Techno-Economic Comparison of Solar and Geothermal Energy-based Systems: A Case Study in Western Sichuan

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Abstract. The application of renewable energy can effectively alleviate energy shortages and environmental pollution. However, electric heating and traditional combustion heating are still widely used in western Sichuan. This paper analyzes a techno-economic comparison between a solar-air energy heating system (System 1) and a geothermal-air energy heating system (System 2) designed for Litang. First, the distribution of renewable energy in Litang is analyzed. The system devices and operating modes of the two systems are described. According to the system design results, the paper compares the initial cost, operation cost, and net present value (NPV) of the two systems. The results show that both schemes are feasible from the perspective of technical analysis. While System 2 has lower initial investment, operation cost and higher NPV, which meets the actual needs of the project and local development planning. Using geothermal resources for urban central heating can achieve good energy saving and emission reduction benefits, and provide a reference for improving the proportion of local renewable energy use and optimizing the energy structure. Keywords: Western Sichuan, Geothermal, Solar energy, Heating system, Techno-economic analysis.

1 Introduction

Currently, global temperatures have continued to increase due to the world’s increased use of fossil fuels [1–3]. With continued reliance on fossil fuels as the primary energy source, a 3°C or higher temperature increase is predicted by the end of this century. In addition to the temperature rise, the fossil fuels on which the world still depends for over 80% of its energy needs are finite and will be critically depleted within 50 years at current use levels [3, 4].

One way to solve these problems is to find environmentally friendly, economical, and safe energy. Natural energy which is naturally supplemented after use, such as solar energy, geothermal and biomass energy, is defined as renewable energy sources (RES) [5]. Solar energy is becoming widespread for electricity generation and heating. Although the areas exposed to the sun are extensive lands and do not depend on a specific source, their use has increased rapidly due to their practical application and high theoretical power potential [6]. Compared with solar energy, geothermal energy is independent of weather conditions and has great potential to become a reliable source [7]. Geothermal is a form of energy conversion
from the interior of the earth, which is cost-effective, sustainable and renewable energy [8, 9]. China has abundant geothermal resources, accounting for 1/6 of the world’s total. Developing geothermal is of critical importance to China’s energy mix restructuring and environmental protection [9, 10].

Over the years RES has evolved on many different fronts [11]. Its role is increasing also in the heating field. Francesca Ceglia et al. designed a renewable polygeneration system connected to a district heating and cooling network fed by geothermal well, which provided thermal energy for heating and cooling, and domestic hot water for a residential district located in the metropolitan city of Naples [12]. The design and thermal response modeling of a solar air heating system, which consists of an air vacuum tube solar collector and latent heat storage, was presented by Ciril Arkar et al [13]. In addition, ground source heat pump (GSHP), water source heat pump (WSHP), solar air collector and passive solar heating have been widely studied and applied in heating.

However, relying only on one kind of renewable energy could no longer meet the energy demands of any country. Hybrid renewable energy systems supply a comprehensive energy supply solution for the global energy market [14]. Through the realization of multi-energy collaborative optimization and complementarity, the advantages of different RES can be maximized, and energy consumption can be reduced [15].

On hybrid renewable energy system design and analysis, scholars have done the following research. Tian et al. studied a hybrid renewable energy system, consisting of a solar thermal system, seasonal thermal energy storage (STES), heat pump systems, and district heating network for a net zero energy community has been conducted [16]. Georgiev Aleksandar et al. established two buried wells with a depth of 50m and a spacing of 13 m in the No.2 campus of Sofia University. The different operation modes of solar energy and GSHP in series and parallel were studied through experiments. The results showed that the heat pump in parallel mode has higher efficiency [17]. Seyed Houman Razavi et al. used TRNSYS to simulate five different combinations of solar energy and GSHP to provide the best seasonal heat storage system for a residential building [18].

It can be inferred from the reviewed literature that although the use of hybrid renewable energy systems has been relatively mature, scholars rarely consider the characteristics of local renewable energy to choose the optimal solution. It is an important issue to use various types of renewable energy heating technology according to local conditions. This paper takes the western Sichuan region as an example, the western Sichuan belongs to the cold area in China’s thermal partition, which has heating demand. However, most areas in western Sichuan still use single heating methods such as electric heating or traditional combustion in winter [19]. Therefore, the improvement of the heating method is an important part of infrastructure construction in western Sichuan.

In the present study, the distribution of available renewable energy in Litang is analyzed firstly. Then two multi-energy complementary heating systems are designed based on the resources of Litang in the third sections. Finally this paper analyzes their technical feasibility and compares initial cost, operating cost and NPV for economic analysis. This method is suitable for quick comparison of initial plans at the beginning of a project, aiming to provide some reference for the design and optimization of RES heating projects.

2 Overview of Renewable Energy in Litang

2.1 Case Description

The research object of this paper is a project of an urban heating construction project in Litang, China, which has a heating area of about 100,000 square meters. The climate in
Table 1. Main uses of geothermal resources

<table>
<thead>
<tr>
<th>Type of resource</th>
<th>Resource temperature</th>
<th>Main Uses</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-temperature geothermal</td>
<td>Above 150°C</td>
<td>Power generation</td>
</tr>
<tr>
<td>Medium-temperature geothermal</td>
<td>90~150°C</td>
<td>Industry, planting, breeding, heating</td>
</tr>
<tr>
<td>Low-temperature geothermal</td>
<td>25~90°C</td>
<td>cooling, tourism</td>
</tr>
<tr>
<td>Shallow geothermal</td>
<td>Below 25°C</td>
<td>Heating and cooling by GSHP and WSHP</td>
</tr>
</tbody>
</table>

Litang belongs to the plateau climate zone. The average temperature is 3.7°C, the extreme maximum temperature is 25.9°C, and the minimum temperature is -30.6°C.

According to the design department’s heat load calculation, the research object’s average load is 4071kW, and the annual heat consumption is 60779.7GJ.

2.2 Litang-Kahui Geothermal Group

Conventional geothermal resources refer to deep geothermal or partially exposed geothermal water resources buried hundreds of meters below the ground [20]. The main uses of geothermal resources are shown in Table 1.

The Litang area belongs to the western Sichuan geosyncline area, and the geothermal resources are extremely rich [21]. As the county with the most abundant geothermal resources in Sichuan Province, there are 43 natural outcrops of thermal water in the county. Among them, the self-flow flow rate of the Kahui geothermal group is about 56.5 L/s, the total reserves are 4881.6 m³/d, and the average water temperature is 55-83°C, which belongs to low-temperature geothermal [22].

Geothermal in the Kahui area belongs to convection type geothermal in upheaval mountains. Due to the communication of fractures and fissures, the higher geothermal energy in the deep underground is released by deep circulating heating of groundwater in the crust. In addition, the radioactive elements contained in intrusive rocks metamorphosed to release heat will also provide part of the heat, thus becoming part of the heat source [22]. This ensures a stable heat of the thermal water. Therefore, it is feasible for Litang to use deep geothermal for urban central heating.

2.3 Solar energy

Litang is located in east longitude 99°19 ‘- 100°56’, north latitude 28°57 ‘- 30°43’. The heating degree day based on 18°C (HDD18) is 5207°C · day, and the total solar radiation is 5080.7MJ/m² · year. Annual variations of daily and monthly total solar radiation in Litang are shown in figure. 1 and figure. 2 respectively.

Based on the assessment method for solar energy resources, Litang is rich in solar energy [23]. At the same time, according to figure. 3, it can be seen that during the winter heating season, Litang has more than 200 hours of sunshine hours in each month, which is very suitable for the development and utilization of solar energy resources.

3 System Design

Considering the abundant solar energy and geothermal thermal water resources in Litang, two kinds of multi-energy complementary heating system systems are proposed, which are solar-air energy heating systems (System 1); geothermal-air energy heating systems (System 2). Meanwhile, the system design scheme and operation mode are given.
3.1 Solar-air Heating System

The proposed solar-air system uses a parabolic trough solar collector (PTSC), air source heat pump (ASHP) and electric boiler (EB). Among them, the PTSC, heat transfer oil pumps and their accessories constitute the collector system; the heat storage system is mainly composed of an oil-water heat exchanger (HEX1), storage tank (ST) and circulating water pump (CWP).

The heat-collecting area of the indirect solar system is calculated as follows [24]:

\[
E = \frac{Q}{\eta_{c}}
\]

where:
- \(E\) is the heat-collecting area of the solar collector (in m²);
- \(Q\) is the required heat (in W);
- \(\eta_{c}\) is the efficiency of the solar collector.

References:

[24] ...
Table 2. Aain equipment parameters of System 1

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
<th>Value</th>
<th>Unit</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>PTSC</td>
<td>Spotlight area</td>
<td>15</td>
<td>m² / group</td>
<td>240</td>
</tr>
<tr>
<td>HEX1</td>
<td>With 2 heat exchangers, a single heat exchange</td>
<td>1000</td>
<td>kW</td>
<td>2</td>
</tr>
<tr>
<td>ST</td>
<td>Volume</td>
<td>100</td>
<td>m³</td>
<td>30</td>
</tr>
<tr>
<td>ASHP</td>
<td>Heating capacity of single</td>
<td>18</td>
<td>kW</td>
<td>12</td>
</tr>
<tr>
<td>CWP</td>
<td>Multi-stage start-up</td>
<td>5.5</td>
<td>kW</td>
<td>4</td>
</tr>
<tr>
<td>Control cabinet</td>
<td>Soft start cabinet</td>
<td>/</td>
<td>/</td>
<td>4</td>
</tr>
<tr>
<td>EB</td>
<td>Heating capacity of single</td>
<td>500</td>
<td>kW</td>
<td>4</td>
</tr>
</tbody>
</table>

$$A_c = \frac{86400Q_hf}{J_T\eta_c\eta_o\eta_{ex}}.$$  \hspace{1cm} (1)

Where $A_c$ is the collector area of the system, $m^2$, $Q_h$ is the heat consumption of the building, W, $f$ is the solar fraction and equals 50%, $\eta_c$ is the average heat collection efficiency of the collector and equals 60%, $\eta_o$ is the heat exchange efficiency of solar heating pipeline and heat storage equipment and equals 90%, $\eta_{ex}$ is the indirect system HEX1 heat transfer efficiency and equals 90%; $J_T$ is the average daily solar radiation during the heating period, $J/(m^2 \cdot d)$.

According to the calculation and analysis of solar energy resources and heat load in Litang, the average daily solar radiation during the heating period in Litang is 12.6 $MJ/(m^2 \cdot d)$, and the average heat load of heating is 4071 kW. Therefore, the area of the solar collector required by the system is calculated to be 28720 $m^2$ by using the above formula.

To prevent the heat collection system from being unable to collect heat on continuous rainy and snowy days, an auxiliary heat source system needs to be designed. The auxiliary heat source system is selected according to the average heating load, that is, the combined design heating power of low-temperature ASHP and EB is 4071 kW. The total heating power required to install the ASHP is 2160 kW.

Considering the long-term operation characteristics of PTSC and its supporting heat storage system, the auxiliary heat source system is only used in a few extreme weather. Also taking into account the investment cost and operation cost of the project construction, the EB is selected as the supplementary auxiliary heat source. Therefore, four 500 kW EB are added to meet the heating demand of the project under extreme conditions. The main equipment parameters are shown in table 2.

The solar-air heating system uses the following three heating methods: solar direct heating mode, heat storage system heating mode, and ASHP-EB heating mode. During operation, PTSC is preferentially used as the main heat source to absorb solar radiation to heat the heat-conducting oil, and the heat is transferred to the heating system through the HEX1. The heat can be directly transferred to the end device to meet the demand of indoor heating load, or stored in the ST in the form of sensible heat, and heated at night or when the solar radiation is weak. The ASHP draws heat from the air through the evaporator side. The EB is directly converted by electric heat, and the heat is transported to the end of the room through the thermodynamic cycle to supply heat when there is no available solar energy.

3.2 Geothermal-air Heating System

This hybrid renewable energy system adopts the combined heating of thermal water, WSHP and ASHP. The long-distance thermal water conveyance system consists of the water conveyance pipeline from the ash wild thermal water to the ash thermal water mouth, and the
Table 3. Main equipment parameters of System 2

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
<th>Value</th>
<th>Unit</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>HEX2</td>
<td>Nickel alloy coil</td>
<td>75</td>
<td>tons</td>
<td>2</td>
</tr>
<tr>
<td>Buffer tank</td>
<td>304 stainless steel insulation</td>
<td>/</td>
<td>/</td>
<td>40</td>
</tr>
<tr>
<td>ASHP</td>
<td>KFDX-1720/WI</td>
<td>/</td>
<td>/</td>
<td>12</td>
</tr>
<tr>
<td>CP</td>
<td>Multi-stage start-up</td>
<td>5.5</td>
<td>kW</td>
<td>16</td>
</tr>
<tr>
<td>Booster pump</td>
<td>Heating capacity of single</td>
<td>15</td>
<td>kW</td>
<td>8</td>
</tr>
<tr>
<td>Control cabinet</td>
<td>PCL</td>
<td>/</td>
<td>/</td>
<td>8</td>
</tr>
<tr>
<td>WSHP</td>
<td>Heating capacity of single</td>
<td>25.5</td>
<td>kW</td>
<td>2</td>
</tr>
<tr>
<td>Pipe network</td>
<td>Connecting to the equipment room</td>
<td>/</td>
<td>/</td>
<td>1</td>
</tr>
<tr>
<td>Booster pump</td>
<td>Heating capacity of single</td>
<td>30</td>
<td>kW</td>
<td>8</td>
</tr>
<tr>
<td>Thermal water heat pump</td>
<td>Heating capacity of single</td>
<td>30</td>
<td>kW</td>
<td>4</td>
</tr>
<tr>
<td>Buffer tank</td>
<td>Heating capacity of single</td>
<td>70</td>
<td>T</td>
<td>2</td>
</tr>
</tbody>
</table>

ash thermal water mouth to the heating station. The air source heat pump system and water source heat pump system are composed of the ASHP unit and the WSHP unit located in the heating station. Thermal water through the two-stage heat exchanger (HEX2) and WSHP for three-level gradient utilization, with the ASHP unit to supplement Litang heating heat energy to achieve Litang district heating.

The heat loss of thermal water transported from the Kahui thermal water collection tank to the heating station is 4.02°C, and the temperature of the Kahui thermal water after transportation to the heating station is 78.01°C. According to the design of the HEX2 in the heating station, the water temperature is 28°C. The primary heat source hot water network design temperature is tentatively set to 75/25°C. Combined with the water intake flow of Kahui thermal water, the thermal power calculation process of thermal water is as follows:

\[ Q = \frac{\rho \times c \times G \times \Delta t}{3600} \] (2)

Where \( \rho \) is the water density and equals 1000 kg/m³, \( c \) is the specific heat capacity of water and equals 4.2 kJ/kg/°C, \( G \) is the circulating water quantity and equals 75.0 m³/h, \( \Delta t \) is the temperature difference between supply and return water and equals 50°C.

Therefore, it is calculated that the heating power provided by the thermal water after transportation is 4375kW.

Meanwhile, two WSHPs and twelve ASHPs are used in this system, which a heating capacity is 180kW.

In daily operation, the Kahui thermal water is transported into the heating station through a long-distance pipeline, and the thermal water is extracted by the HEX2, and then enters the WSHP to raise the temperature, to realize the multi-stage cascade utilization of the Kahui thermal water. The heating power is 4735kW. In addition, in the daily operation process, part of the ASHP needs to be turned on to meet the average heat load demand for heating. In low-temperature months and extreme weather, the ASHP can operate at full load, and cooperate with Kahui thermal water and WSHP to achieve urban heating in Litang.

4 Techno-economic Analysis

4.1 Technical Feasibility Analysis

The heating technology and equipment of PTSC, ASHP and EB in System 1 have been developed relatively mature, and the heating system composed of trough solar energy and heat
storage system can meet the daily basic heating demand in Litang with sufficient solar energy. Meanwhile, the combined ASHP and EB can realize the full coverage of heating demand.

The technical key of the System 2 heating system with Kahui thermal water as the main heat source lies in long-distance heat preservation and water transmission. At present, pipes and insulation materials for long-distance heating have developed more mature. Among them, heat-resistant polyethylene pipe II has good temperature resistance and mechanical properties, and rigid polyurethane foam has good thermal insulation properties. Both of them can be used as ideal water pipelines and insulation materials to ensure the long-term stability of long-distance water transmission. At the same time, the terrain between Kahui thermal water group and Litang is flat, which meets the requirements of long-distance pipeline construction.

In summary, the two systems are both technically feasible to meet the heating demand of Litang.

### 4.2 Initial Cost

According to the system design, the investment cost of System 1 is about 175 million CNY, with an investment cost per unit area of 175\(CNY/m^2\). The solar heating system is the main cost in the initial investment, which accounts for 41\% of the initial cost. The investment cost of System 2 is about 121 million CNY, with an investment cost per unit area of 121\(CNY/m^2\). The results in Table 4 show that System 2 requires 53.91 million CNY less on the initial investment in comparison to the base System 1.

### 4.3 Operation Cost

The operation cost of a heating system includes electricity, water, labor, depreciation and maintenance costs [25]. Electricity price is calculated by time-of-use price. According to the analysis of operating power consumption, it is concluded that the power consumption of the heating station in the peak period, flat section, and trough period is about 1.5792 million degrees. The work conducted in the computer room requires four workers who are responsible for daily maintenance, repairs, and the recording of data. The annual operating costs of a GSHP system are shown in Table 5.

The results show that although the operating costs of System 1 and System 2 are close, the maintenance and depreciation costs of the solar system are higher, and the total operating cost of System 2 is 25.2\% lower than that of System 1.
Table 5. System operation cost

<table>
<thead>
<tr>
<th>Project</th>
<th>System 1</th>
<th>System 2</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy cost</td>
<td>4961.04</td>
<td>4738.84</td>
<td>10,000 CNY</td>
</tr>
<tr>
<td>Cost of labor</td>
<td>662.4</td>
<td>662.4</td>
<td>10,000 CNY</td>
</tr>
<tr>
<td>Maintenance cost</td>
<td>3722.2</td>
<td>2758.68</td>
<td>10,000 CNY</td>
</tr>
<tr>
<td>Depreciation cost</td>
<td>12407.6</td>
<td>9195.6</td>
<td>10,000 CNY</td>
</tr>
<tr>
<td>Annual operating cost</td>
<td>24247.42</td>
<td>18127.44</td>
<td>10,000 CNY</td>
</tr>
</tbody>
</table>

Figure 4. NPV of System 1 and System 2 as a function of time

4.4 NPV

This paper assumes that the operating cycle of the heating system is twenty years in terms of the time value and movement of funds. The dynamic evaluation method was selected to evaluate the economics of the project.

The NPV reflects the profitability of the project. The economic benefits of the investment project were analyzed by assessing the magnitude of the NPV. When comparing two investment modes, the scheme with the larger NPV is preferred [25, 26]. When the NPV of both schemes is negative, the scheme with a smaller absolute value is selected. Figure 4 shows the changes in the NPV values of System 1 and System 2 over 20 years. The results show that the NPV of System 1 is -57.92 million CNY, and the NPV of System 2 is -18.78 million CNY. In summary, System 2 is more proper from the perspective of economic analysis.

As the heating price is 30 yuan/m²·year, sales revenue cannot cover the heating operating costs, so the NPV is negative. This can be solved by applying for government subsidies. To ensure that the project reaches the industry benchmark investment internal rate (IRR) of return of 4%, from the beginning of the project construction to the first 10 years after the operation, a total of 103.18 million CNY of subsidies are required to meet the expenditure needs. In the next 10 years, an annual subsidy of 900,000 CNY is required to make up for the operating losses. At the same time, the more government subsidies, the higher the NPV value. After calculation, the pre-tax IRR of subsidized investment is 4.07%.
5 Conclusion

This study proposed two different hybrid renewable energy systems considering the rich RES in Litang: solar-air heating and geothermal-air heating systems. The equipment and operation modes of the two systems are analyzed in detail. In addition, techno-economic analysis was performed to compare the suitability of the two systems. The conclusions of this study can be summarized as follows:

1) The Litang-Kahui geothermal group belongs to low-temperature geothermal, and its heat source mainly comes from the deep circulation heating of groundwater in the crust and the metamorphic heat release of radioactive elements in the rock. At the same time, Litang has more than 200 hours of sunshine hours in winter, and the total solar radiation is $5080.7 \text{MJ} / \text{m}^2 \cdot \text{year}$. Therefore, it is very suitable for developing and utilizing solar and geothermal energy resources.

2) System 1 and System 2 are both technically feasible. From the perspective of economic analysis, the initial cost of the solar-air heating system was higher by up to 44.4% (53.91 million CNY) than that of the geothermal-air heating system. And the operation cost could be reduced by up to 25.2% by using System 2. However, the energy cost of System 1 was just 4.7% higher than System 2, which means the effect of the energy cost on operation costs was insignificant. Meanwhile, the NPV of System 1 is -57.92 million CNY, and the NPV of System 2 is -18.78 million CNY in twenty years. System 2 is profitable after government subsidies, and the pre-tax IRR of subsidized investment is 4.07%. This confirmed that System 2 is more effective than System 1 in terms of the system’s economic efficiency.

3) To promote the sustainable development of geothermal energy, the state should reasonably increase its support for multi-energy complementary projects, give them long-term stable state subsidies, and encourage local governments to give them reasonable local subsidies according to their actual development levels and economic conditions. At the same time, according to the same or a variety of renewable energy in different regions, weather, season and other factors affecting the heating characteristics of differentiated subsidies. Encourage more people to actively respond to the country’s call as soon as possible to achieve the goal of carbon neutrality and emission peak.

4) Due to the limitation of some factors, this paper only analyzes the design of heating system in the alpine region of western Sichuan, which has certain limitations and shortcomings. The research on other climate regions will be carried out in depth.

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