An Optimization Model Applied to Active Solar Energy System for Buildings in Cold Plateau Area

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Abstract

The large-scale utilization of solar energy in buildings is one of the most promising technologies to solve the global energy shortage problem and reduce the carbon dioxide emissions. The present paper has proposed an optimization model coupled with solar thermal and photovoltaic systems. Optimization results of active solar energy system from the energy saving view and economical view have been obtained for typical hotel and office buildings in cold plateau area, respectively.

1. Introduction

With the remarkable growth of the plateau architectural scale, shortage of traditional building energy supply and fragility of ecological environment are becoming the prominent factors to restrict the development of the plateau areas. Considering the solar energy as an effective, economic and safe energy resource, Qinghai-Tibet Plateau, Inner Mongolia Plateau and other plateau areas which are rich in solar energy resources have the potential to develop and utilize solar energy resources on a large scale. In addition, solar thermal and photovoltaic technologies have been widely applied in plateau buildings due to rapid development of solar energy technologies and gradual cost reduction of solar energy utilization equipment. Therefore, it has been attracting significant attentions to efficiently utilize the plateau solar energy resources and economically integrate with low energy consumption plateau buildings in recent years.

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Active solar heating technologies have recently become the research emphasis in the field of building solar utilization because of the rapid development of active solar energy products. Maurer et al. [1] presented four new and simple models for building-integrated solar thermal system, which are more accurate than neglecting the coupling to the building and less complicated than detailed physical models. Lamnatou et al. [2] evaluated their patented building-integrated solar thermal collector, and revealed that configuration with collectors in parallel connection can considerably improve the environmental profile of the configuration with collectors in series. Hwang et al. [3] analyzed the maximum electric energy production according to the inclination and direction of photovoltaic installations and the effects of the installation distance to the module length ratio. Vats et al. [4] carried out comparative studies between building integrated semitransparent photovoltaic thermal system and building integrated opaque photovoltaic thermal system, which are respectively integrated to the facade and roof of a room with and without air duct for the cold climatic conditions of Srinagar, India. Michael et al. [5] combined the electrical and thermal components in a single unit area and proposed a reference guide for flat plate solar photovoltaic-thermal systems, to overcome the disadvantages of low energy of the solar PV module, the low exergy of the solar flat plate thermal collector and limited usable shadow-free space on building rooftops.

Even though a variety of researchers have studied the independent solar thermal technologies and photovoltaic technologies applied in the buildings, the comprehensive utilization system of solar energy which combines the solar thermal and photovoltaic technologies has seldom been investigated. In addition, most plateau areas are limited to the utilization of single thermal technology or single photovoltaic technology due to complexity of solar integrated thermo-electricity coupling system and shortage of corresponding design methodology, significantly hindering the promotion of the integrated photovoltaic and thermal systems. Therefore, the present paper proposes an optimization model coupled with solar thermal and photovoltaic systems, to reasonably configure the solar thermal and photovoltaic system, thus achieving the optimization utilization and economical efficiency of solar energy resources for buildings in cold plateau area.

2. Method

2.1. System Physical Model

The schematic drawing of the proposed physical model is shown in Figure 1.
The solar heat collector and air source heat pump auxiliary thermal source provide heat source for buildings heating in winter, while the photovoltaic supplies power for the building electrical appliances, air source heat pump and delivery water pump. When the generated energy is higher than the electricity demand of the whole building, the excessive electricity will be delivered to the grid. On the contrary, the urban grid will supply the shortfall.

In the proposed model, there is strong coupling relationship between the heating power and electricity. The solar collector size may affect the heat load of the auxiliary heat source, which will further affect the power balance relation of photovoltaic system and installation area of solar photovoltaic cells. On the other hand, the change of power photovoltaic area will reversely affect the heat collecting capacity and thermal storage characteristics of solar thermal system. The interaction between solar thermal and photovoltaic is not only reflected during the solar thermal/photovoltaic conversion process and thermal storage/electric power storage process, but also reflected during the annual energy consumption of the building, which also has significant influence on the economic aspects of the integrated utilization system. The coupling relationship among building energy consumption, energy generation and energy storage, coupled with dynamic changes of meteorological parameters, ultimately forms a complicated multi-variable dynamic coupling process.

2.2. Optimized mathematical model

The System hourly electricity balance relation can be expressed by:

$$Q_{e}(h,A_{s},A_{r}) - Q_{q}(h) - Q_{g}(h,A_{r}) = Q_{s}(h,A_{s},A_{r},A_{w})$$  \(1\)

Where $Q_{e}(h,A_{s},A_{r})$ is the hourly power generation capacity of photovoltaic equipment, kWh; $Q_{q}(h)$ is the hourly power consumption of other equipment excluding heating equipment, kWh; positive $Q_{g}(h,A_{s},A_{r})$ represents hourly on-grid power, while negative value represents hourly power consumption from urban grid, kWh; $Q_{s}(h,A_{s},A_{w})$ is hourly power consumption of heating system, kWh; $A_{s}$ is the coverage roof area of photovoltaic generation assembly, m²; $A_{r}$ is the coverage roof area of solar thermal equipment, m².

At time $h$, the system hourly heat balance relation:

Direct heating capacity of the collector is expressed by:

$$Q_{s}(h) = \begin{cases} Q_{e}(h) - Q_{g}(h) - Q_{q}(h) \\ Q_{q}(h), Q_{g}(h) < Q_{q}(h) \end{cases}$$  \(2\)

Heat balance equation of the residual heat in water tank can be expressed by:

$$Q_{r}(h) = \begin{cases} Q_{s}(h) - Q_{e}(h) - Q_{g}(h) - Q_{q}(h) \\ 0, Q_{s}(h) - Q_{g}(h) - Q_{q}(h) < 0 \end{cases}$$  \(3\)

Insufficient heat after direct heat supplied by solar collector can be expressed by:

$$Q_{r}(h) = \begin{cases} Q_{s}(h) - Q_{g}(h) - Q_{q}(h) \\ 0, Q_{s}(h) - Q_{g}(h) - Q_{q}(h) > 0 \end{cases}$$  \(4\)

The water tank instant heat storage capacity can be expressed by:

$$Q_{w}(h) = \begin{cases} Q_{r}(h) - Q_{g}(h) - Q_{q}(h) \\ 0, Q_{r}(h) - Q_{g}(h) - Q_{q}(h) \leq 0 \end{cases}$$  \(5\)

Heating capacity of auxiliary heat source can be expressed by:

$$Q_{a}(h) = \begin{cases} Q_{w}(h) - Q_{g}(h) - Q_{q}(h) \\ 0, Q_{w}(h) < 0 \end{cases}$$  \(6\)

Where $Q_{s}(h)$ is the heat storage capacity of the collector at time $h$, kJ; $Q_{w}(h)$ is the required heat for heating at time $h$, kJ;
Annual on-grid energy, kWh, can be expressed by:
\[
Q_{\text{on}}(A_{\text{on}}, A_{\text{on}}) = \sum_{h=0}^{\text{h, sd w r w}} \left( Q_{(h, A_{\text{on}}, A_{\text{on}})} Q_{(h, A_{\text{on}}, A_{\text{on}})} > 0 \right)
\]
(7)

Annual urban grid electricity consumption, kWh
\[
Q_{\text{u}}(A_{\text{on}}, A_{\text{on}}) = \sum_{h=0}^{\text{h, sd w r w}} \left[ Q_{(h, A_{\text{on}}, A_{\text{on}})} Q_{(h, A_{\text{on}}, A_{\text{on}})} < 0 \right]
\]
(8)

Annual energy consumption (calculated by electricity consumption), kWh, can be expressed by:
\[
Q_{\text{on, u}}(A_{\text{on}}, A_{\text{on}}) = Q_{\text{on}}(A_{\text{on}}, A_{\text{on}}) - Q_{\text{on}}(A_{\text{on}}, A_{\text{on}})
\]
(9)

Roof area limited constraint, m², can be expressed by:
\[
A_{\text{on}} + A_{\text{on}} \leq A_{\text{on}}
\]
(10)

Annual operation cost, Yuan, can be calculated by:
\[
P(A_{\text{on}}, A_{\text{on}}) = P_{\text{on}}(A_{\text{on}}, A_{\text{on}}) + \sum_{h=0}^{\text{h, sd w r w}} \left[ Q_{(h, A_{\text{on}}, A_{\text{on}})} Q_{(h, A_{\text{on}}, A_{\text{on}})} > 0 \right] \times 0.42 +
\]
\[
\left[ Q_{(h, A_{\text{on}}, A_{\text{on}})} \times (0.38 + 0.42) Q_{(h, A_{\text{on}}, A_{\text{on}})} > 0 \right] \times 0.8521
\]
(11)

Where \( P_{\text{on}}(A_{\text{on}}, A_{\text{on}}) \) is annual maintenance cost, Yuan.

Dynamic analysis method is used to carry out technical economical analysis. Annual calculation cost can be obtained by:
\[
Z(A_{\text{on}}, A_{\text{on}}) = \theta K(A_{\text{on}}, A_{\text{on}}) + P(A_{\text{on}}, A_{\text{on}}) = \frac{\theta}{(1+i)^n - 1} K(A_{\text{on}}, A_{\text{on}}) + P(A_{\text{on}}, A_{\text{on}})
\]
(12)

Where \( k \) is initial investment, Yuan; \( i \) is interest rate/yield rate, %, which is 8% in the present study; \( n \) is the production period, which is the collector service life (15 years) in the present study; \( p \) is operation cost; \( \theta \) is the capital recovery coefficient.

Considering from the energy saving view, the objective function is:
\[
S = \min \left[ Q_{\text{on, u}}(A_{\text{on}}, A_{\text{on}}) \right] = \min \left[ Q_{\text{on}}(A_{\text{on}}, A_{\text{on}}) - Q_{\text{on}}(A_{\text{on}}, A_{\text{on}}) \right]
\]
(13)

Considering from the economical view, the objective function is:
\[
S = \min \left[ Z(A_{\text{on}}, A_{\text{on}}) \right] = \min \left[ \frac{\theta}{(1+i)^n - 1} K(A_{\text{on}}, A_{\text{on}}) + P(A_{\text{on}}, A_{\text{on}}) \right]
\]
(14)

3. Case study

The developed simulation model was applied to typical buildings located in Lhasa city lying in the center of Tibetan Plateau as the capital of the Tibet Autonomous Region of China. With an elevation of 3650m, Lhasa is also known as the “city of sunlight” mainly due to its received strong solar radiation and extensive sunshine hours, ranking first in cities of China. Therefore, solar energy has been considered as a promising option to upgrade heating systems in Lhasa, which could reduce the demands in fossil fuel and eliminate carbon dioxide emission.

3.1. Building parameters
Typical three-floor office buildings and hotel buildings in Lhasa, both with the story height of 3m, are selected as the research objects. Three dimensional models for office buildings and hotel buildings are shown in Figure 2 and Figure 3, respectively.

3.2. Optimization results of active solar energy system from the energy saving view

The influences of solar thermal/photoelectric area on annual power consumption of typical buildings in Lhasa are shown in Figure 4. In Lhasa, for the solar energy comprehensive utilization proposal, all roof areas are covered by solar photovoltaic to achieve the minimum annual power consumption both in hotel buildings and office buildings. In other words, considering from maximum energy saving in the buildings, the building roofs shall preferably adopt solar photovoltaic system.

The above calculation results can be attributed to the following four reasons. Firstly, the annual utilization period of solar photovoltaic system is 2-3 times of that of solar thermal system. Solar photovoltaic system can be used in the whole year, generating available energy for 12 months; while the solar thermal system is only utilized in the heating season, only generating available energy for 4-5 months. Secondly, the daily utilization periods of solar photovoltaic system and solar thermal system are different. The heat collecting efficiency of solar thermal system is not only affected by radiation intensity,
but also relevant with outdoor dry-bulb temperature. Lower outdoor temperature is unfavorable for solar thermal system to obtain solar radiation energy. Therefore, during the sunrise and sunset period with lower temperature, the collector surface receiving solar radiation could not generate available energy, consequently reducing the effective heat collecting time by more than 2 hours in comparison with the solar radiation time. Thirdly, the urban power grid with infinite energy storage capacity can be used as the ideal energy storage system of solar photovoltaic system. However, the heat storage capacity of solar thermal system is restricted by the heat storage tank volume and heating water supply quality requirement. The received effective solar radiation energy could not be completely utilized, and the system energy saving is significantly reduced due to the existence of waste heat energy. Fourthly, the electric energy generated by solar photovoltaic system is high quality energy compared to the hot water around 55°C generated by solar thermal system, which also improves the energy saving property of photovoltaic system.

3.3. Optimization results of active solar energy system from the economic view

The influences of solar thermal/photoelectric area on annual calculation costs of typical buildings in Lhasa are shown in Figure 5, taking the government photovoltaic allowance and taxes into account. It can be obviously observed that, as to the solar energy comprehensive utilization proposal, all roof areas are covered by solar photovoltaic to achieve the minimum annual calculation costs both in hotel buildings and office buildings. In other words, considering from the building economical view, the building roofs shall preferably adopt solar photovoltaic system.

![Fig. 5. Influence of solar thermal/photoelectric area on annual calculation costs of typical buildings in Lhasa](image)

In addition to the reasons as previously described in section 3.2, the economical efficiency of the solar photovoltaic system is superior to that of solar thermal system because of the better financial allowance policy of photovoltaic system compared with the latter. Further, the service life of the photovoltaic system is generally 25 years, 10 years more than the service life of the solar thermal system, so the initial investment difference is reduced taking the service life into account.

4. Conclusion

As mentioned above, the photoelectric conversion efficiency of the photovoltaic system is lower than the heat collecting efficiency of the solar thermal system, but with consideration of the differences in utilization period, energy storage system characteristics and generated energy quality, the solar utilization efficiency of the photovoltaic system is higher than that of the solar thermal system during the whole year operation. Even though the unit area cost of the photovoltaic system is higher than that of the solar
thermal system, after taking the energy saving, financial allowance and other factors, the economical efficiency of the photovoltaic system is still superior to the solar thermal system during the whole year operation.

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References


Biography

Yuexia Lv graduated with the doctorate degree in Energy and Environmental Engineering at Mälardalen University in 2011. Research mainly focuses on solar energy utilization and CO₂ capture by membrane gas absorption technology.