Research on design and control methods of medium-depth geothermal heat pump energy storage system for clean electric utilization

Chenwei Peng  Jiewen Deng  Qingpeng Wei

ABSTRACT

Electric-driven heat pump systems, commonly used for space heating and cooling in buildings, have emerged as a crucial component in integrating with the power grid, promoting clean electricity consumption. This paper introduces a high-efficiency space heating and cooling system that combines heat pumps with medium-depth ground heat exchangers and a cooling tower. Additionally, it employs a heat storage system for daily thermal and cooling storage. The system encompasses a design methodology and control strategy optimized for maximizing the use of local photovoltaic power generation and municipal clean power sources. Furthermore, the paper presents a case study of a large public building, including a quantitative analysis to assess its energy-saving capabilities and CO2 emission reduction impacts. Results showed that the proposed system has a payback period of less than six years, and reduces carbon dioxide emissions by over 14,900 tons, showcasing substantial energy savings and emission reduction benefits.

INTRODUCTION

Electrically driven heat pump technology, notable for its flexibility and high efficiency, has become pivotal in the energy-efficient and low-carbon transformation of urban and rural infrastructure (Jiang, et al., 2021). Concurrently, this technology has been applied to enhance the clean electricity utilization of building sector (Jiang, et al., 2022). However, there are still challenges influencing the application of heat pump systems. Research highlights issues such as notable heat loss in pipelines, elevated energy consumption for heating, and suboptimal system performance (Deng, et al., 2019), alongside instability in low-grade heat sources like air and shallow geothermal energy (Zhou, et al., 2017). These factors impede long-term operational effectiveness and broader adoption. In grid coordination, the mismatch between building thermal supply and demand and clean electricity generation intensifies the power grid's burden (Huang, et al., 2021).

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This aggravates the energy production-demand imbalance, notably impacting renewable energy development in China (Chen, et al., 2016). Thus, enhancing the operational performance of electrically driven heat pumps and their regulation flexibility is imperative for building energy saving.

Recently, the mid-deep heat pump heating systems have been applied in Northern China. It extracts geothermal energy from mid-deep layers via borehole wall heat exchangers, offering a stable, high-temperature heat source for heat pumps, ensuring consistent and efficient building heating (Deng, et al., 2019). Coupled with cooling towers, the heat pump system could also serve space cooling. Then to reconcile the mismatch between space heating/cooling demand from the clean electricity utilization demand, energy storage technology can be applied (Osterman, et al., 2019 & Deng, et al., 2023). Recently, the global study and application of electrically driven heat pump thermal storage heating have expanded significantly (Khudhair, et al., 2021). Therefore, this paper proposes an electrically driven heat pump energy storage system designed for optimal clean electricity consumption. It presents system design methods and operational control strategies, targeting optimal use of local photovoltaic power and municipal clean electricity. A quantitative analysis, using a large public building in China as a case study, clarifies the actual energy-saving and emission reduction impacts.

**ANALYSIS OF THE CASE STUDY’S BASIC SITUATION**

**Project Overview and Load Characteristic Analysis**

This study takes a large public building in a cold region of Northern China as an example to conduct research, with a total area of approximately 489,000 square meters. The heating season in the climate zone where the building is located is from November 1 to March 31 of the following year, and the cooling season is from May 1 to September 30. The load of the building was calculated by the design institute through load simulation software (DeST). The designated outdoor temperature for summer air conditioning is 31.5°C, and for winter heating, -12.8°C. Based on the results provided by the design institute, this study first analyzes the annual heating and cooling supply demand of the building and illustrated in Figure 1. Specifically, the peak heating load reaches 28,258 kW, equating to 57.8 W/m² across the total area. For cooling, the peak load is 47,993 kW, or 98.2 W/m². During the heating season, the cumulative heating totals 37.857 million kWh, amounting to an annual figure of 77.4 kWh/m² (0.28 GJ/m²). The cumulative cooling over the season is 43.095 million kWh, translating to an annual total of 88.1 kWh/m².

![Figure 1](https://doi.org/10.22488/okstate.24.000007)

**Analysis of Low-Carbon Heating and Cooling Supply Demands**

Upon determining the building's hourly heating and cooling needs, employing mid-deep borehole heat pump technology for clean, efficient heating was proposed. Alongside heat pump units and cooling towers, an effective summer cooling
system was also devised. The system's detailed configuration and operational plans target an operational EER of 5.0 or higher for both winter heating and summer cooling systems (China "Evaluation Standard for High-efficiency Air Conditioning and Chiller Plant Rooms T/CECS 1100-2022"). Additionally, integrating cold and thermal storage technologies facilitates full utilization of onsite photovoltaic and municipal clean electricity, advancing towards a near-zero carbon heating and cooling system.

Situated in the mid-latitude and plateau regions of the Northern Hemisphere, the building receives over 1400 kWh/m² of annual solar radiation, placing it in China's second-tier solar resource category. To advance the construction of a clean electricity-oriented mid-deep borehole heat pump system, PVsyst software was used to employ a results-oriented design method, calculating the total clean electricity needs for the HVAC system. Figure 1 illustrates that the building's total annual electricity consumption for heating and cooling is approximately 17.02 million kWh, derived from annual usage and system efficiency.

A photovoltaic grid-connected system, designed and simulated using PVsyst, optimizes based on the annual radiation amount with a fixed installation orientation. The calculated total installed photovoltaic capacity, necessary to meet the building's annual energy needs, is 12.13 MWp, requiring an installation area of 67,000 m². The required installation area represents 9.0% of the total feasible photovoltaic area, affirming its viability. Figure 2 displays the hourly photovoltaic generation over the year, aligned with the building's electricity demands.

While photovoltaic generation meets the annual electricity demand for heating and cooling, Figure 3 illustrates a notable real-time demand mismatch. This mismatch is particularly evident during the heating season on cloudy and rainy days, with higher heating needs and reduced photovoltaic generation. Consequently, coordinating onsite photovoltaic and municipal electricity usage, with a primary reliance on onsite generation supplemented by municipal clean power, is vital for attaining net-zero emissions in the heating and cooling systems. To achieve this, integrating user-side energy storage technology separates the building's heating and cooling demands from its utility production capacity. This approach facilitates orderly electricity demand management.

**Figure 2**  Annual hourly power generation of proposed photovoltaic installation for the research case.

**Figure 3**  Difference between hourly electricity generation and building electricity consumption throughout the year for the research case (electricity generation-electricity consumption).
ANALYSIS OF THE CASE STUDY'S BASIC SITUATION

As previously outlined, this design capitalizes on the efficient heating properties of mid-deep borehole heat pump technology, in conjunction with cooling tower and user-side energy storage technologies. The objective is to construct a heat pump-based clean energy system that maximizes the use of onsite photovoltaic generation and municipal clean electricity. Figure 4 depicts a schematic of the system, encompassing mid-deep borehole pipes, cooling towers, heat pump units, user-side thermal storage tanks, and water systems. The system employs user-side energy storage tanks to separate the building's heating and cooling needs from production capabilities. Through intermittent storage and release of cold and heat, the system consistently fulfills the building's cooling and heating requirements.

**Figure 4**  Schematic diagram of medium-depth geothermal heat pump energy storage system.

**System Design Method**

Leveraging mid-deep borehole heat pump technology, this approach integrates photovoltaic technology to transform solar energy into zero-carbon electricity. This setup powers a combined system of mid-deep borehole heat pumps and cooling towers, delivering zero-carbon cooling and heating to the building. Energy storage tanks are utilized to decouple the ongoing end-use cooling and heating demand from the source side. By strategically selecting operation times aligned with photovoltaic generation and municipal grid clean electricity output, the system efficiently stores adequate cooling and heating in the energy storage tanks. This facilitates intermittent operation, satisfying the building's ongoing cooling and heating needs, thereby optimizing zero-carbon electricity usage and achieving zero-carbon thermal management.

**Figure 5**  Design and operation control strategy flowchart of a medium-depth geothermal heat pump energy storage system. Figure 5 illustrates the design and operational control strategy flowchart for the system, detailing the following specific

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design steps: The method integrates building-specific meteorological data, solar radiation, electricity pricing, and photovoltaic generation cycles to compute daily cooling and heating demands and photovoltaic output. This information is then used to determine daily stored cooling and heating, system electricity consumption, surplus photovoltaic generation, and required clean electricity from the municipal grid. Utilizing Equation 1, the daily cumulative cooling and heating capacity \( Q_s \) are calculated by combining yearly photovoltaic output with the chosen COP of the cold and heat source system. The system's operation, detailed in section 2.2, employs various logics based on daily cumulative photovoltaic generation, cooling and heating capacities, and demand. Steps one to three establish daily stored cooling and heating, leading to the calculation of maximum daily storage capacity with a designated temperature difference for storage. The system's installed capacity is determined by the maximum heating/cooling demand. Geothermal geological conditions inform the calculation of optimal cumulative heat extraction for mid-deep borehole pipes, subsequently determining the required number of borehole pipes and their serving area in the modular system. The installed capacity of user-side water pumps, energy storage water pumps, and cold and heat source side water pumps for borehole pipes is determined by peak loads and temperature differentials between supply and return water.

\[
Q_s = W_{s,d} \cdot COP
\]

Where \( Q_s \) is the daily cumulative cooling and heating capacity (kWh), \( W_{s,d} \) is the daily cumulative photovoltaic generation (kWh), and \( COP \) is the cooling and heating efficiency of the cold and heat source system (dimensionless).

Analysis of Operational Control Strategies

Figure 5 illustrates the flowchart for the design and operational control strategies of the system. The strategy harnesses daytime solar photovoltaic generation for energy storage, utilizing surplus electricity for other project functions. During night-time or cloudy conditions, surplus photovoltaic or grid valley electricity is preemptively used for energy storage. Stored cold and heat are subsequently released from the tank to meet the building's needs as required. Detailed analyses of the specific operational control strategies follow:

1. When the daily cumulative cooling and heating capacity \( Q_s \) exceeds the building's daily demand \( Q_{h,d} \), surplus photovoltaic electricity is generated. Sunny period demand \( Q_1 \) is met by photovoltaic electricity, and non-sunny period demand \( Q_2 \) is stored in the water tank during photovoltaic generation. Accumulated storage is calculated using Equation 2, and surplus electricity using Equation 3.

\[
Q_{h,s} = Q_2
\]

\[
W_{s,e} = \frac{(Q_s - Q_{h,d})}{COP}
\]

Where \( Q_{h,s} \) is the accumulated cooling and heating storage in the tank (kWh), \( Q_2 \) is the cumulative cooling and heating demand during periods without photovoltaic generation capacity (kWh), \( Q_{h,d} \) is the building's daily cumulative cooling and heating demand (kWh), and \( W_{s,e} \) is the surplus electricity (kWh).

2. If daily capacity \( Q_s \) falls below sunny period demand \( Q_1 \), storage operation during low-peak electricity periods is necessary to meet remaining demand. Cooling and heating during low-peak periods \( Q_3 \) is supplied by the municipal power-driven system. Accumulated storage calculation follows Equation 4, and municipal power usage in low-peak periods Equation 5.

\[
Q_{h,s} = Q_{h,d} - Q_3 - Q_s
\]

\[
W_o = \frac{(Q_{h,d} - Q_s)}{COP}
\]

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Where \( Q_{h,s} \) is the accumulated cooling and heating storage in the tank (kWh), \( Q_3 \) is the cumulative cooling and heating demand during low-peak electricity pricing periods (kWh), and \( W_0 \) is the municipal power usage (kWh).

3. When daily capacity \( Q_s \) exceeds sunny period demand \( Q_1 \) but is less than non-low-peak demand \( Q_4 \), surplus electricity from photovoltaic generation should be stored. Concurrently, storage during low-peak periods should accommodate non-low-peak demand \( Q_3 \), supplied by the municipal power system. Accumulated storage follows Equation 6.

\[
Q_{h,s} = Q_4 - Q_1 \tag{6}
\]

Where \( Q_{h,s} \) is the accumulated cooling and heating storage in the tank (kWh), and \( Q_4 \) is the cumulative cooling and heating demand during non-low-peak electricity pricing periods (kWh).

4. If daily capacity \( Q_s \) is below daily demand \( Q_{h,d} \), yet above non-low-peak demand \( Q_4 \), remaining photovoltaic-driven cooling and heating must be fully stored. Remaining cooling and heating in low-peak periods \( Q_3 \) are directly met by the municipal-powered system. No storage occurs in low-peak periods. Accumulated storage follows Equation 7.

\[
Q_{h,s} = Q_s - Q_1 \tag{7}
\]

Where \( Q_{h,s} \) is the accumulated cooling and heating storage in the tank (kWh).

**ANALYSIS OF THE APPLICATION EFFECTS OF THE MID-DEEP BOREHOLE HEAT PUMP ENERGY STORAGE SYSTEM**

**Analysis of Actual Application Effects**

Utilizing load simulation results, the mid-deep borehole heat pump energy storage system design was further refined. The heating source system of the project has a cumulative heating output of 37.85 million kWh, equivalent to 136,000 GJ. With the heat pump's average efficiency coefficient at 5.0, about 109,000 GJ of annual heating is derived from mid-deep geothermal energy. Considering the large number of actual tests and research results of the research team (Specifically in the references) and the project's geothermal conditions and an annual average soil temperature drop of no more than 0.2°C, each borehole pipe can extract 3,000 GJ of heat per heating season. Consequently, 37 borehole pipes, each 2,500 meters deep, are required. Given the project's use of energy storage, the heat pump system's installed capacity for cooling and heating is based on peak storage demand. Besides, an analysis of the cold and heat storage system was conducted, following the design method outlined in Section 2.1. For the energy storage water tank, the design temperature difference is set at 7K (4°C/12°C) for cooling and 25K (40°C/65°C) for heating.

Based on daily stored cooling and heating amounts under the system's operational control strategy, the energy storage tank volume can be calculated. Given practical considerations, the building opted not to guarantee 5% of days, leading to a cooling water tank capacity of 8,588 m³ and a design storage capacity of 69,806 kWh. For heating, the corresponding water tank capacity is 7,595 m³, with a designed heating storage of 220,453 kWh. Considering both cooling and heating, the total energy storage tank capacity for the building is established at 8,500 m³. Based on the building's storage needs for cooling and heating, the heat pump system's installed capacity is calculated to be 40 MW for heating and 48 MW for cooling. To adapt to cooling and heating demands, the building installed four 3,000 RT (Refrigeration Ton) dual-purpose heat pump units and two 900 RT chillers. Then an analysis of daily electricity consumption for both heating and cooling seasons, based on the designed capacity and the building's demands, is presented in Figure 6. The cumulative electricity consumption is 7.57 million kWh for the heating season, peaking from mid-December to mid-January, and 8.62 million kWh for the cooling season, with a peak from mid-July to mid-August.

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Figure 6  Daily power consumption of the heating and cooling seasons system for the research case.

Incorporating the system's operational control strategy, an analysis was conducted on surplus clean electricity and supplemental municipal electricity for both cooling and heating seasons, as depicted in Figures 7. In the cooling season, municipal electricity supplements the chiller operation on days when photovoltaic-generated cooling storage falls short. Photovoltaic generation typically meets demand, with notable electricity surpluses at the start and end of the cooling season. In the heating season, surplus electricity primarily occurs at the beginning and end, with increased municipal electricity use during the peak period from late December to early January. The "scissor gap" analysis between demand and supply reveals that summer is the peak for photovoltaic generation, whereas winter experiences a lull. The transition to electrified heating results in peak electricity consumption in winter, contrasted with lower usage in summer and transitional seasons. Future grid coordination can facilitate the absorption of green electricity and help bridge the mismatch gap.

Figure 7  Analysis of daily electricity of the research case's energy storage system.

Comparative Analysis of Energy Saving and Emission Reduction Benefits

Simulation results indicate the building's cumulative heating is 40.152 million kWh, with heat pump units having an installed capacity of 40,995 kW, and cumulative cooling at 44.2 million kWh, with chillers having an installed capacity of 47,992 kW. Comparative analysis of conventional energy supply options for equivalent heating and cooling amounts reveals economic and energy-saving benefits. Tables 1, 2, and 3 outline the methods for initial investment estimation, investment comparison results, and carbon emission comparisons, respectively. Five heating scenarios were compared: Scenario 1 features the earlier described photovoltaic-driven system, achieving zero operational costs due to meeting or exceeding annual electricity generation demands. Scenarios 2 to 4 involve a conventional mid-deep borehole system with municipal electricity, a gas boiler with a water-cooled chiller, and an electric boiler with a water-cooled chiller, respectively.
Table 1. Preliminary Investment Estimation Unit Price List for the Research Case

<table>
<thead>
<tr>
<th>Cost of Each Equipment Unit (Type)</th>
<th>Unit Price (RMB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medium-depth Borehole Heat Exchangers</td>
<td>4,000,000/Hole</td>
</tr>
<tr>
<td>Medium-depth Geothermal Heat Pump System</td>
<td>1,000/kW</td>
</tr>
<tr>
<td>Gas Boiler System (Including Supporting Fees)</td>
<td>2,000/kW</td>
</tr>
<tr>
<td>Electric Boiler System</td>
<td>1,000/kW</td>
</tr>
<tr>
<td>Power Transmission and Distribution System</td>
<td>2,000/kW</td>
</tr>
<tr>
<td>Energy Storage Water tank</td>
<td>1,500/m³</td>
</tr>
<tr>
<td>Photovoltaic Panels</td>
<td>4/Wp</td>
</tr>
</tbody>
</table>

The calculations for energy savings, emission reductions, and initial investment of the chosen system are based on these conditions: 1) During practical operation, the condensing temperature of mid-deep heat pump reaches 66 °C, with 1 °C difference from supply water temperature. And with ground-side water temperatures of 30/20°C, thus the evaporating temperature could reach 19 °C. Then the theoretical COP of mid-deep heat pump reaches 7.22. Considering the compressor efficiency could reach 0.70, which is the average standard of current devices, the COP of mid-deep could be assumed at 5.0. 2) The COP was assumed at 3 for the air-source heat pump, heating efficiencies of 1.0 for gas boilers and 0.95 for electric boilers, and a user-side water pump efficiency of 80 for both boiler systems. 4) For cooling, the COP for a conventional high-efficiency chiller system is set at 5.0. These parameters lead to calculated construction costs and annual operating expenses for each scenario, detailed in Table 2.

Table 2. Comparison of Economic and Energy Saving Effects in Different Scenarios

<table>
<thead>
<tr>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
<th>Scenario 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Investment</td>
<td>248.31</td>
<td>201.91</td>
<td>133.50</td>
</tr>
<tr>
<td>Total Electricity Consumption</td>
<td>0</td>
<td>16.87</td>
<td>9.64</td>
</tr>
<tr>
<td>Total Gas Consumption</td>
<td>0</td>
<td>0</td>
<td>4.23</td>
</tr>
<tr>
<td>Annual Operating Expenses</td>
<td>0</td>
<td>13.35</td>
<td>19.88</td>
</tr>
<tr>
<td>Total Investment+Total Operating Expenses for 15 Years</td>
<td>248.31</td>
<td>454.96</td>
<td>278.10</td>
</tr>
<tr>
<td>Primary Energy Consumption (tce)</td>
<td>0</td>
<td>5229.82</td>
<td>8610.62</td>
</tr>
<tr>
<td>Carbon Dioxide Emissions (t)</td>
<td>0</td>
<td>14918.49</td>
<td>17233.98</td>
</tr>
</tbody>
</table>

The initial investment for Scenario 1 is calculated at 248 million yuan, totaling the same over 15 years when including operating costs. Scenario 2 requires an initial investment of 244 million yuan, with a 15-year total of 454 million yuan including operating costs. The initial investment for Scenario 3 is 128 million yuan, amounting to 278 million yuan over 15 years with operating costs. Scenario 4 involves an initial investment of 164 million yuan and a 15-year total of 930 million yuan including operating costs. Despite Scenario 1's higher initial investment compared to other scenarios, its significant savings on operating costs become evident when considering efficiency and energy conversion rates. Additionally, the payback period for the incremental investment in Scenario 1, in comparison to other scenarios, was calculated. The payback period for Scenario 1 is 3.4 years relative to Scenario 2, 5.7 years compared to Scenario 3, and 2 years compared to Scenario 4. Consequently, the selected system for this building is the most appropriate, considering both investment and long-term operational aspects. Besides, the carbon emission factor method, which involves multiplying activity data by emission factors based on a carbon emission inventory, was employed for these calculations. The specific parameters adhere to China's GB/T 51366—2019 "Building Carbon Emission Calculation Standards," effective since late 2019. For the building's chosen Scenario 1, aimed at near-zero carbon, the system exhibits zero primary energy consumption and carbon dioxide emissions annually, in a broad sense. While some carbon emissions may occur in practice, the selected system remains the most suitable for the building, considering energy efficiency and emission reduction.

CONCLUSION

This study centers on a large public building in China's cold region, targeting net-zero carbon operation in the design...
and analysis of its heating and cooling systems. The main conclusions are as follows: 1) To minimize operational energy use and carbon emissions, the project adopted an efficient heating system using mid-deep borehole heat pump technology. Coupled with cooling tower technology, this system ensures efficient summer cooling. The system's design, in terms of configuration and operation, aimed to achieve an EER of over 5.0 for both winter heating and summer cooling. 2) Extensively installing photovoltaic systems on public buildings and open campus spaces is crucial for achieving zero-carbon electricity for heating and cooling. The project's total designed photovoltaic capacity is 12.13 MWp, with photovoltaic generation fulfilling all electricity demands for heating and cooling. Integrating user-side energy storage technology allows the system to separate the building's cooling and heating demands from the production capacity of its sources. This approach enables the building to consistently meet its cooling and heating demands. It adjusts electricity demand for these systems according to the production patterns of photovoltaic and municipal clean electricity, thus reducing carbon emissions and operational costs, and achieving zero-carbon cooling and heating. 3) Economically, the mid-deep borehole heat pump energy storage system's incremental investment cost, compared to conventional systems, has a payback period of less than six years. Annually, the system reduces carbon dioxide emissions by over 14,900 tons, showcasing substantial energy savings and emission reduction benefits.

ACKNOWLEDGMENTS

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NOMENCLATURE AND GREEK

\[ Q_s = \text{Daily cumulative cooling and heating capacity (kWh)} \]
\[ Q_{h,s} = \text{Accumulated cooling and heating storage in the tank (kWh)} \]
\[ Q_{h,d} = \text{Building's daily cumulative cooling and heating demand (kWh)} \]
\[ Q_1 = \text{Cumulative cooling and heating demand during periods with photovoltaic generation capacity (kWh)} \]
\[ Q_2 = \text{Cumulative cooling and heating demand during periods without photovoltaic generation capacity (kWh)} \]
\[ Q_3 = \text{Cumulative cooling and heating demand during low-peak electricity pricing periods (kWh)} \]
\[ Q_4 = \text{Cumulative cooling and heating demand during non-low-peak electricity pricing periods (kWh).} \]
\[ W_{s,e} = \text{Daily cumulative photovoltaic generation (kWh)} \]
\[ W_{s,e} = \text{Surplus electricity (kWh)} \]
\[ W_0 = \text{Municipal power usage (kWh)} \]
\[ COP = \text{Cooling and heating efficiency of the cold and heat source system (dimensionless).} \]
\[ RT = \text{Refrigeration ton.} \]

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