the National Energy Administration, pointed out at the operation ceremony of the Zhejiang Haiyan nuclear energy heating demonstration project that nuclear energy heating is a major livelihood project and a popular project. [9]

GB 6249-2011 "Nuclear power plant environmental radiation protection Regulations" requires that the nuclear power plant site from more than 100,000 people of the radius of the town is not less than 10km; The Regulations on radiation protection of nuclear thermal power plants require that when nuclear thermal power plants are used for heating of urban residents, the linear distance from the development boundary of large cities with a population of more than 1 million should not be less than 25km. To carry out nuclear cogeneration in large cities and towns in China, heat transmission must be achieved in combination with long-haul heating pipe network technology. At present, the coastal nuclear power plants located in the northern central heating area include four nuclear power plants: Hongyanhe Nuclear Power Plant, Haiyang Nuclear Power Plant, Shidaowan Nuclear Power Plant and Tianwan Nuclear Power Plant, the Xudapu Nuclear Power Plant under construction and the "Guohe No. 1" demonstration project. In addition, central heating has been carried out in Jiaxing city, where Qinshan Nuclear Power Plant is located, and Lianyungang City, where Tianwan Nuclear Power Plant is located. The Zhuanghe nuclear power project in Liaoning has been started. Haiyang Nuclear Power Plant "warm core No. 1" to Yantai city, Qingdao city, Qinshan nuclear power plant, Tianwan nuclear power plant to Jiaxing city, Lianyungang city, Hongyanhe nuclear power plant to Wafangdian mayor heat supply (referred to as Hongwa nuclear power plant long distance heat supply) need to carry out the long distance heat supply routing analysis of these coastal nuclear power cogeneration. At present, there are only two nuclear cogeneration demonstration projects in China, and their scale is still relatively small, which does not belong to the long-haul nuclear energy heating system. There are still many problems to be solved in the evaluation, planning, design, operation, regulation and standardization of nuclear cogeneration. Among them, the comprehensive evaluation of nuclear cogeneration is the first link to demonstrate the feasibility of the project to be built and evaluate the comprehensive benefit of the project already built. The long-distance transmission of heat from nuclear cogeneration is the main feature and technical difficulty of China's current nuclear cogeneration. [10]

4.6. Power, Heating, and Energy Storage Using Mid-deep Geothermal Resources Offer Reliable Alternatives to Fossil Fuels

With the continuous rise in the proportion of new energy, it has become increasingly evident that once the penetration rate of renewable energy surpasses a certain threshold, conventional energy sources essentially function as backup storage for intermittent renewables. This realization has sparked concerns about the potential phased withdrawal of coal power from the energy mix. However, considering the rigid demand for combined heat and power (CHP) generation for centralized heating, the complete phase-out of coal-fired CHP plants appears to be a distant prospect. Moreover, given that the heating needs of numerous small and medium-sized cities in northern regions remain inadequately addressed, there is an urgent requirement for a renewable energy source characterized by wide distribution, stability, reliability, and scalability to meet both heating demands and local power supply security. Geothermal energy has emerged as a viable option. Geothermal power generation and heating have become crucial alternatives to replace traditional urban power and heat sources—primarily thermal power plants—to achieve zero-carbon, stable power supply and heating.

In fact, the community where my home is using groundwater to cool and heat the central air conditioning program. My hometown Hunan Huitang Hot spring, Beijing Jiuhua Hot spring, Yunnan Tengchong Daguhuo Hot spring and Yellowstone Hot Spring in the United States have given me a little direct perception of geothermal resources. However, my intuition of these scarce shallow hot spring tourism and health care resources led me to an intuition that shallow geothermal resources are scarcer than oil and gas resources, which has always constrained my imagination of geothermal as an important energy resource. It was not until I listened to Academician Sun Huanquan's lecture on the exploration and development technology and direction of geothermal resources in China on May 27, 2024 [11] that I gradually realized the abundance and wide distribution of geothermal resources, especially the medium and deep geothermal resources, and that China has carried out a lot of effective exploration on the development of geothermal resources.

Geothermal energy is a kind of renewable energy that exists in the earth's interior rock, soil, fluid and magma bodies. Due to the solar radiation on the earth's surface and the decay of radioactive elements in the earth's interior, the earth's interior is constantly generating heat energy, so the earth's interior temperature is very high, and the deeper the temperature is, the higher the average depth of 100 m stratum temperature rises by about 3.0 ℃. According to the temperature, it can be divided into high temperature (≥150 ℃), medium temperature (90~150 ℃) and low temperature geothermal resources (<90 ℃); According to the different burial depth and occurrence state, it is usually divided into shallow (200m to shallow), medium-deep (200~3000m) and deep (3000m to deep) geothermal resources, and the medium-deep and deep geothermal resources include hydrothermal and dry hot rock geothermal resources. Geothermal energy has the unique advantages of abundant reserves, wide distribution, stability and reliability, clean and low carbon, which is of great significance in coping with the global energy transition and reducing greenhouse gas emissions, and has become one of the important development directions of energy transition at home and abroad. The main forms of geothermal energy development and utilization include shallow geothermal energy, hydrothermal geothermal energy, rock thermal geothermal energy, etc. The main technical forms and characteristics of geothermal energy development and utilization are shown in the following figure.

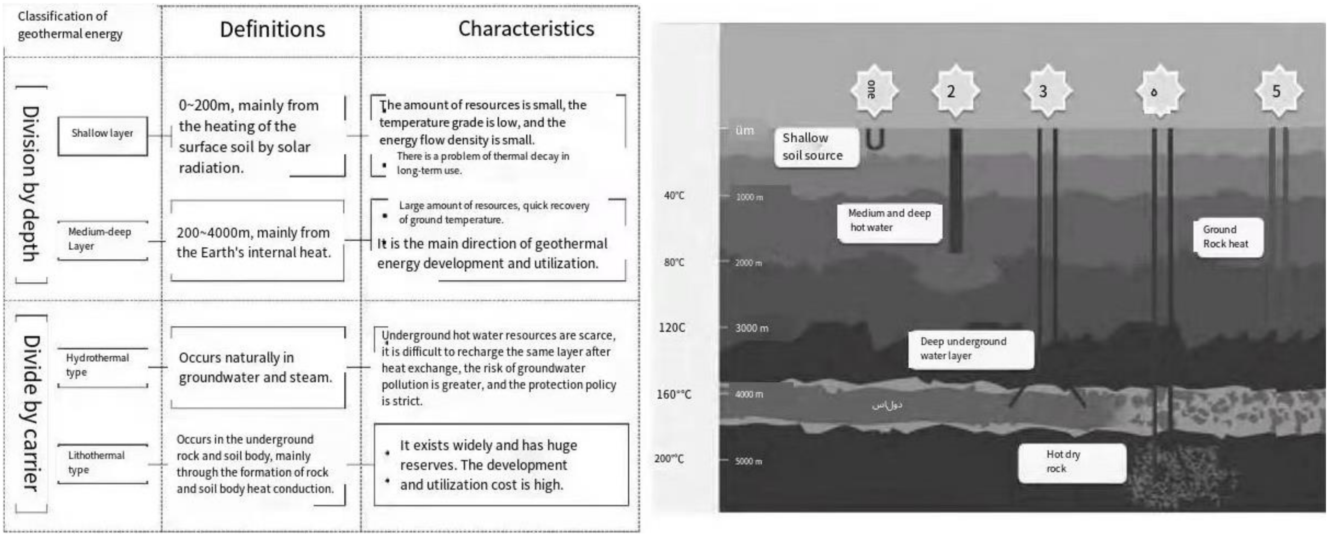

Figure 1. *Technology and characteristics of geothermal energy development and utilization [12].*

According to the "China Geothermal Energy Development Report (2018)", the global total of basic geothermal energy resources is estimated at 1.25×10^{27} J, with the portion located within 5,000 meters depth equivalent to 4.95×10^{7} million tons of standard coal. China possesses an abundant and widely distributed geothermal resource base, accounting for approximately one-sixth of the global total. Medium and low-temperature geothermal fields (25 - 150 ℃) are prevalent across the country. The hydrothermal geothermal resources amount to approximately 1.25 trillion tons of standard coal, with an annual exploitable quantity equivalent to 1.9 billion tons of standard coal. Deep dry hot rock geothermal energy resources, found between 3,000 and 10,000 meters underground, are estimated to be equivalent to 856 trillion tons of standard coal. Based on the internationally accepted 2% exploitation rate, this equates to roughly 3,000 times China's current annual energy consumption. Presently, the primary forms of geothermal energy utilization in China are hydrothermal and shallow geothermal energy. Within the planned areas of 336 prefecture-level cities and above, the annual exploitable amount of shallow geothermal energy resources is equivalent to 700 million tons of standard coal, while that of medium and deep geothermal energy resources is equivalent to 1.9 billion tons of standard coal.

Since the founding of New China, China's geothermal industry has entered a period of rapid development. Since 2004, the scale of direct utilization of geothermal energy in China has been ranked first in the world, and its share has been increasing. Especially under the strong demand for clean heating, it has gradually formed a development path based on heating (cooling), which has become a new model for the development of the international geothermal industry. By the end of 2022, China's shallow geothermal heating (cooling) equivalent installed capacity of 42,320MW, accounting for 5‰ of China's primary energy consumption, heating area has reached 810 million m^2; The converted installed capacity of medium and deep hydrothermal geothermal heating is 50030MW, which has become the most important mode of utilization. The total heating area has reached 582 million^2 meters, of which more than 70% is concentrated in Hebei, Henan, Shandong, Tianjin, Shaanxi, Shanxi and other provinces (municipalities), playing an important role in clean heating and air pollution prevention in northern China. The utilization of geothermal energy has played an increasingly prominent role in the transformation of energy structure and green and low-carbon development.

Through theoretical and technological innovation and large-scale promotion and application, Sinopec has developed into China's largest medium and deep geothermal energy utilization enterprise. The accumulated geothermal heating capacity has exceeded 100 million meters, and the medium and deep geothermal heating capacity has exceeded 85 million m^2. The "Xiongxian Model" of geothermal heating in the whole city has been established, replacing more than 100 coal-fired heating boilers in the county seat, and creating the first non-smoking demonstration city of geothermal clean heating in China. In July 2021, Xiongan geothermal project was listed in the International Renewable Energy Agency's global promotion project list, and Xiongan New Area has become a global model for China's geothermal energy utilization, with a built heating capacity of more than 10 million m^2. The medium and deep geothermal heating capacity in the Beijing-Tianjin-Hebei region has exceeded 200 million m^2, and 10 "smoke-free cities" for geothermal heating have been built in China, including Rongcheng in Hebei Province, Wugong in Shaanxi Province and Qingfeng in Henan Province.

According to the application prospect of Yang Haihong's medium and deep geothermal heating technology in Ningxia [12], in recent years, medium and deep geothermal heating technology has been rapidly developed in Shaanxi, Henan, Shandong, Inner Mongolia, Beijing and other places, and the construction area has been put into use of more than 20 million m^2. Among them, the West China Science and Technology Innovation Port project in Xixian New Area of Shaanxi Province has a heating area of 1.59 million m^2, a total heat load of 75.69 MW, a total of 6 distributed energy stations and 91 geothermal Wells. The deep geothermal demonstration project in the comprehensive transportation hub project of Beijing City Deputy Central Station has passed the review and acceptance. The Diyan heat exchange well of the project is 2745 m deep, with a stable heat transfer capacity of 550 kW, which can heat 25,000 m^2 buildings. Tianshui City, Gansu Province Vocational Education Park in the deep layer of non-interference geothermal thermal system heating (cooling) project, heating area of 600,000 m^2, 3 distributed energy stations using 32 heat exchange Wells to meet the heating and cooling needs. In Tianjin and Hebei, there are also middle-deep geothermal heating projects built, which has played a leading and demonstration role in the promotion and application of this technology in different regions of the country. According to the application experience of relevant demonstration projects, the use of middle-deep geothermal heating technology, the whole system per square meter heating area investment of 230 ~ 260 yuan, one-time initial investment is slightly higher. However, the later operating cost is low, the minimum operating cost of the whole heating season (150 days) is 0.9 yuan/(month ㎡), and the maximum is 2.3 yuan/(month ㎡) [the electricity price is calculated by 0.5 yuan/(kWh)]. To 100,000 m^2 building calculation, if the medium and deep rock heat heating system is used, according to the current northern heating charge standard, the annual cost can be saved by more than 1.5 million yuan compared with central heating, which begins to reflect the economy.

The medium and deep rock thermal heating technology has the characteristics of closed underground heat exchange, heat extraction without water, and no interference to the natural environment. It is a green and low-carbon clean heating method, and also one of the important ways to achieve the goal of carbon peak and carbon neutrality. Compared with several other major renewable energy sources, the medium and deep geothermal rock heating does not exist solar energy, wind energy and other easy to be affected by weather changes, unstable, discontinuous, need to increase energy storage, peak adjustment and other links of the problem, but also can overcome the shallow soil source heat pump heat total amount is small, heat compensation is not easy to balance, long-term use is prone to "thermal decay", Resulting in a decline in efficiency and a gradual increase in operating costs in the later period, it can also completely avoid the problems of hydrothermal technology using groundwater, 100% of the same layer recharge difficulties, and strict protection of groundwater resources. It has the characteristics of universal application, green and low-carbon, safe and reliable, on-demand heating, moderate scale, low operating cost and so on. There is geothermal energy everywhere in the underground, the heat source is renewable and stable, and it has a wide range of universal applicability. The selection of the location of the heat exchange hole is flexible, and it is generally not restricted by regional and site conditions. The energy comes from deep geothermal energy, and the carbon emission reduction effect is remarkable; The system is physically isolated from underground rock formations, and only takes heat but not water, which has no interference to the above-ground and groundwater environment. The system has no exhaust gas, waste liquid and waste residue discharge. Low temperature and low pressure operation of the whole system, no chemical reaction, system stability, no safety hazards, high reliability; The pore size of the ground rock heat exchange hole is small (about 200 mm), and the depth is above 1 000 m, which has no impact on the building foundation; The underground heat exchanger can be made of special steel, corrosion resistance, high temperature resistance, high pressure resistance, long life (not less than 30 years). The system heating is not restricted by the climate environment, gas, heat and other purchased energy, independent heating, flexible regulation, and wide application range. The system has no long-distance transmission power energy consumption and temperature drop loss along the process, a single heat exchange hole can meet the heat load of 500 ~ 700 kW, the whole system energy efficiency ratio COP value can reach 5.0 or more, and the operating cost is low.

Gansu Province has also carried out the exploration and research on the multi-energy complementary heating technology of solar energy and medium-deep geothermal heat supply system [13]. They combined the solar collection system with the medium-deep geothermal heat supply system, and designed and built a set of solar collection area of 202 m^2 by using the solar energy resources in Lanzhou. A single medium and deep strata heat exchange well with a diameter of 200 mm and a depth of 2500 m is used to simulate the heat supply of the well and the geothermal temperature recovery under the condition of continuous heat extraction and geothermal gradient of 30 ℃/km. Then, the control system of the multi-energy complementary heating system is optimized, and 6 operating modes are proposed. Finally, the actual operation of the multi-energy complementary heating system in the heating season is tested and analyzed. The results show that: 1) the heating heat of the solar heating system in the heating season accounts for 31.6% of the total annual heat; 2) the thermal influence radius of the middle-deep strata heat exchange well is about 8 m, and the recovery cycle of the strata temperature after the end of the heating season is about 120 days, which can realize the continuous heating of the middle-deep strata heat; 3) In the heating season, the multi-energy complementary heating system can provide about 11% of the heat for the whole multi-energy complementary heating system; 4) the multi-energy complementary heating system has 6 operating modes, which can be automatically controlled according to the change of the user's heat load and sunshine conditions, flexibly allocate energy, give full play to the advantages of the two energy sources, in order to achieve the purpose of the lowest heating cost.

The Changsha Huanghua Airport geothermal exploration and production combination well represents a pioneering effort in central and southern China, being the first to adopt coaxial casing heat transfer technology and distributed fiber-optic temperature monitoring for medium-deep geothermal scientific research. It is also the first large-scale airport geothermal utilization project in China that integrates multiple energy sources to provide terminal energy supply [14]. The project encompasses comprehensive activities including construction, testing, and monitoring of medium-deep geothermal exploration and production combined wells. Specific tasks include geological design, well structure design, pre-drilling engineering, drilling operations, coring, logging, rock sample analysis, geophysical logging, cementing, completion, installation of coaxial casing heat exchangers with subsequent heat transfer capacity tests, optical fiber system installation and monitoring, as well as comprehensive data collection throughout the entire process. This project was designed by China Energy Engineering Group Hunan Electric Power Design Institute Co., Ltd., and jointly executed by Hunan Institute of Engineering Geology, Mine Survey and Monitoring, and Hunan Kechuang Electric Power Engineering Technology Co., Ltd.

On May 23, 2023, the geothermal exploration and production combined well project at Changsha Airport successfully passed the expert review, with the project results rated as "excellent." The review panel comprised renowned experts and professors from China specializing in geothermal energy, geology, HVAC, and drilling. Led by Academician He Jishan of the Chinese Academy of Engineering, the expert group concluded that the project effectively validated the applicability of middle-deep ground source heat pump technology in the working area. It provides crucial technical support for the development and utilization of middle-deep geothermal energy in central and southern China, serving as a demonstrative model with significant potential for further promotion in these regions.

From September 19 to 21, 2024, the 14th National Geothermal Congress was held in Jinan, Shandong Province. The Hunan Engineering Geology and Mine Geological Survey and Monitoring Institute received the Geothermal Energy Industry Innovation Technology Award for its groundbreaking achievements in constructing and conducting heat transfer tests on a medium-deep geothermal exploration and production combined well at Changsha Airport. According to the report, this project involved advanced techniques such as drilling, logging, cementing, core testing, heat transfer testing, distributed fiber monitoring, geological exploration, and comprehensive research and analysis. It not only explored medium-deep geothermal resource exploration and production technologies but also successfully integrated various key technologies, including axial bushing heat transfer technology and data simulation technology. This comprehensive innovation provided critical technical parameters and demonstrated significant potential for the exploration, development, and utilization of medium-deep geothermal energy in Hunan Province and the entire South-Central region. The project reached a completion depth of 2611.58 meters, achieving several research outcomes, including superconducting thermal cementing materials, high-thermal-resistance central pipes, and high-temperature mud systems. The final heat transfer test results exceeded design expectations, validating the suitability of medium-deep ground source heat pump technology in this region and highlighting the leading role and innovative nature of this technology in the development and utilization of medium-deep geothermal energy in the central and southern regions.

In October 2023, the feasibility study report for the Changsha Airport Green Energy project, contracted by Xiangtou Natural Gas, successfully passed the review. On April 16, 2024, the National Development and Reform Commission (NDRC) issued Notice No. 272 of the Development and Reform Office, announcing the "List of Green Low-carbon Advanced Technology Demonstration Projects (First Batch)." The Changsha Airport green energy demonstration project, declared and planned by Hunan Xiangtou Natural Gas Investment Co., Ltd., was included in this list. This project employs integrated deep geothermal and multi-energy technologies to comprehensively optimize the airport's energy supply system. It achieves collaborative optimization of cooling, heating, electricity, water, and gas, ensuring comprehensive low-carbon operation under various working conditions. Key construction components include a mid-deep geothermal + composite energy supply system, cold storage and heat storage systems, distributed photovoltaic power supply systems, light storage and charging micro-grid systems, and a source-network-load-storage coordination and control platform. Upon completion, the project is expected to achieve a 29% renewable energy utilization rate, provide over 75% of annual green energy heating, meet approximately 29% of winter clean and stable heating loads, and reduce carbon emissions by about 12,000 tons annually. The Changsha Airport green energy project, including six geothermal wells, is progressing as scheduled.

Deep geothermal energy [15] is mainly distributed in the depth of more than 2 000m from the ground, and the average temperature of rock and soil is 150 ~ 350 ℃, and the vertical distribution range is wide. According to the geological survey of China, the amount of dry hot rock geothermal resources in the underground range of 3000 meters to 10000 meters in China's land area is equivalent to 856 trillion tons of standard coal, even if only 2% is extracted, it can reach 2993 times of China's annual energy consumption in 2023. As an emerging clean and green energy, deep geothermal energy is increasingly valued for its inexhaustible, inexhaustible, low regional requirements, safe and reliable, green and energy-saving characteristics that can be widely promoted in northern China.

Drilling has always been the natural advantage of China's petroleum and chemical industry. Ultra-deep drilling has become the main area of oil and gas discovery in China. In 2023 alone, CNPC completed 72 deep Wells over 8,000 meters in the Tarim Basin, and the number of Wells above 8,000 meters has now exceeded 200. On March 4, 2024, the drilling depth of the deep-ground Tako-1 well exceeded 10,000 meters, making China the third country in the world to drill a 10,000-meter deep well. It took 89.92 days to drill well Fuyuan 304-H2 to a depth of 8,322 meters in Tarim Oilfield, setting a record for the fastest drilling cycle of over 8,000 meters in China. On April 8, 2024, SINOPEC successfully completed the drilling of the Fushenre 1 well in Hainan with a depth of 5,200 meters, setting a new record for the deepest geothermal scientific exploration well in China.

Most of the national key research and development projects in the geothermal field set up in the past five years are aimed at deep geothermal or dry hot rock fields, and a certain research foundation has been laid. However, the theoretical research, development and utilization technology of deep geothermal resources belong to the forefront of international academic technology, and China started late. Compared with the representative advanced technology of deep geothermal resources in the world, China is at a parallel stage in the field of geothermal geology, geophysics and geochemistry. In the dry hot rock fracturing and mining and other aspects are in the parallel stage, only the dry hot rock exploration and test mining in Gonghe, Qinghai Province, and other places have been initially carried out, and there is no large-scale development practice of resource utilization. Although there are still technical problems in the development of geothermal resources, such as complex geological conditions, unclear resource enrichment mechanism, foreign engineering technology is not adapted to the key, development costs should be greatly reduced, and soil and water environmental protection should be attached great importance, but with the progress of science and technology in China, the technical level of deep geothermal energy development and utilization has gradually improved. Deep geothermal energy will occupy an increasingly important position in the field of new energy in China. At the same time, with the continuous expansion of the scale of geothermal industry, it is an inevitable trend to enter the field of deep geothermal resources with higher resource quality and wider application range, and the development and utilization of deep geothermal energy will usher in the peak of development.

The development of geothermal resources in China, especially the middle and deep geothermal resources, is not satisfactory, mainly because there is no deep understanding of the strategic significance of geothermal resources. In particular, there is a lack of extensive and profound understanding of the unique advantages of rich reserves, wide distribution, stable and reliable, clean and low-carbon geothermal energy in the middle and deep layers. All walks of life focus too much on the competition for scarce shallow geothermal resources, and restrict the imagination of geothermal resources development. Moreover, the electric power and heat industry, which undertakes the main responsibility of heating, and the petroleum and petrochemical industry, which is known for geological exploration, lack cross-border communication and do not form a joint force. Local heat enterprises lack capital and technical strength, and the initial investment in middle and deep geothermal development and deep geothermal development is large and the technical threshold is high. In addition, it is not easy to form a large-scale demonstration effect for the early middle-deep geothermal heating demonstration project in a single small and medium-sized city, which leads to some unsatisfactory geothermal energy development.

That is, the middle and deep geothermal heating demonstration project has not yet formed a good driving role, the deep geothermal heating project initial exploration, deep well investment is not low, the middle and deep geothermal heating and cooling, especially the early demonstration project needs to have a certain scale to have a better economy. After all, it can not change the reality of the wide distribution of cities, especially small and medium-sized cities, the demand for primary energy for urban heating is large, and after all, it can not ignore the huge carbon emissions of urban central heating for a long time. The power and heat load of the city itself is relatively large and the requirements are relatively high. After the gradual withdrawal of conventional fossil energy from the historical stage, it is difficult to ensure the reliability of urban electricity and heat energy supply by relying only on scenery new energy and energy storage. Now more and more people realize the indispensability of thermal power plants in the power grid peak regulation, if coupled with the irreplaceability of thermal power plants in urban central heating, thermal power plants, especially cogeneration thermal power plants, it is difficult to withdraw from the historical stage, at best, it is to reduce the number of annual utilization hours and sustainable operation and development capacity. Therefore, it is a rare choice to replace thermal power generation and heating with medium and deep geothermal resources with wide distribution, huge resource reserves, stability (non-intermittent) and zero carbon. It is necessary to speed up the development of deep geothermal power generation and heating technology in urban load centers, in accordance with the principle of first standing and then breaking, to find a substitute for thermal power plants -- geothermal power generation and heating.

In short, geothermal resources are important non-carbon-based renewable energy sources, with huge reserves, wide distribution, green, low carbon, stable and adjustable advantages. Combined with China's deep well drilling capability and the preliminary formation of the medium and deep hydrothermal geothermal resource exploration and development technology system, compared with the 2019 report "Geothermal Vision: Harness the heat beneath our feet " issued by the U.S. Department of Energy, the target of "By 2050, the scale of geothermal power in the United States is 20 times larger than the current scale, and the electricity generation will account for 8.5% of the total electricity generation in the United States". And the "Deep Geothermal Energy Implementation Roadmap" issued by Europe in 2019 proposed that "deep geothermal energy can meet 50% of Europe's electricity demand and 80% of its heating demand by 2050", which makes me even feel: In 2021, the eight departments of China issued "Several Opinions on Promoting the development and utilization of geothermal energy" proposed that "by 2025, the geothermal energy heating (cooling) area will increase by 50% compared with 2020, and the installed capacity of geothermal power generation in the country will double than 2020; By 2035, the geothermal energy heating (cooling) area and the installed capacity of geothermal energy power generation strive to double than 2025 "the target is a bit too stable and conservative. There are reasons to believe that: "renewable energy development" 14th Five-Year Plan "involving shallow geothermal energy development, medium and deep geothermal energy heating and cooling, geothermal energy power generation and other aspects of the active promotion of large-scale development of geothermal energy planning goals will mostly be realized in advance; Continue to strengthen basic theoretical research and original technological innovation, the development of higher quality, wider application scenarios of deep geothermal resources will be accelerated. Because the realization of efficient and sustainable development of geothermal resources is of great strategic and practical significance to ensure national energy security, help the transformation of the petroleum and petrochemical industries, and accelerate the construction of a clean, low-carbon, safe and efficient energy system.

4.7. The Integration of Rural Distributed Zero-carbon Power, Energy Storage, and Heat Supply Remains in Its Nascent Stages

The potential for clean, zero-carbon power and heating in vast rural areas is significant. However, compared to farmers' disposable income, the initial investment remains prohibitively high. Additionally, technical and economic uncertainties, as well as limited affordability of prices, continue to pose constraints. Therefore, the integration of distributed zero-carbon power generation, energy storage, and heat supply in the rural area faces considerable challenges and has a long way to go. [16]

Distributed energy resources in China's rural areas are very rich. In 2018, China's rural household electricity consumption was about 26.23 million kWh, while the annual power generation potential of rooftop PV in rural areas alone was 2.9 trillion kWh, more than 10 times the former. China's rural areas contain abundant distributed zero-carbon resources represented by rooftop photovoltaic, biomass and rural hydropower, which are far from being fully developed and utilized. Under the guidance of the dual-carbon goal, rural areas should be transformed from fossil energy consumers to zero-carbon energy producers, and contribute to the realization of China's dual-carbon goal and the improvement of farmers' living standards, economic income and environmental quality.

The team of Professor Yang Xudong of Tsinghua University used low-resolution images to identify the outline of villages across the country. Then, by sampling typical areas in different provinces, they identified the roofs of rural buildings in the region from high-resolution satellite images, determined the coefficient of building roofs in each province, and calculated the area of rural roofs in each province. Thus, the total installed potential of rural rooftop PV is about 2 billion kW, and the annual power generation potential is about 2.9 trillion kwh. Based on the method of multi-temporal remote sensing satellite image identification of various crops and relying on the statistical data of departments, the annual total biomass energy in rural China is calculated to be equivalent to 736 million tce of standard coal. And from the perspective of resource potential analysis and calculation, China's rural hydropower installed capacity potential is about 128 million kW, annual power generation potential is about 535 billion kWh.

Many of China's revolutionary changes have been carried out from the countryside. The encircling of the cities by the countryside and the seizure of political power by armed force is a revolutionary path that the Chinese Communists creatively summed up from their experience in leading the Red Army and the struggle in the base areas after the defeat of the Great Revolution and which suits China's reality. China's reform and opening up was also a clarinet that began with the rural household contract responsibility system. Now more and more research teams dedicated to energy revolution and zero-carbon transition have realized the importance of rural issues, and China's energy revolution in the new era may follow the same path.

First of all, the resources and space for zero-carbon energy are mainly in rural areas. The power of zero-carbon energy mainly relies on wind power and photoelectric power, which requires a huge space; The fuel of zero carbon energy is mainly from biomass fuel, which needs to be based on huge land resources. Rural production and life will be fully electrified, and rural energy increment and flexibility provide new energy system with space and flexibility to absorb new energy. These are the urgent resources that the development of rural areas can provide for the construction of a new type of power system. In the new zero-carbon energy system, rural areas will be the main source of electricity (30% of wind power), the main source of zero-carbon fuel (70% of zero-carbon fuel), and the main undertakers of electricity storage (25% of electricity storage).

Second, accelerating the development of new energy emission reduction in rural areas will achieve positive interaction with rural revitalization. China's large proportion of scattered land that is not suitable for large-scale mechanization must also be used as cultivated land to ensure food security, resulting in China's farmers, who account for 35% of the total population, receiving only 10% of their total income (the international average). This gap between urban and rural areas is due to the shortage of arable land suitable for large-scale mechanized production as a means of production. The increased output of new energy, zero-carbon electricity and zero-carbon fuel is through tapping existing resources in rural areas to form new means of production and obtain new income. At present, the expenditure of purchasing energy in rural areas accounts for about 10% to 15% of the total income of farmers. Speeding up the development of new energy in rural areas and realizing rural electrification as soon as possible can not only reduce the economic burden of farmers' energy purchases, but also reduce environmental pollution and carbon emissions caused by combustion. It can also increase the income of grain growing by about half through the sale of zero-carbon electricity and zero-carbon fuel. It is possible to lay an important economic foundation through the development of new energy to achieve rural revitalization, narrow or even eliminate the difference between urban and rural areas, as rural areas from assuming the supply of food for the whole society to complete the task of energy revolution at the same time, the social and economic conditions in rural areas will undergo great changes. It is the resource advantages and growth space of rural areas in this round of energy revolution that have laid the foundation for obtaining financial support for the rural energy revolution. The difficulty lies in the need for long-term capital support, which just matches the investment of long-term special government bonds.

Third, in the construction of zero-carbon power system and zero-carbon heating system, especially in the process of corresponding mechanism construction, the construction of rural comprehensive new energy system will play an important experimental and demonstration role.

The construction of a new zero-carbon power (heat) system is a revolution in the power (heat) system. The power supply from the current controllable thermal power plant to a large proportion of unregulated wind power, photoelectric power supply mode from the current centralized mode to the combination of centralized and distributed. As a result, the regulation and stability of the power system is completely dependent on the centralized regulation of the power supply side, and is changed to the joint regulation of the centralized and distributed power supply and energy storage and load, which makes the adjustment and control method of the power grid system appear great changes, and the corresponding adjustment and balance operation mechanism, pricing policy must be adjusted accordingly. Without changing the policy mechanism of the existing power system, it is difficult to realize the construction of a new type of power system with zero carbon as the goal. China's power grid is already the world's largest, most secure and reliable power grid with the best universal service. Without large-scale experiments and demonstrations, it is difficult to comprehensively change the existing power system policy mechanism to adapt to a large proportion of distributed renewable power supply policy mechanism. The change of operation mode and policy mechanism can only be attempted, experimented and demonstrated from the system that is relatively simple and has little impact on the national economy. The countryside has become the first experimental demonstration area to try and demonstrate the new policy mechanism of the new energy system. China's new energy system model can start from a village, from several villages to a town to a county, from a county to a prefecture to a provincial city, and finally to a first-tier major city. It is believed that the construction of new energy system in rural areas will be able to make beneficial exploration of the whole new energy system in China.

Fourth, rural areas can take the lead in transforming from energy consumers to energy producers and consumers.

Rich in renewable resources and with little demand for their own energy, rural areas will transform from traditional energy consumers to new energy producers and consumers. There are natural conditions to realize the above transformation. However, realizing the transformation of rural role in the energy system requires sound top-level design and technological path planning. First, the current rural electrification rate is low, and heating and cooking, agricultural machinery and transportation mainly rely on fossil energy, and the infrastructure supporting new energy is still far from perfect. Secondly, the capacity of transformers and transmission lines in rural areas is limited, it is difficult to carry ten times the current rural electricity load of photovoltaic Internet access, a large number of photovoltaic disorderly access to the grid will cause transformers, lines overload, and even threaten the security of the grid. Third. Although rural areas have huge new energy resources that are far greater than their own energy needs, but because of the strong volatility of photovoltaic, electricity demand and randomness and regulation, how to make good use of the growing rural heating demand as a flexible energy storage resource has become an important topic of rural "light storage direct and soft" new distributed power system and rural electrification.

There is a certain gap between the electrification level of living energy in rural areas and the city, and the research and development and application of electrification machinery in agricultural production are also in their infancy. In order to strive to achieve the goal of "dual carbon" and promote the clean transformation of energy use in rural areas, comprehensive electrification is the main path of future rural energy development. To this end, work needs to be carried out from the following aspects to promote the overall improvement of the level of agricultural and rural energy use electrification.

First, vigorously develop distributed clean energy and establish a rural power system with rooftop photovoltaic and decentralized wind power as the core. Strengthen the grid connection of rural distributed clean energy to realize the grid connection of clean energy.

Second, on the basis of reducing costs and electricity prices, taking heating, cooling, freezing and cooking as breakthroughs, popularize the use of electric steamers, induction cookers, electric ovens, etc. for green electricity in rural cooking, promote the transformation of rural families' habits of using traditional energy in cooking and heating, combine the upgrading and renovation of rural houses with building energy conservation, promote the application of efficient air conditioners, electric heating products, especially high-efficiency equipment such as air source heat pumps, vigorously stimulate the potential of rural residents' energy consumption for daily life, and improve the level of rural life electrification; promote low-cost partition wall power supply in rural areas and improve the level of local power balance.

The third is to encourage electric vehicle enterprises to pay attention to rural customers and oil and gas agricultural machinery manufacturing enterprises to transform and upgrade electric agricultural machinery, reduce the production cost and sales price of electric agricultural vehicles and electric agricultural machinery, and promote the popularization of pure electric vehicles in rural areas and the electrification of agricultural vehicles and agricultural machinery. In rural public institutions, transportation hubs, trade logistics bases, tourist attractions and other key areas to build charging facilities, accelerate the construction of public charging facilities in rural areas, in order to meet the needs of rural electrified travel, improve farmers on electric vehicles, electric agricultural machinery convenience, recognition and willingness to use. In areas where conditions permit, rural comprehensive energy demonstration zones with villages and towns as units can be built to provide cheap electricity for new forms of rural business, promote the electrification of rural family farms, modern agriculture and other operations to promote the electrification and upgrading of agricultural industries, and promote the development of circular ecological comprehensive energy that combines smart energy and green ecology.

In Europe and the United States, where rural areas are relatively rich, there are many successful solutions for rural power supply and heating. However, due to the large gap between urban and rural areas in China, the solutions of Western rural areas may not be feasible or applicable in China. Whether to use excess distributed photovoltaic power generation, distributed wind power generation, biomass power generation, small hydropower generation of abundant electricity plus water source or air source heat pump, or renewable energy generation plus electrochemical energy storage or molten salt heat storage system, hot water heat storage system, or solar heat collection system plus medium and deep geothermal well heating system, Or the use of special solar heat pump system, etc., the need for specific analysis. Can learn from the experience of European and American countries, in the more developed areas of the countryside demonstration, practice, and then gradually promoted. In short, China's rural areas will surely accelerate development, China's rural power supply, heating must be guaranteed, China's rural renewable energy resources to benefit farmers, China's rural renewable energy power generation should be developed first and even surplus to reduce electricity prices, China's rural renewable energy power generation and rural electrification as well as energy storage, heat storage, heating should be integrated and balanced development. China's rural power supply, electrification, energy storage, heat supply to increase investment and policy support. [17]

5. Conclusion

In summary, Heating (cooling) is one of the largest end-use energy and a key area for energy conservation and carbon reduction. Heating has increasingly become a necessary guarantee in more and more regions, and the requirements for clean and low-carbon are becoming more and more explicit. The eternal theme is affordability of prices, development of enterprises, and return on investment. The fundamental solution lies in large-scale development and technological innovation to achieve the goals of ensuring supply, reducing costs, and achieving clean and low-carbon. Heat pumps are the key technologies and equipment for the electrification of heating. Low-carbon ultimately needs to be addressed from low-carbon and zero-carbon sources, that is, the main body of primary energy should be clean and low-carbon nuclear energy, geothermal energy, wind energy, and solar energy. Looking into the future, if coal power and cogeneration of heat and power are destined to exit the historical stage due to the dual-carbon goals, then approximately the current amount of coal-fired cogeneration may need to be replaced by an equivalent amount of geothermal power generation and heating. Considering the incremental heating demand in the vast number of small and medium-sized cities that has not yet been met, once geothermal power generation and heating form a scale economy of tens thousands kilowatts of electricity and heating that matches the scale of medium and deep geothermal energy, the almost inexhaustible, unrestricted by time and space, and self-equipped with long-cycle energy storage characteristics of geothermal energy has the potential to challenge the leading position of photovoltaic and wind power in renewable energy. This is because people will increasingly recognize that wind and solar green electricity + energy storage may ultimately be difficult to solve the inherent contradiction of temporal and spatial mismatch of energy supply and demand in an economically feasible way.

The area around the nuclear power plant is likely to give priority to the zero-carbon heating scheme of nuclear + long-range heating because of its economy, stability and maturity, and it is necessary to determine the most economical nuclear long-range heating radius. There are numerous rural electricity and heating solutions characterized by diversity, wide coverage, and small individual scales. The rural energy supply market has significant potential but is highly sensitive to initial investment and operating costs, making it currently challenging to determine the optimal approach. Ultimately, the issue needs to be addressed through on-site consumption, balance, and the most cost-effective diversified distributed green energy systems. Heating is a very important livelihood project, especially for residents in less developed areas. It is also an essential means for rural areas to leverage their resource advantages to alleviate poverty and enhance living standards. Rural zero-carbon heating (and cooling) serves as the optimal testing ground and demonstration area for achieving the energy revolution and double carbon goals through systemic, mechanistic, and technological innovation. Moreover, it represents an ideal sector for long-term special Treasury bond investments.

However, low-carbon heating (including cooling) remains a formidable challenge in constructing a new energy system and achieving the dual carbon goals. The current obstacles and development opportunities faced by the heating industry closely resemble those encountered by the power industry during its early stages of reform and development. The historical evolution of China's power industry, marked by reform, development, and innovation, offers particularly valuable insights for the heating sector. Establishing a dedicated ministerial-level department to oversee the advancement, innovation, and reform of the heating (cooling) industry is essential. Clean and renewable energy sources such as geothermal, nuclear, and solar power, combined with technological advancements like heat pumps, thermal storage, and smart heating systems, will serve as the primary technical foundations for achieving clean, low-carbon, safe, and affordable heating solutions.

Abbreviations

COP	Coefficient of Performance
KWH	Kilo Watt Hour
SPIC	State Power Investment Corporation Limited
SINOPEC	China Petroleum & Chemical Corporation
CNPC	China National Petroleum Corporation
TCE	Ton of Standard Coal Equivalent
HTGR	High Temperature Gas-cooled Reactor

Author Contributions

Dian Yi is the correspondence author. She was the sole author of the first draft accepted. Binghua Wang was the supervisor of the whole research, and guided Dian Yi to revise the part 4 and 5 substantially after the initial acceptance of the paper according to the requirements of the reviewer. The authors read and approved the final manuscript.

Conflicts of Interest

I disclosed no relevant relationships.

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