A coupling energy system of 10 clean-energy heating systems: A case study in Shandong province in China

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A coupling energy system of 10 clean-energy heating systems: A case study in Shandong province in China

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ABSTRACT
A variety of clean-energy heating systems were applied in China with multiple energy systems complementing each other according to local conditions. The purposes are pushing forward a supply-side structural reformation; coordinating the utilization of waste heat in high energy-consuming enterprises; realizing the energy cascade use; improving the ecological environment. This paper introduces a coupling energy station of 10 new clean-energy heating systems located in the central city district in Jinan. It could make full use of renewable energy and ensure high-quality heating in winter, increase energy utilization efficiency, replace fossil fuels, and reduce primary energy consumption. Furthermore, it can make up for the deficiency of a single system and reduce the emissions from fossil fuels. After comparing the heating parameters, the authors got the conclusions that the heating area of this new energy system is equal to the traditional coal system burning 9,508.032 tons of standard coal, which means in each heating season, about 7,233.33 × 10^7 m^2 of waste gases, 45.64 tons of SO_2 emissions, 69.586 tons of NO emissions, and 139.52 tons of soot emissions will be avoided. So, this new energy heating system is safe, stable, energy-saving, environmentally friendly, and effective, which can completely replace the heating system of traditional coal-fired boilers.

1. Introduction
In the twentieth century, the world population quadrupled and energy requirement escalated 16 times (V. Kamat 2007). Furthermore, the usage of fossil fuels such as gasoline, coal, and natural gas has risen the number of greenhouse gases (GHGs) which is pernicious to the environment and human health (Caliskan and Hepbasli 2010). The discharge of carbon dioxide (CO_2) and other GHGs due to human activity is increasing the global average surface air temperatures, disordering weather modes, and acidifying the ocean (Stocker et al. 2014). So, energy and the way it is being produced are of great importance (Ali et al. 2019). Energy consumption in China increased at an annual average rate of 7.2% during the period 1953–2006. Annual pollution emissions, measured by CO_2 in metric tons of carbon, grew from just 36.6 million in 1953 to 1625.7 million in 2006, showing a more than 40-fold increase integral (Ang 2009). For the above reasons, fossil energy conversion is to substitute conventional fuels with renewable, sustainable, and environmentally friendly/clean energy sources (Srirangan et al. 2012).

Today, energy availability is one of the important issues worldwide, especially in developing countries. Most countries conducted an extensive plan for providing the energy needed through new energies (Javad et al. 2019). The new energy referred to in this paper is clean energy, that is, green energy which does not emit pollutants and can be used for production and living directly. Green energy includes renewable energy and nonrenewable energy. Renewable energy can be recycled after consumption and produces little or no pollution. Nonrenewable energy can minimize environmental pollution during production and consumption, including low-polluting fossil fuels such as natural gas, etc. The term “renewable energy” includes all types of energies that are created as a result of the energy transfer of energy through different natural renewable processes (Marinescu 2019), which are solar energy, geothermal energy, tidal energy, wind energy, biomass, and so on. Some low carbon technologies such as photovoltaic panels, electric vehicles, and heat pumps as well as use of fuel cells have been developed with the aim to cut CO_2 emissions (Lyons et al. 2015). Suggested by diverse reasons, a lot of up-to-date researches propose an integrated system view including multiple energy carriers, instead of focusing on a single carrier (An, Qing, and Gedra 2003; Gil et al. 2003; Bakken and Holen 2004; Mello and Takaaki 2005; Shahidehpour, Yong, and Wiedman 2005; M Geidl and Andersson 2007; Martin Geidl and Andersson 2006). Multi-energy systems (MES) have become popular recently which can use multiple types of energy sources and which are capable of simultaneously providing heating, cooling and electrical energy (Luo et al. 2020). There are some coupling energy systems...
system examples worldwide, for example, residential PV-battery systems in Turkey, integrating multi-crystalline PV and lithium-ion battery (Üçtügen and Azapagic 2018); biomass gasification technology coupling with microturbine in Austria (Karellas, Karl, and Kakaras 2008); direct coupling of a solar-hydrogen system in Mexico (Arriaga et al. 2007); combining a reversible geothermal heat pump with thermal solar collectors for building heating and cooling in France (Trillat-Berdal, Souyri, and Achard 2007); 100% renewable energy supply in Brazil (Gils, Simon, and Soria 2017). It is a tendency to combine different energy systems together. Integrating renewable energies with the traditional fossil fuel systems will obviously decrease energy consumption and GHGs (Jahangiri, Shamsabadi, and Saghaei 2019). Comparing the above systems, the energy station in this paper is the first one to combine 10 different forms of energy sources into one heating system to realize energy complementarity. At the same time, the combination makes full use of renewable energy, combining renewable energy with natural gas and off-peak electricity. It reasonably adjusts the proportion of each heat source, reduces heating cost, and controls system investment. This new energy station is an innovative attempt for reducing the usage of coal and decreasing pollutant gas emissions from fossil fuels.

Shandong province is located on the eastern coast of China. Jinan is the provincial capital of Shandong province, as well as the political, economic, cultural, scientific, technological, educational, and financial center of the province. Jinan is located at 36 degrees 40 minutes north latitude, 117 degrees east longitude, and at the junction of the low mountain hills and flatslands (Cui et al. 2020). The annual average temperature is 13.6°C, the lowest temperature is in January which is around −1.9°C, the highest temperature is in July which is around 27°C (Zhang, Peng, and Hiller 2008). The average annual rainfall is around 614 mm. Jinan belongs to a warm temperate continental monsoon climate zone with four distinct seasons, sufficient sunshine and rich geothermal resources, which provides a benefit for developing geothermal energy and solar energy. Solar energy is significantly one of the most encouraging solutions for the world energy problem (Buker and Riffat 2015). Jinan is a typical energy-consuming city, which has formed an energy consumption structure of generally coal, supplemented by oil and electricity. Coal is widely used for industrial processes, especially in winter (Gu et al. 2014). The annual coal consumption of Shandong province is 3.73 × 106 tons which ranked first in coal consumption in China in 2013 (Pu et al. 2017). Coal accounts for 70% of all energy consumed in Jinan. Coal combustion will lead to increased concentrations of NOx, SO2 and particulate matter (Yang et al. 2007). In recent years, with the strengthening of government environmental protection measures, the coal consumption in 2017 decreased by 1.3 million tons compared with 2012. From 2018 to 2020, the total coal consumption in Jinan city will be controlled within 17.14 million tons, 17.03 million tons and 16.92 million tons, respectively (Government, Jinan People’s n.d.).

Environmental air pollution in Jinan is relatively serious. The SO2, soot, and dust caused by coal combustion have been the dominant factors that have affected air quality for a long time. During 2011–2015, the average density of daily particulate matter ≤10 μm (PM10) was 169 μg/m3, fine particulate matter (PM2.5) was 100 μg/m3, sulfur dioxide (SO2) was 77 μg/m3 and nitrogen dioxide (NO2) was 54 μg/m3 (J. Zhang et al. 2017).

In recent years, the infrastructure construction of central heating in Jinan has developed rapidly. A central heating system has been established, which is mainly composed of boiler houses with combined heat and power generation and supplemented by regional coal-fired hot water boiler houses. In order to solve the two urgent problems of “energy crisis” and “environmental pollution”, this new energy heating station was designed. The new energy heating station includes the mentioned 10 new energy systems, which are full-premixed condensing natural-gas hot water boilers system, primary sewage source heat pump system, low-temperature phase change heat storage system for air source heat pump, electrode boiler heat storage system, molten salt thermal storage system, noninterference geothermal heating system, cold water phase change energy heat pump system, heating cable system, solar photovoltaic power generation system, and long-distance pipeline heating exchange system with the utilization of waste heat in power plants. The design heating area of this new energy station is to serve a community that is 700,000 m².

2. Methodology

In the present study, the applied methodologies include the description of each energy system which is explicitly defined in detail in section 2.1, and the data study which is explicitly defined in detail in section 2.1.

2.1. Description of the 10 energy systems

2.1.1. Full-premixed condensing natural-gas hot water boilers system

Basic introduction: This new type of natural-gas hot water boilers system combines the technologies of fully premixed technology and condensing technology together. The system adopts six boilers and their supporting heating and power facilities. The power of each boiler is 2200 kW (rated power according to manufactory specifications), so the maximum power of the total system can reach 13200 kWh, which can meet the heating requirements of more than 170,000 m².

Operating principle: This system is designed as an atmospheric-pressure interval heating system. The heat exchanges through the original plate heat exchanger. The fully premixed technology is a new burning method that mixes the air and methane firstly before the burning so that does not need any more air during the burning process. The condensing technology is to use the energy which was released from the condense process from water vapor becoming water. The atmospheric-pressure system reduces the pressure of the boiler body, so that weakens the risk of exploding due to the overpressure. The boiler uses 2–3 kpa civil low-pressure gas.

System features: The advantage is that the boiler can fully recover the heat from the flue gas. From the perspective of the design, there is no waste of energy in this system because the boiler will start or stop its procedure according to the actual heat demand. Comparing to the traditional boiler, it can save 20% of the fuel cost. This system is super safe with a total
intelligent operation, without noise and pollution. The condensing boiler can realize three main achievements of low nitrogen emission, high condensing efficiency, and long service life at the same time. The design temperature of the supply and return water of the heating system is 60°C/45°C, and the design pressure is 1.6 MPa.

### 2.1.2. Primary sewage source heat pump system

Basic introduction: The sewage source heat pump system is the technology that converts the low-quality heating source from civil sewage and groundwater to high-quality heating energy such as electricity. The designed heating area is 100,000 m², and the actual heating area is 120,000 m². The system overcomes the obstacle of extracting water from long distances.

System features: The whole operation of the equipment has no combustion so it has zero-emission. The system can save 75% of energy consumption, which is in line with the development direction of energy-saving, environmental protection, and circular economy advocated by the country. It is the only system that realizes the dual supply of heating and cooling in this energy station.

Operating principle: The sewage source heat pump system takes sewage as the low-temperature heat source and uses heat pump technology to recover or extract the low-temperature heat energy from sewage to heat and cool buildings. Sewage includes untreated raw sewage from municipal pipe networks and sewage treatment plants. The design temperature of the supply and return water of the heating system is 53°C/45°C, and the design pressure is 1.6 MPa.

### 2.1.3. Low-temperature phase change heat storage system for air source heat pump

Basic introduction: This system is a new clean energy system that includes an air source heat pump and a medium/low-temperature polymer heat storage device. The actual heating area for this system is 100,000 m².

Operating principle: In the valley-electricity-consumption period at night, the heat storage heat pump is turned on to store heat in the heat storage device, and the direct heat pump is turned on meanwhile to provide heat to users; during the daytime peak-electricity consumption period and the high-electricity consumption period, the system extracts heat from the heat storage device to users, the heat pump is turned off at the same time. The system uses a medium and low-temperature macromolecule heat storage device. This system combines the benefits of the high efficiency of the air source heat pump and the low price of the valley-electricity-consumption period through the medium/low-temperature-polymer energy storage device, which reduces the operating cost of the system, and responds to the national policy of "replacing coal in electricity" and the electricity policy of "cutting peak and filling valley". The design temperature of the supply and return water of the heating system is 53°C/45°C, and the design pressure is 1.6 MPa.

### 2.1.4. Electrode boiler heat storage system

Basic introduction: This system includes four sets of 8 MW electrode hot water boilers, five 357 m³ volume high-temperature pressurized hot water storage tanks, and associated heating and power facilities. The maximum heat output of this system can reach 32 MW, which can meet the heating requirements of 300,000 m² of the community (according to the Chinese design specification of heating pipe network).

System features: This system balances the load difference between peak and valley consumption, makes full use of the cheap valley electricity, reduces the operation cost. The operation automation degree is high. There is no noise, no pollution, no fire during the operation process. Water is the heat medium. The sensible heat of water is used to store heat energy. The method is simple, clean, and low maintenance cost.

Operating principle: The electrode boiler heat storage system adopts 10KV high voltage electrode hot water boilers as the heat source. In the valley-electricity-consumption period at night, it makes use of the abundant off-peak electricity for heat storage and generates 130°C hot water used for external heating. In the peak-electricity consumption period during the daytime, the electric boilers are turned off. The heat stored by electrode boilers during the valley period will be used to heat the building. The design temperature of the supply and return water of the heating system is 75°C/45°C, and the design pressure is 1.6 MPa.

### 2.1.5. Molten salt thermal storage system

Basic introduction: This technology is an electronic heating technology that is based on molten salt sensible heat storage. The actual heating area of this system is 25,000 m². The heat storage scale is 12.3 MWh. In the valley-electricity-consumption period at night, the molten salt thermal storage is heated by electricity and then stores energy through the heat exchanger during the daytime.

Operating principle: The energy storage medium of this system is ternary molten salt. The molten salt thermal storage system is only turned on during the valley-electricity-consumption period (23:00–7:00) for heat storage, at the same time it provides heat to the extremity. The melting temperature of the high-temperature molten salt is between 190°C and 400°C. After the first heat exchange between the salt and water, the temperature becomes to 180–390°C, after the second heat exchange between the salt and water, the water supply temperature becomes 100°C, and the return water temperature becomes 80°C. After the final heat exchange through the secondary plate heat exchanger, the supply and return water temperature is 75°C/45°C, and the system will provide terminal heat to the collector and divider. The molten salt thermal storage system effectively overcomes the problem of the large volume of traditional water heat storage system. It has the function of cutting peaks and filling valleys then promoting the consumption of surplus electricity. The molten salt thermal storage system can effectively reduce carbon emissions, it is highly consistent with the direction of energy development. The design pressure of the heating system is 1.6 MPa.

### 2.1.6. Noninterference geothermal heating system

Basic introduction: Geothermal energy is a renewable energy source from the deep earth, which originates from the molten magma and radioactive materials contained in the earth. The principle of this technology is to drill a hole in the deep rock layer until reaching the high-temperature rock layer. A metal
exchanger will be installed in the hole. Some oil (heating medium) will be injected into the metal exchanger. The heat exchange will occur between the heating medium and the rock layer. The designed heating area of the system is 10,000 m², but the actual heating area is about 20,000 m². So, this system has truly realized green heating, energy-saving, and emission reduction.

Operating principle: The metal heat exchanger is installed in the drilling hole in the high-temperature rock. The hot oil medium is injected into the heat exchanger. Heat is exchanged with the underground lithosphere through a hot medium, and then it provides heat to buildings on the ground. This system truly realizes "heat extraction without water extraction".

System features: There are lots of advantages of this system, such as widely applicable, safe and reliable operation, long system life, economical operation, water conservation, environmental protection, high efficiency and energy saving, clean and green. The design temperature of the supply and return water of the heating system is 55°C/45°C, and the design pressure is 1.6 MPa.

2.1.7. Cold-water phase change energy heat pump system
Basic introduction: The design heating area of this system is 7,000 m² and the actual heating area is 10,000 m². Under the pressure of the water pump, the 0°C water enters the cold water phase change energy unit from the low-temperature water tank, releases the latent heat from its phase change, and becomes a 0°C ice water mixture, and then returns to the water tank through the pipeline.

System features: The cold-water phase change energy heat pump system runs stably and efficiently, and its application scope covers almost all forms of buildings. Moreover, the equipment runs without combustion during the whole process with zero emissions. It is an ideal renewable clean-energy heating and cooling technology with good social benefits.

Operating principle: The heat extracted from cold water phase change energy storage technology is equivalent to 16 times of the traditional water source heat pump technology, and the heating area can reach 16 times of the original. This means that the use of water source heat pump heating technology will no longer be limited by water source and water volume. This technology can be upgraded in the "no water" zone and achieve cold and warm supply. The system uses a very small amount of water and extracts a huge amount of latent heat from solidification to heat and cool buildings. The design temperature of the supply and return water of the heating system is 53°C/45°C, and the design pressure is 1.6 MPa.

2.1.8. Heating cable system
Basic introduction: The heating area of this system is 300 m² and the energy efficiency ratio is 0.95. Half of the heat source of the heating cable is electricity, and the temperature is between 40°C and 60°C. Through contact conduction, the surrounding cement layer is heated, and then the heat is transferred to the floor or tile. Another half of the heat source is the 7–10 μm far infrared rays that are most suitable for the human body after the heating cable is electrified and is radiated to the human body and the surrounding space.

System features: The heating cable is made of a cable structure and uses electricity as the energy source. According to the power grid operation, the system adjusts the demand. There are few operation and maintenance works required in this system.

Operating principle: The heating cable uses alloy resistance wires to conduct electricity and heat to achieve the effect of heating or heat preservation. There are usually single and double conductors called heating cables. This system buries the heating element, heating cable, and energy storage tube under the floor and converts all electrical energies directly into thermal energy. The system uses temperature sensors to set the heating temperature.

2.1.9. Solar photovoltaic power generation system
Basic introduction: The solar panels are located on the roof of the energy station, covering an area of 1,000 m² and with a construction scale of 80 kW. This system could generate about 272 kWh per day, about 8160 kWh per month, and 97 MWh per year.

System features: This system is easy to install, reliable, stable, and long-time depreciating. The life of the solar photovoltaic power generation system is 25 years, so the total power generation in 25 years is about 2.425 GWh from the predicted calculation.

Operating principle: Photovoltaic power generation is based on the principle of the photovoltaic effect, using solar cells to directly converts solar energy into electrical energy.

2.1.10. Long-distance pipeline heating exchange system with the utilization of waste heat in power plants
Basic introduction: This system is a high-temperature and long-distance heat transmission pipe network system, which uses the waste heat from a power plant in Jinan. The heating area is 800,000 m². As a waste heat utilization project of a power plant, this system is a successful case of energy cascade utilization and coal substitution. This system can be used as a backup system of the new energy heating system and can also realize joint supply in a double heating capacity if the new energy heating system runs stably.

System features: This system uses six plate heat exchangers in parallel operation. The capacity of each heat exchanger is 8 MW. The heat transfer area of each plate heat exchanger is 250 m². The heat exchanger in this system has the advantages of high heat exchange efficiency, low heat loss, compact structure, lightweight, small floor area, easy installation and cleaning, wide application, long service life, and so on. The temperature of the supply and return water for the long-distance pipeline is 90/50°C. After the high-temperature water passes through the heat exchange, the temperature of the supply and return water in the secondary network is 60°C/45°C.

2.2. Data of the 10 sets of new energy systems
2.2.1. Process flow chart of the energy station
These 10 energy systems work separately and supply the heat and cold together to users. The process flow chart please is shown in Figure 2.1.
2.2.2. Process flow chart of the energy station

(1) The basic strategy:

The different heating period temperature divisions in Jinan: Initial period of heating (0–4.9°C), Cold period (0–14.9°C), Extremely cold period (−15°C to -19.9°C), Final period of heating (0–4.9°C). The specific equipment operation conditions are shown in the Appendix (Table A1).

3. Results and discussion

This section is divided by subheadings. It contains a concise description of the experimental results, their interpretations as well as the experimental conclusions.

3.1. The comparison of data in this new energy station

3.1.1. The comparison of actual operating data and design rated parameters

(2) The design rated parameters

The heating area of this energy station is 700,000 m², the design amount of replenishment water is 361.6 m³/h, the design power consumption is 43,185.7 kWh, the design index of heating is 45 W/m².

So, the maximum heat consumption ($Q_{\text{max}}$) is:

$$Q_{\text{max}} = 700000 \times 45 = 31.5MW = 113.4GJ/h$$  \hspace{1cm} (1)

The outdoor design temperature for heating is −5.3°C, the average outdoor temperature is 2.05°C, the indoor design temperature for heating is 18°C.

So, the average heating load factor ($q_v$) is:

$$q_v = (18 - 2.05)/(18 - (-5.3)) = 0.685$$  \hspace{1cm} (2)

The average heat consumption ($Q_{\text{avg}}$) is:

$$Q_{\text{avg}} = Q_{\text{max}} \times q_v = 113.4 \times 0.685 = 77.68GJ/h$$  \hspace{1cm} (3)

The minimum heating load factor ($q_{\text{min}}$) is:

$$q_{\text{min}} = (18 - 5)/(18 - (-5.3)) = 0.558$$  \hspace{1cm} (4)

The minimum heat consumption ($Q_{\text{min}}$) is:
3.2.2. The design rated parameters of this new energy station.

<table>
<thead>
<tr>
<th>Rated water supply</th>
<th>Instantaneous maximum water recharge (m³/h)</th>
<th>Rated electricity consumption (per hour, maximum) (kWh)</th>
<th>The average heat consumption (GJ/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>361.6</td>
<td>43,185.7</td>
<td>77.68</td>
</tr>
</tbody>
</table>

\[ Q_{\text{min}} = Q_{\text{max}} \times q_{\text{min}} = 113.4 \times 0.558 = 63.28 \text{GJ/hEq} \] (5)

So, the design rated parameters are shown in Table 3.1.

(2) The actual running data

The actual heating area of the new energy station is 551 km². For the convenience of comparing the actual operating parameters with the design rated parameters, the data listed in Table A2 are calculated according to the heating area of 551 km². The data come from the actual operation record data of Jinan Ruiguan energy station of Shandong Ruiguan Thermoelectric Limited Co., Ltd. The heating period is from 01/12/2019 to 31/12/2019.

(3) The comparison of actual operating data and design rated data

Based on the above tables and data, under the same heating area, the actual operating heat consumption of the new energy system is slightly higher than the design rated heat consumption; the actual operating water consumption is lower than the design rated water consumption; the actual operating electricity consumption is slightly higher than the design rated electricity consumption.

3.2. The comparison of data between this new energy station and traditional coal-fired heating system

3.2.1. Energy consumption analysis

Jinan is a typical energy-consuming city, which has formed an energy consumption structure of generally coal, supplemented by oil and electricity. In 2019, coal consumption in Shandong province accounts for 68.1% of total energy consumption, of which power generation coal accounts for 48.5%, coal for heating accounts for 19.2%, coal for gas for 0.4%, and other coal consumption accounts for 29.3% (Statistics, Shandong, n. d.). So now coal is still the main energy source in China. Energy consumption is a problem in the process of traditional energy production. It is good to control and eliminate energy consumption in each link through effective technology and management means. This new energy station uses new energy sources such as air sources, sewage sources, and solar energy according to the weather features and resource situation in Jinan.

3.2.2. Resource-saving measurements of this new energy station

The main energy-saving measures of this new energy station are heat pump technology, natural gas technology, and electric heat storage technology.

The main measures are as follows:

1. Natural-gas hot water boilers system
   ① The use of heat pipe preheater can effectively reduce the exhaust temperature.

   ② The harmful gas in the smoke can be condensed and flow into the pool.

   ③ The condensing-gas water heater improves thermal efficiency, reduces pollution, and saves energy consumption.

2. Primary sewage source heat pump system

   ① In winter, the temperature of sewage is higher than the ambient air temperature, so the evaporation temperature of the heat pump cycling system increases, and the energy efficiency ratio also increases.

   ② There is no burning process and smoke exhaust pollution.

   ③ The urban sewage heat pump system only consumes a small amount of electricity in winter.

   ④ The average temperature of original sewage diversion can reach 17°C, which is fully suitable for the use of sewage source heat pump.

   ⑤ Based on the constant properties of sewage, the heat pump unit runs more reliable and stable and has higher efficiency and economy.

   ⑥ The temperature of the sewage is relatively stable throughout the year, and its fluctuation range is much smaller than that of air. So, the sewage is a good heat source for a heat pump and a good cold source for air conditioners.

3. Air source heat pump system

   ① During 80% of the heating periods, where the ambient temperature is above 0°C, the heat pump is no longer in operation. Heat is taken from the heat storage system, and only the circulating water pump is in operation.

   ② In the valley-electricity-consumption period at night, the air source heat pump unit operates at 60°C, and part of the generated heat is stored in the heat storage system, when the temperature decreases to 55°C, the heat pump provides heat directly.

4. Electrode boiler heat storage system

   ① The heat storage system of the electrode boiler only accumulates heat in the valley-electricity-consumption period at night, and the steam with the output temperature of 130°C is returned to the electrode boiler at 90°C after heat exchange.

   ② During the daytime, the system is turned off. The water supply temperature at the secondary side of the terminal heat exchanger is 75°C, and the return water temperature is 45°C.

5. Molten salt thermal storage system

   ① Make use of the electricity in the valley-electricity-consumption period to heat molten salt at night and supplies energy through the heat exchanger during the day.

   ② This technology transfers the surplus power produced in the peak-electricity-consumption period, improves the stability of the power grid and usage rate of electricity.

   ③ Energy storage can be stored by heating molten salt with low-valley electricity at night, and energy can be
transferred through a heat exchanger during the day to realize heating demand.

6. Other measures

1. The auxiliary equipment is selected for being very high-efficient and energy-saving, such as variable frequency pumps and Y-series motors, etc.
2. The motor capacity of each auxiliary machine is reasonably chosen to avoid the phenomenon of exceeding energy supply and low efficiency.
3. The diameter of the hot water pipeline is carefully designed to ensure the flow rate of the medium meeting the specifications, and the working pressure dropping in the control station is compatible with the specifications of the pump.
4. The new energy station uses low-loss transformers.
5. The increase of the insulation thickness of the hot water pipe network appropriately reduces the loss of heat dissipation.

3.2.3. Analysis of heating effect of the new energy system

Table 3.3 shows under the same heating area, the supply and return water temperature of the new energy station comparing with the supply and return water temperature of the traditional coal-fired boiler room (data: 01/12/2019–31/12/2019). The data shown in Table 3.3 come from the actual operation record data of Jinan Ruiguan energy station of Shandong Ruiguan Thermoelectric Limited Co., Ltd.

The following comparison curves (Figures 3.4 and 3.5) show this tendency more clearly.

<table>
<thead>
<tr>
<th>Heating period (Date)</th>
<th>The supply water temperature of the new energy station (°C)</th>
<th>The return water temperature of the new energy station (°C)</th>
<th>The supply water temperature of the secondary network of the traditional coal-fired heating boiler room (°C)</th>
<th>The return water temperature of the secondary network of the traditional coal-fired heating boiler room (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>01/12/2019</td>
<td>46</td>
<td>41.13</td>
<td>49.6</td>
<td>40.6</td>
</tr>
<tr>
<td>02/12/2019</td>
<td>49.55</td>
<td>39.38</td>
<td>45.6</td>
<td>40.5</td>
</tr>
<tr>
<td>03/12/2019</td>
<td>45.1</td>
<td>39.73</td>
<td>48.4</td>
<td>42.5</td>
</tr>
<tr>
<td>04/12/2019</td>
<td>45.0</td>
<td>39.73</td>
<td>48.2</td>
<td>42.5</td>
</tr>
<tr>
<td>05/12/2019</td>
<td>49.78</td>
<td>40.95</td>
<td>46.1</td>
<td>40.8</td>
</tr>
<tr>
<td>06/12/2019</td>
<td>45.38</td>
<td>40.78</td>
<td>45.9</td>
<td>40.8</td>
</tr>
<tr>
<td>07/12/2019</td>
<td>42.95</td>
<td>37.53</td>
<td>44.9</td>
<td>40.1</td>
</tr>
<tr>
<td>08/12/2019</td>
<td>49.6</td>
<td>41.25</td>
<td>46.9</td>
<td>41.4</td>
</tr>
<tr>
<td>09/12/2019</td>
<td>49.58</td>
<td>41.46</td>
<td>46.8</td>
<td>41.3</td>
</tr>
<tr>
<td>10/12/2019</td>
<td>47.98</td>
<td>41.93</td>
<td>47.5</td>
<td>41.7</td>
</tr>
<tr>
<td>11/12/2019</td>
<td>46.4</td>
<td>42.58</td>
<td>47.8</td>
<td>42.3</td>
</tr>
<tr>
<td>12/12/2019</td>
<td>51.35</td>
<td>42.98</td>
<td>48.8</td>
<td>43</td>
</tr>
<tr>
<td>13/12/2019</td>
<td>51.6</td>
<td>43.71</td>
<td>49.3</td>
<td>43.6</td>
</tr>
<tr>
<td>14/12/2019</td>
<td>51.6</td>
<td>43.7</td>
<td>49.3</td>
<td>43.6</td>
</tr>
<tr>
<td>15/12/2019</td>
<td>50.58</td>
<td>43.3</td>
<td>48.8</td>
<td>43.3</td>
</tr>
<tr>
<td>16/12/2019</td>
<td>50.55</td>
<td>43.08</td>
<td>48.3</td>
<td>42.9</td>
</tr>
<tr>
<td>17/12/2019</td>
<td>50.75</td>
<td>42.45</td>
<td>48.2</td>
<td>42.6</td>
</tr>
<tr>
<td>18/12/2019</td>
<td>47.45</td>
<td>42.43</td>
<td>48</td>
<td>42.3</td>
</tr>
<tr>
<td>19/12/2019</td>
<td>51.45</td>
<td>42.68</td>
<td>48.0</td>
<td>42.3</td>
</tr>
<tr>
<td>20/12/2019</td>
<td>47.08</td>
<td>42.13</td>
<td>47.7</td>
<td>42.0</td>
</tr>
<tr>
<td>21/12/2019</td>
<td>47.9</td>
<td>43.08</td>
<td>48.5</td>
<td>42.9</td>
</tr>
<tr>
<td>22/12/2019</td>
<td>48.8</td>
<td>42.63</td>
<td>47.9</td>
<td>42.4</td>
</tr>
<tr>
<td>23/12/2019</td>
<td>44.25</td>
<td>42.25</td>
<td>47.6</td>
<td>42.1</td>
</tr>
<tr>
<td>24/12/2019</td>
<td>48.23</td>
<td>42.95</td>
<td>49.3</td>
<td>43.3</td>
</tr>
<tr>
<td>25/12/2019</td>
<td>47.33</td>
<td>41.8</td>
<td>47</td>
<td>41.5</td>
</tr>
<tr>
<td>26/12/2019</td>
<td>46.68</td>
<td>43.23</td>
<td>49.2</td>
<td>43.1</td>
</tr>
<tr>
<td>27/12/2019</td>
<td>50.65</td>
<td>44.5</td>
<td>50.7</td>
<td>44.2</td>
</tr>
<tr>
<td>28/12/2019</td>
<td>50.78</td>
<td>44.68</td>
<td>50.4</td>
<td>44.5</td>
</tr>
<tr>
<td>29/12/2019</td>
<td>47.83</td>
<td>44.73</td>
<td>50.2</td>
<td>44.5</td>
</tr>
<tr>
<td>30/12/2019</td>
<td>45.58</td>
<td>44.26</td>
<td>50.1</td>
<td>44.1</td>
</tr>
<tr>
<td>31/12/2019</td>
<td>46.95</td>
<td>44.08</td>
<td>49.6</td>
<td>43.4</td>
</tr>
</tbody>
</table>

Based on the above data, under the same heating area, the difference of the supply and return water temperature between the new energy station and the traditional coal-fired boiler system is very small, yielding the conclusion that, the heating effect of the new system is the same as for the traditional system.

3.2.4. The comparison of coal consumption between the new energy heating system and the traditional system

The total coal consumption reduction per heating season is calculated as follows: In Jinan, the outdoor design temperature for heating is −5.3°C, the average outdoor temperature is 2.05°C, the indoor design temperature for heating is 18°C, and the number of days in the heating period is 120 days. The index of design load for heating is 45 W/m², and the total heating area is 700 km².

The average heating load factor is:

\[ k_{avg} = \frac{(18 - 2.05)}{(18 - (-5.3))} = 0.685 \] (6)

The minimum heating load factor is:

\[ k_{min} = \frac{(18 - 5)}{(18 - (-5.3))} = 0.0558 \] (7)

where 5°C is the average outdoor design temperature in Jinan during the heating period.

The maximum heat load is:

\[ Q_{max} = 45(W/m^2) \times 700000m^2 = 31500000W = 31.5MW \]
\[ = 113.4GJ/h \] (8)
Table 3.4. Coefficient value of excess air of furnace (a).

<table>
<thead>
<tr>
<th>The type of furnace</th>
<th>Hand burning boiler</th>
<th>Chain-grate boiler</th>
<th>Pulverized coal-fired boiler</th>
<th>Boiling boiler</th>
<th>Oil boiler</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>1.40</td>
<td>1.30</td>
<td>1.2–1.25</td>
<td>1.05–1.1</td>
<td>1.15–1.2</td>
</tr>
</tbody>
</table>

Table 3.5. Coefficient value of fuel (b).

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Soft coal</th>
<th>Anthracite</th>
<th>Lignite</th>
<th>Oil</th>
</tr>
</thead>
<tbody>
<tr>
<td>b</td>
<td>0.08</td>
<td>0.04</td>
<td>0.16</td>
<td>0.08</td>
</tr>
</tbody>
</table>

Table 3.6. \(D_{24}\) value of various furnace types.

<table>
<thead>
<tr>
<th>The furnace type</th>
<th>(D_{24}) (%)</th>
<th>The furnace type</th>
<th>(D_{24}) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hand burning boiler</td>
<td>15–25</td>
<td>Reciprocating boiler</td>
<td>15–20</td>
</tr>
<tr>
<td>Coal thrower boiler</td>
<td>25–40</td>
<td>Vibration boiler</td>
<td>20–40</td>
</tr>
<tr>
<td>Boiling boiler</td>
<td>40–60</td>
<td>Oil boiler</td>
<td>0</td>
</tr>
<tr>
<td>Pulverized coal-fired boiler</td>
<td>70–80</td>
<td>Natural gas boiler</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 3.7. Nitrogen contents of fuel (n).

<table>
<thead>
<tr>
<th>The name of the fuel</th>
<th>Percent nitrogen (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>0.5–2.5</td>
</tr>
<tr>
<td>The inferior heavy oil</td>
<td>0.2–0.4</td>
</tr>
<tr>
<td>Ordinary heavy oil</td>
<td>0.08–0.04</td>
</tr>
<tr>
<td>High quality heavy oil</td>
<td>0.005–0.08</td>
</tr>
</tbody>
</table>

\((1 \text{ MW} = 3.6 \text{ GJ/h})\)

The average heat load is

\[Q_{\text{avg}} = 113.4 \text{ GJ/h} \times 0.685 = 77.68 \text{ GJ/h}\] (9)

The minimum heat load is

\[Q_{\text{min}} = 113.4 \text{ GJ/h} \times 0.558 = 63.28 \text{ GJ/h}\] (10)

The average total heat consumption per heating season is

\[Q_1 = 120 \times 24 \times 77.68 = 223718.4 \text{ GJ}\] (11)

The calorific value of standard coal is 29.4 MJ/kg, then the mass per MJ is

\[(1/29.4) = 0.034 \text{ kg/(standard coal)/MJ}\] (12)

The mass of standard coal burned in order to produce 1MJ of heat is

\[m_c = 0.034/0.8 = 0.0425 \text{ kg/MJ}\] (13)

where the heat efficiency is 80%.

When the heating capacity is 223,718.4 GJ, the coal consumption of the coal-fired boiler is

\[m_c = 223718.4 \times 10^3 \text{ MJ} \times 0.0425(\text{kg/MJ}) = 9508032\text{kg} = 9508.032\text{tons} = 0.95\text{ten thousand tons}\] (14)

According to the above calculation results, comparing to the coal-fired boiler system under the same heating amount, the total coal consumption of this energy station in each heating season is 9,508.032 tons (standard coal), which is a significant energy-saving effect.

3.2.5. The calculation of pollutant emissions

Formulas for calculating the amount of smoke, soot, sulfur dioxide, and nitrogen oxide emissions from coal-fired boilers (according to the environmental statistics manual).

The average total heat consumption per heating season is 223718.4 GJ From Eq.(11)

When the heating capacity is 223718.4 GJ, the coal consumption of the coal-fired boiler is 0.95 ten thousand tons From Eq.(14)

The formula for calculating the amount of waste gas from burning coal is

\[V = (\vartheta + b) \times k \times Q_1 \times B = (1.25 + 0.08) \times 1.1 \times 5200 \times 9508.032 = 7233.33 \times 10^3 \text{ m}^3\] (15)

where \(V\) – the amount of waste gas from burning coal, \(\vartheta\) – the excess air ratio in boiler chamber (according to Table 3.4, the pulverized coal-fired boiler is 1.25),

\(b\) – the ratio of the fuel (according to (Table 3.5), the bituminous coal is 0.08)

\(k = 1.1\) (correction factor)

\(Q_1\) – low calorific value of standard coal, \(Q_1 = 5,200 \text{ kcal}\)

\(B\) – the amount of standard coal reduced (9,508,032 tons based on above calculation)

The formula of \(\text{SO}_2\) emissions from coal burning is

\[G = 2 \times 0.8 \times B \times S \times (1 - \eta) = 2 \times 0.8 \times 9508.032 \times 0.01 \times (1 - 0.7) = 45.64\text{tons}\] (16)

where \(B\) – the amount of standard coal reduced (9,508,032 tons based on above calculation).

\(S\) – the content of total sulfur in standard coal (Select 1%)

\(\eta\) – sulfur dioxide removal rate (Select 0.7)

The calculation of soot is

The calculation formula of soot in pulverized coal-fired boiler, boiling boiler, and coal thrower boiler is

\[G = B \times A \times d_h \times (1 - \eta)/(1 - C_{sof}) \times 1000 = 9508.032 \times 0.2 \times 0.75 \times 0.1 \times 1000/0.92 = 155.022\text{tons}\] (17)

The calculation formula of soot in other types of boilers

\[G = B \times A \times d_h \times 1000 = 9508.032 \times 0.2 \times 0.75 \times 1000 = 1426.20\text{tons}\] (18)

The calculation of the soot is: (Select 155.022 tons)

\[Y = G \times (1 - \eta) = 155.022\text{tons} \times 1000 \times (1 - 0.1) = 139.52\text{tons}\] (19)

where \(G\) – the amount of soot produced by burning coal (kg),

\(B\) – the amount of standard coal reduced (9,508,032 tons based on above calculation).

\(A\) – the ash content of coal, \(A = 26.99\%\) in normal analysis, the ash content is 20% in this calculation.
\(d_f\) – the percentage of soot in ash (according to Table 3.6, the pulverized coal-fired boiler is 75%).

\(C_f\) – the percentage of combustible matter in soot (the pulverized coal-fired boiler is 4–8%, boiling boiler is 15–25%).

\(\eta\) – the efficiency of the dust collector (90% in this project).

The calculation of NOx production of coal burning is

\[
G_{NOx} = 1.630 \times B \times \left( \beta \times n + V_y \times CNOx \times 10^{-6} \right) \\
= 1.630 \times 9508.032 \times 1000 \\
\times (0.25 \times 0.015 + 7.8936 \times 0.0000938) \\
= 69586.43 \text{ kg} = 69.586 \text{ tons}
\]  

(20)

where \(B\) – the amount of standard coal reduced (9,508.032 tons based on above calculation).

\(\beta\) – the conversion rate from N to NO in the fuel %, oil burning boiler 32–40%, pulverized coal-fired boiler (20–25%, 25% in this project).

\(n\) – the N content of the fuel (according to (Table 3.7), select 1.5%).

\(V_y\) – the amount of smoke produced by 1 kg fuel (standard m³/kg, select 7.8936 standard m³/kg in this project).

\(C_{NOx}\) – the concentration of NO produced when the fuel is burned (mg/standard m³, 93.8ppm = 93.8 mg/standard m³ in this project).

According to the above results, compared with the coal-fired boiler system with the same heating amount, the total reduced exhaust gases of burning coal of this energy station in each heating season is 723.33 \(\times 10^3\) m³, the total reduced SO\(_2\) emissions of this energy station in each heating season is 45.64 tons, the total reduced sulfur dioxide emissions of this energy station in each heating season is 69.586 tons, and the total reduced soot emissions of this energy station in each heating season is 139.52 tons. The environmental protection and energy-saving effect is very remarkable.

Tables 3.4–3.7 show some coefficient value.

The comprehensive heat index calculation formulas for the heating load and the calculation formulas of coal consumption and pollutant discharge adopted by the author in this paper are derived from:

“The design specification of urban heating pipe network”

“Design standards for energy conservation in civil buildings (heating and residential parts)”

“Energy conservation design standard for residential buildings in Shandong province”

“Design code for heating ventilation and air conditioning (gb50019–2003)”

“Environmental statistics manual” (Published by Sichuan Science and Technology Press, accessed in December 1985)

4. Conclusions

This paper is a case study of an energy station that combines 10 different energy forms. After the description of their running operation principles, the comparison between the actual operating data and rated data, and the comparison between the actual data from the energy station and the traditional coal-fired system, conclusions were obtained as follows:

(1) According to the comparison between the actual operating heat consumption and the rated heat consumption in Figure 3.1, under the same heating area, the actual operating heat consumption of the new energy station is slightly higher than the rated heat consumption.

(2) According to the comparison between the actual operating water consumption and the rated water consumption in

![Figure 3.1](image1.png) The comparison of actual operating heat consumption and design rated heat consumption.

![Figure 3.2](image2.png) The comparison of actual operation water consumption and design rated water consumption.
Figure 3.2, under the same heating area, the actual operating water consumption of the new energy station is lower than the rated water consumption.

(3) According to the comparison between the actual operating electricity consumption and the rated electricity consumption in Figure 3.3, the actual operating electricity consumption is higher than the rated electricity consumption under the same heating area.

(4) According to the comparison between the supply and return water temperatures of the new energy station and the supply and return water temperatures of the traditional coal-fired boiler room in Figures 3.4 and 3.5, the heating effect of the new system is the same as for the traditional system.

(5) According to the above calculation results (Eq.(6)- Eq. (14)), compared with the coal-fired boiler system with the same heating amount, the total coal consumption of this energy station in each heating season is reduced: 9508.032 tons (standard coal), which means 9508.032 tons of standard coal can be saved using the new energy station instead of the traditional coal-fired system.
(6) According to the above calculation results (Eq.(15)-Eq.(20)), compared with the coal-fired boiler system with the same heating area of 700,000 m², if the coal-fired system is chosen as the heat source, the total amount of exhaust gas in each heating season will be 7233.33 × 10^7 m³, the total SO_2 emissions will be 45.64 tons, the total NO_x emissions will be 69.586 tons, and the total soot emissions will be 139.52 tons. So, if the new energy station can be used instead of the coal-fired system, the above-mentioned pollution discharge can be avoided completely.

(7) This system is worth popularizing in northern China where solar energy resource is abundant, heat supply-demand is high and power supply is relatively surplus.

(8) The solar photovoltaic power generation system in this energy station makes full use of solar energy, which is the concrete embodiment of the diversified development of the solar energy industry.

(9) The power plant waste heat utilization heating system in this energy station has fully realized the resource utilization of industrial waste steam and power plant waste heat.

To sum up, we come to the conclusions that the operation of the new energy heating system is safe, stable, energy-saving, environmentally friendly, and effective, which can completely replace the heating system of traditional coal-fired boilers, which can save 9,508.032 tons of standard coal in each heating season, which will be an efficient step of decreasing the coal consumption. The new energy supply system completely corresponds to the environmental protection index and the energy supply index, and the new energy station is the best choice for the energy supply enterprise.

Disclosure statement
The authors declare that there is no conflict of interests regarding the publication of this article.

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References


Table A1. The specific operation conditions of different equipment.

<table>
<thead>
<tr>
<th>Operating equipment</th>
<th>Opening phase</th>
<th>Capacity of the equipment</th>
<th>Characteristics of energy conservation and environmental protection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full premixed natural-gas hot water boilers system</td>
<td>Initial period of heating</td>
<td>100%</td>
<td>The exhaust temperature is reduced because of the usage of heat-pipe preheater. The condensing furnace effectively controls the harmful gases in the flue gas. Since the condensing water heater reduces the flue gas below the dew point temperature, so most acidic substances such as SO₂ and CO₂ can be condensed well, therefore reduce the pollution.</td>
</tr>
<tr>
<td></td>
<td>Cold period</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Extremely cold period</td>
<td>100%</td>
<td>In winter, the temperature of sewage is higher than the ambient air temperature, so the evaporation temperature of the heat pump cycling system is increased, and the energy efficiency ratio is also increased.</td>
</tr>
<tr>
<td></td>
<td>Final period of heating</td>
<td>100%</td>
<td>The air source heat pump uses the contact of refrigerant and air, through the carrier medium with a freezing point below zero to efficiently extract low-grade heat energy in air with high humidity in a low-temperature environment. By inputting a small amount of high-grade energy into the air source heat pump unit, low-temperature environment high-grade heat energy is transferred to the building for heating and hot water. Make use of electricity in valley-electricity-consumption period to store the heat and release it during the day time. Energy saving and emission reduction is the highlight.</td>
</tr>
<tr>
<td>Primary sewage source heat pump system</td>
<td>Initial period of heating</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cold period</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Extremely cold period</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Final period of heating</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>Low-temperature phase change heat storage system for air source heat pump</td>
<td>Initial period of heating</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cold period</td>
<td>The outlet water temperature is adjusted by the system</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Extremely cold period</td>
<td>According to the capacity</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Final period of heating</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>Electrode boiler heating storage system</td>
<td>Initial period of heating</td>
<td>The outlet water temperature is adjusted by the system</td>
<td>Make use of the electricity in valley-electricity-consumption period to heat molten salt at night and supplies energy through the heat exchanger during the day. This technology transfers the surplus power produced in peak-electricity-consumption period, improve the stability of power grid and usage rate of electricity. The system can store energy by heating molten salt with low-valley electricity at night, and energy can be transferred through heat exchanger during the day to realize heating demand. The temperature of layer increases gradually from the top to bottom. The temperature increases by 3°C for every 100 m drop generally, which is called geothermal gradient. The development of geothermal energy is mainly in the upper part of the heating layer.</td>
</tr>
<tr>
<td></td>
<td>Cold period</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Extremely cold period</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Final period of heating</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>Molten salt thermal storage system</td>
<td>Initial period of heating</td>
<td>100%</td>
<td>Make use of the electricity in valley-electricity-consumption period to heat molten salt at night and supplies energy through the heat exchanger during the day. This technology transfers the surplus power produced in peak-electricity-consumption period, improve the stability of power grid and usage rate of electricity. The system can store energy by heating molten salt with low-valley electricity at night, and energy can be transferred through heat exchanger during the day to realize heating demand. The temperature of layer increases gradually from the top to bottom. The temperature increases by 3°C for every 100 m drop generally, which is called geothermal gradient. The development of geothermal energy is mainly in the upper part of the heating layer.</td>
</tr>
<tr>
<td></td>
<td>Cold period</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Extremely cold period</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Final period of heating</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>Noninterference geothermal heating system</td>
<td>Initial period of heating</td>
<td>100%</td>
<td>With non-clean water as the cold and heat source, driven by electricity, the equipment runs without combustion and emissions, which is an ideal renewable clean energy heating and cooling technology.</td>
</tr>
<tr>
<td></td>
<td>Cold period</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Extremely cold period</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Final period of heating</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>Cold water phase change energy heat pump system</td>
<td>Initial period of heating</td>
<td>100%</td>
<td>Radiation instead of convection which reduces the amount of dust in the air.</td>
</tr>
<tr>
<td></td>
<td>Cold period</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Extremely cold period</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Final period of heating</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>Heating cable system</td>
<td>Initial period of heating</td>
<td>100%</td>
<td>Improve the quality of the high temperature hot water pipe network and reduce the amount of circulating water as much as possible.</td>
</tr>
<tr>
<td></td>
<td>Cold period</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Extremely cold period</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Final period of heating</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>Long-distance pipeline heating exchange system with the utilization of waste heat in power plants</td>
<td>Initial period of heating</td>
<td>The outlet water temperature is adjusted by the system</td>
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<td>Final period of heating</td>
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Table A2. The comparison of actual operating parameters and design parameter.

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<th>Date</th>
<th>Actual heating area (ten thousand m²)</th>
<th>Heat consumption (GJ)</th>
<th>Water consumption (m³/h)</th>
<th>Electricity consumption (kWh)</th>
<th>Calculation of heating area (m²)</th>
<th>Average stated heat consumption (GJ)</th>
<th>Average rated parameters (calculated rated parameters)</th>
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Design rated parameters: (calculated at 78.7% of the full load, because the actual heating area 551 km² accounts for 78.7% of the designed area 700 km²).
Figure A1. The air source heat pump system of this coupling energy system of Shandong Ruiguan Thermoelectric Limited Co., Ltd.

Figure A2. The solar photovoltaic power generation system of this coupling energy system of Shandong Ruiguan Thermoelectric Limited Co., Ltd.

Figure A3. The molten salt thermal storage system of this coupling energy system of Shandong Ruiguan Thermoelectric Limited Co., Ltd.

Figure A4. The long-distance pipeline heating exchange system of this coupling energy system of Shandong Ruiguan Thermoelectric Limited Co., Ltd.

Figure A5. The electrode boiler heat storage system of this coupling energy system of Shandong Ruiguan Thermoelectric Limited Co., Ltd.

Figure A6. The primary sewage source heat pump system of this coupling energy system of Shandong Ruiguan Thermoelectric Limited Co., Ltd.
Figure A7. The geothermal heating system of this coupling energy system of Shandong Ruiguan Thermoelectric Limited Co., Ltd.

Figure A8. The natural-gas hot water boilers system of this coupling energy system of Shandong Ruiguan Thermoelectric Limited Co., Ltd.

Figure A9. The cold water phase change of this coupling energy system of Shandong Ruiguan Thermoelectric Limited Co., Ltd.