A multi-integrated renewable energy system in a commercial building in Beijing: lessons learnt from an operating analysis

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Abstract
In this case study, calculations and analyses were performed mainly for a solar-ground source heat pump system using a newly built office–factory building. Calculations for the collector panels, the water heater system and the saving for natural lighting system were also performed. Results have shown that the energy consumption in ground source system is 34.1% more efficient than that of air source system in normal days in winter. The required data for the calculations were measured using calorimeters and electricity meters which form part of the building automation system (BAS). The BAS works through a direct digital control system. On the basis of the observation and research on the actual operation, suggestions related to the design, operation and inspection are given.

Keywords: renewable energy; building energy saving; heat pump; low carbon building

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1 INTRODUCTION
Climate change has raised concerns over the rapidly growing environmental pollution and depletion of natural resources. In this scenario, international programs and policies indicate the construction sector as one of the most promising sectors for a sustainable development [1]. Laws and regulations worldwide are asking the construction sector to build sustainable buildings, such as green buildings. The number of sustainable buildings is now increasing worldwide and assessment of their sustainability is becoming a common practice [2].

The increased attention towards buildings is due to their energy consumptions and green house gas (GHG) emissions, which, in developed countries, account for 30 and 40% of the total consumption, respectively [1,3]. In China, the energy consumption by buildings accounts for about 28% of the national energy consumption. According to the Intergovernmental Panel on Climate Change (IPCC), the construction sector has higher energy and pollution reduction potentials than any other sectors. Figure 1 shows the historical trend and the forecasting of CO₂ emissions, including through the use of electricity [1]. The figure also shows how critical is the situation, especially given the huge increase in the requirement of energy as well as GHG emissions in East Asia and South Asia. The IPCC stated that, in countries that are not members of the Organization for Economic Cooperation and Development and in transition economies, buildings’ potential CO₂ saving could be 3 and 1 GtCO₂-eq/year by 2030, respectively, with a total possible reduction of 6 GtCO₂-eq/year worldwide [1]. Given this context of analysis, the article explores the measures of energy saving through the integration of renewable energy systems in a commercial building in China.

In China, the prominent sources of energy consumption are air-conditioning systems [3]. The power consumption in summer is high due to the use of air-conditioning systems, and recently it has increased more and more. In fact, in summer, the air-conditioning load accounts for >50% of the entire peak load, as air-conditioning systems are often required for cooling in the hotter parts of the country and for heating in the cooler areas [4]. Figure 2 shows the percentages of energy consumption of commercial buildings in the USA and China. The figure also shows that the energy consumption for space heating and cooling accounts for 22 and 59% of the total energy consumption in the USA and China, respectively. The percentage of energy consumption for lighting purposes is comparable between the two countries. Finally, it is important to consider the energy requirement for several ‘other uses’, including for all appliances, which contribute to the US energy demand, will probably increase in the following years in China also, making the consumption more critical in the country.

Owing to the pressure of international agreements, the energy production from renewable sources by buildings is...
increasing worldwide. It has reached >45% in Sweden and 65% in Norway [5]. On the contrary, this value is <10% in China. However, the energy production in China is rapidly increasing, and the country’s electricity generation from renewable sources is increased from 397.331 billion kWh in 2005 to 576.883 billion kWh in 2009 [6]. Finally, the installation of renewable energy sources in buildings in general, and in China in particular, has become an urgent measure to increase the renewable energy production and to create a diffused energy production system. In this paper, the integration of various renewable energy sources is considered [7].

2 A MULTI-INTEGRATED RENEWABLE ENERGY SYSTEM

A newly built factory–office building was considered for the case study to look at its integrated renewable energy system. Many reasons justify the focus on office buildings, as their demand and consumptions of energy are high. A recent research [8] has investigated strategies to reduce energy requirement through internal loads in office buildings. Moreover, automation systems are more and more considered to adjust the energy requirement of buildings with the real occupancies [9].

The building selected is a combined factory–office building located in Beijing. It has five floors: three lower floors are dedicated to workshops, depots and mess hall, whereas the two upper floors are working and public areas. The total area of the building amounts to ~25 500 m².

The building has both solar and geothermal energy systems: the solar-ground source heat pump system, the solar hot water system and the natural lighting system.

2.1 The solar-ground source heat pump system

Ground heat pumps have received a considerable attention in recent years as shown by numerous publications [10–12]. In particular, this article considers a solar-ground source heat pump system which integrates solar and ground heat energy exchanges to meet the energy needs of the building both for cooling and heating [13].

The system comprises 220 high-density polyethylene pipes of 8000 m² length at the depth of 80 m underground, and these pipes are joined by 65.54 m² solar collector panels. Figure 3 shows the facade with the panels. The heat collected by the solar panels is stored in collector tanks whose capacity is 6 tons. The pump engine room is equipped with two ground-source heat pumps, two circulating pumps (one operation, the other standby) and four ground-coupling circulating pumps.

In Summer, the inlet and outlet water temperatures of the pump units are 15 and 30°C, whereas the temperatures of the supplying cold water are between 7 and 12°C. In Winter, the inlet and outlet temperatures are 15 and 6°C, whereas the supplying hot water temperatures are 40 and 45°C.

The collector tank and the pump units are connected in series, and different functions are controlled by adjusting proportional valves (Figure 4). In a sunny winter day, proportional valves open, and let air-conditioning circulating backwater first go through the collector tank to exchange heat and, then exchange heat with the hotter water of the pump units. In the case of lack of sun light, and when it operates in summer

Figure 1. Real data and forecasting of CO₂ emissions through the use of electricity up to 2030 [1].

Figure 2. Sources of energy consumptions for commercial buildings in the USA and China [1].
conditions, proportional valves close, and let air-conditioning circulating backwater first directly to exchange heat with the water of the pump units.

2.2 The solar hot water system
The solar hot water system is a semi-centralized system which adopts concentrated collecting heat, household heat storage and auxiliary heating. The system includes three parts.

- The mess hall system: it comprises 24-m² solar collector panels on the facade. These panels supply heat to two tanks, each of which has a capacity of 450 l.
- The east system: it comprises 57.6-m² solar collector panels distributed in two rows over the roof. These panels supply heat to three tanks, two with a capacity of 340 l located on fifth and fourth floors and one with a capacity of 270 l situated on the third floor. After auxiliary heating by electricity power in the water heater, the boiling drink water is supplied to satisfy the needs in the public offices. The heated water is also supplied for heating of temperature aging workshop on the third floor.
- The west system: it comprises 28.8-m² solar collector panel distributed in one row over the roof. This panel supplies heat to two water tanks, with a capacity of 450 l. Water in the tanks is supplied for washing hand purposes in the public toilets.

2.3 The natural lighting system
The natural lighting system is constituted by an integrated system composed of solar collector panels, solar photovoltaic (PV) panels and glass curtain walls. All four rows shown in Figure 5 comprise the integrated system installed with the same inclination angle.

This configuration integrates the solar energy systems in the building envelope and allows three different functions:

- Three rows of solar collector panels preheat water for workers. These rows are divided into two solar hot water systems unequally: one system is connected with 57.6 m² collector panels and the other with 28.8 m² panels.
- The PV panels provide power for office lighting and supply energy to the billboard lighting outside the building.
- The curtain walls contribute to light the fifth floor and allow for saving a considerable amount of energy otherwise necessary for lighting.

3 ENERGY-SAVING RESULTS FOR THE MULTI-INTEGRATED SYSTEM
The integration of renewable energy in this building is obtained by three systems, i.e. solar-ground source energy system, solar
hot water system and the natural lighting system. The required data for the calculation are taken from calorimeters and electricity meters. These are controlled through the building automation system (BAS) of the building which works with a direct digital control (DDC) system. This section considers mainly on the energy-saving effects resulting from solar and ground energies.

3.1 Energy-saving effect of solar-ground source heat pump system

This section analyses the energy-saving effects related to the integration of solar energy and ground heat energy. The heat pump system power load and the evaluation of system's coefficient of performance (COP) are shown in Table 1.

As shown in Table 1, the heat pump itself has a COP of 4.6. When taking the power loads of the ground circulation pump and the heating water supply pump into consideration, the overall COP reduced to 3.6. In this paper, the operational effect was analyzed by comparing the ground source with a traditional air-source pump system in the same operating conditions in heating. This comparison methodology has already been adopted in literature [14].

Obviously, the operating parameters of the heat pump change along with the external environmental temperatures. Table 2 shows the relationships between some operating parameters and the environmental temperature [15].

Two periods were selected to analyze the system performance, a ‘working period’ from 19 to 31 January 2011, and the ‘Spring Festival holiday period’ from 31 January to 12 February 2011. Heat supply data for those two periods are reported in Table 3. The data under the category of ‘Heat supply’ were the actual heat supply value for the whole heating season (120 days in Beijing). This was estimated along with the 108-day working period and the 12-day off period, referenced to the specific working day load and off day load shown by the data obtained from the BAS.

Figure 6 shows the temperature obtained from the data acquisition system in the period from 08:19 of 25 January 2011 to 07:19 of 26 January 2011.

A comparison has been made on the heating performance between a ground-source and an air-source heat pump. According to the Chinese National Standard [15] and environmental conditions of Beijing, the average COP of the screw-type air-source heat pump units in winter equals to 2.64. The average heating capacity in normal working period in the heating season was 414.6 kW (Table 3; 59 703 kW/(12 × 12) = 414.16 kW, the first ‘12’ stands for the length of selected normal working days and the second ‘12’ represents the 12 h operating time per day). Based on this, we then compare normal heating days in general (Table 4). Despite the different COPs, the air-source unit also needs extra power to defrost, which account for ~10.2% of the total energy consumption [12]. Combining those two aspects, the actual power input needed in the air-source system equals to 174.89 kW. Compared with the 115.17 kW of the ground-source system,

Table 1. Heat pump system power load [kW] and the evaluation of the overall system COP

<table>
<thead>
<tr>
<th>Model</th>
<th>Heat pump unit</th>
<th>Water pumps</th>
<th>Overall COP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qload COP</td>
<td>Ground Supply</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PSRHH11501</td>
<td>637.6</td>
<td>4.6</td>
<td>20 20 3.6</td>
</tr>
</tbody>
</table>

Table 2. Relationships between operating parameters and environmental temperatures

<table>
<thead>
<tr>
<th>Selected season</th>
<th>Relationship of cooling/heating power and environmental temperature</th>
<th>Relationship of power consumption and environmental temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer</td>
<td>W = −0.76 × t + 88 (kW)</td>
<td>N = 0.21 × t + 13.15 (kW)</td>
</tr>
<tr>
<td>Winter</td>
<td>W = 2.15 × t + 52.2 (kW)</td>
<td>N = 0.25 × t + 17.28 (kW)</td>
</tr>
</tbody>
</table>

Table 3. Energy consumption of heating in working and festival periods

<table>
<thead>
<tr>
<th>Period</th>
<th>Working period</th>
<th>Festival period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy reading at the beginning (kWh)</td>
<td>231 327.0</td>
<td>291 030.0</td>
</tr>
<tr>
<td>Energy reading at the end (kWh)</td>
<td>291 030.0</td>
<td>308 474.0</td>
</tr>
<tr>
<td>Energy consumption in the period (kWh)</td>
<td>59 703</td>
<td>14 744</td>
</tr>
<tr>
<td>Heating area (m²)</td>
<td>12 581.5</td>
<td></td>
</tr>
<tr>
<td>Heat supply (kWh/m²)</td>
<td>44.1</td>
<td></td>
</tr>
<tr>
<td>Heat corresponding to coal (kg/m²)</td>
<td>14.7</td>
<td></td>
</tr>
</tbody>
</table>

Table 4. Power consumption comparison between the ground-source heat pump and the air-source heat pump

<table>
<thead>
<tr>
<th>Type of heat pump</th>
<th>Heating capacity (kW)</th>
<th>COP</th>
<th>Power input (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground source</td>
<td>414.6</td>
<td>3.6</td>
<td>115.17</td>
</tr>
<tr>
<td>Air source</td>
<td>414.6</td>
<td>2.64</td>
<td>157.05</td>
</tr>
</tbody>
</table>
the ground-source heat pump is \( \approx 34.1\% \) more efficient than the air-source heat pump in heating operation in a normal working period. Moreover, the integration of solar and ground sources in this building provides a stable operating performance in comparison to a normal ground-source heat pump system.

3.2 Energy-saving effect of solar collector panels

The measured data through the solar calorimeters are used to analyze the energy-saving effects of solar collector panels. The exact calculation is shown in Table 5 for the period from 19 January to 12 February 2011. In this table, the daily CO\(_2\) emission reduction is calculated by assuming the efficiency of power-to-heat as 90%.

3.3 Energy-saving effect of solar hot water system

This analysis primarily focuses on hot water needed for drinking. There are \( \approx 400 \) people working in this building, so considering a request of 2 l for each person to drink everyday, the total hot water needed is \( \approx 800 \) l every day. Considering the average water temperature heated by collectors to be 50°C, and average underground water temperature to be 15°C in Beijing, the solar hot water system can save up to 41%. It is assumed by comparing the energy consumed from 100 to 50°C and from 100 to 15°C, because in traditional non-low-carbon offices, this energy may totally come from electrical energy.

Table 6 shows the actual electricity consumed by water heater systems from 1 July to 12 July. It is shown that the average electricity consumed for auxiliary heating is 11.07 kWh, so the electrical energy saved is \( \approx 7.7 \) kWh each day (41% saving), which equals to 3.8-kg CO\(_2\) emission reduction every day.

![Image](https://academic.oup.com/ijlct/article-abstract/7/3/192/754038)

4 ADVICE FOR INTEGRATED SYSTEMS

On the basis of the analysis of the three portions of the multi-integrated renewable energy system, some advice is reported below to help the processes of design, operation and inspection of such systems in other buildings.

4.1 Advice on design

Regarding the system described in this paper, design advice regards the following aspects:

- In the solar-ground source heat pump system, use high-efficiency solar panels and the size of the circulating pump should be properly chosen to avoid additional energy consumption. For example, during the test run, it can be detected that the temperature of the inlet water in the panels is \( \approx 45°C \), which increases the difference between the inlet water and the ambient environment, thus lower the collecting efficiency. This results from the mismatch between the area of collector panels and the usage of heated water. After reforming the water to a new system in the mess hall, the situation is improved and the panels are used more properly.
- The solar and ground sources can be connected in series with water first going through the collector tank (connection with the heat pump on the condenser side) or going through the underground pipes (connection with the heat pump on the evaporator side), or can be connected in parallel. Figure 7 shows the last two configurations. Obviously, the performance of each system changes along with the temperature of inlet water. The connection in parallel is

<table>
<thead>
<tr>
<th>Table 5. Calculation of energy-saving effect of solar collector panels</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Items</strong></td>
</tr>
<tr>
<td>Solar panels for the mess hall</td>
</tr>
<tr>
<td>Solar panels for the system of west</td>
</tr>
<tr>
<td>Solar panels for the system of east</td>
</tr>
<tr>
<td>Solar panels for the heat pump system</td>
</tr>
<tr>
<td>Total effect for all the solar panels</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 6. Actual electricity used in the water heater systems</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Floor</strong></td>
</tr>
<tr>
<td>Fourth</td>
</tr>
<tr>
<td>Fifth</td>
</tr>
</tbody>
</table>

Figure 7. The solar and ground heat source connected in series with connection on the evaporator side of the heat pump (above) and connected in parallel (below).
generally more complex from a constructive point of view, but it guarantees the highest COP of the heat pump as the temperature difference with the external environmental temperature is the lowest.

- The natural lighting system regards the choices of the glass-roof, as this can provoke an unwanted increase in the indoor temperature. Windows and glass curtain wall should be installed with an appropriate angle. Moreover, a limited heating accumulation in the circulating water is suggested. For instance, in this system, the running circulating water inside the panels on the natural lighting roof and the angled installation can keep the top of roof a modest temperature in hot summer days, and reduce the greenhouse effect slightly.

4.2 Advice on operation and inspection
A multi-integrated renewable energy system needs a careful and complete inspection before normal working period, in order to test and control every district of the system properly. Regarding the solar-ground source heat pump system, there are four main parts of inspection: the power input and heating/cooling supply system, the ground temperature field in the ground heat exchanger installed area, the heat pump system and the solar units [16, 17]. Coherently with this,

- To achieve a sustainable energy saving operation, it is required to keep the ground heat flow balanced and to monitor the heat pump operating conditions closely. An unbalance of soil temperature can generate heat accumulation or cold accumulation. For example, for a cooling system, heat accumulation on the soil gives a COP drop of 2.5% every °C of accumulation. In Eastern China area, there is an unbalanced exchange with a 2 °C rise of the temperature over one year period. Reversely, a cold accumulation of 4°C has been registered in Germany with a drop of COP of 4.1% every °C. Moreover, in the case of large systems of ground-source heat pipes, care must be taken regarding the formation of heat barrier, with peripheral pipes which influences interior ones.
- During the inspection of automatic or manual-controlled function of the heat pump system, the basis of change function should be selected and well defined as needed. It means applying influential factor of outside environment weather. In this control system, it detects the temperature and contents of CO₂ in lawn of square in front of this building. These are essential in the defined parameters of DDC inside.

5 CONCLUSIONS
The necessity to integrate several renewable energy sources in buildings has been the starting point of this paper. In fact, international statistics and agreements show the necessity to increase the diffusion of sustainable technologies and buildings, especially in transition economies. A newly built office building was used for this case study, which helps discussing the status of renewable energy systems in China, focusing in particular on the integration of solar and geothermal energy systems.

After analysis of energy-saving effects of the solar-ground source heat pump system and the comparison with an equivalent air-source heat pump system, the paper has considered the collector panels, the water heater system and the natural lighting system. Results have shown that the energy consumption in the ground-source system is 34.1% more efficient than that of the air-source system in a normal working system in Winter, 174.89 kW of the air-source system compared with 115.17 kW of the ground-source system. The saving is given by the different COPs and extra energy consumption for defrosting in an air-source system. Moreover, the solar collector panels in the system are estimated to contribute 156.11 kWh per day saving for heating in the workshop and for cleaning in the mess hall, and it equals 142.37 kg reduction of CO₂ emission per day. The solar hot water system contributes a 47% power saving in supplying drinking water. In conjunction with a detailed observation and research into their actual operation, the paper has given some advice for the process of design, operation and inspection. The hope is that the analysis of the real integrated system in this office building could be useful for the development and integration of renewable energy systems in other low-carbon buildings in China.

REFERENCES


