Modeling and Optimization for Contribution Rates of Solar Heating and Cooling Systems in Building Energy-Saving

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Abstract

With the increased emphasis on building energy-saving in China, solar heating and cooling (SHC) has become one of the best promised technologies to achieve ultra-low energy consumption. To achieve improved economy performance, enhancing energy system efficiency, SHC system requires scientific calculation and analysis according the architectural features. In this paper, building and system models have been established for hourly simulation of energy consumption. The deviation of tested and simulated solar fraction and system COP is about 5%. It indicates the system model established in this paper is accurate enough for design and optimization of SHC systems. With verified models, SHC system has been optimized considering the solar contribution and economy index. Results show that, after the system scheme and configuration optimization, SHC system applied in office building in Turpan can be achieved in the solar contribution of more than 30%. Meanwhile, the payback period could be reduced to less than 20 years.

Keywords: solar heating and cooling, solar contribution, system design and optimization, payback period

1. Introduction

With the increased emphasis on building energy-saving in China, the limit of building energy consumption is stricter than ever. Nearly zero energy building, passive building has become a new trend (Xu et al. 2016). As the energy consumption for space heating and cooling accounts for a large part of the building energy consumption, solar heating and cooling (SHC) has become one of the best promised technologies to achieve ultra-low energy consumption.

After years of development, SHC technology has made great progress in the technical maturity and practical application. However, SHC system has not been promoted widely because its high initial cost and low efficiency. Sarabia et al. (2011) proposed a design method for solar cooling systems with single effect absorption cooling machine directly coupled to a solar collector field, then analyzed the feasibility of the system in 12 Spanish Cities. Syed et al. (2005) designed a solar cooling system for residential buildings in Madrid. And the test results showed that the average coefficient of performance is around 0.6. Mateus et al. (2009) investigated solar absorption cooling and heating system in different building types and climates. With TRNSYS software, contributions of SHC system in building energy-saving had been analyzed. Li Z. et al. (2000, 2001) proposed a solar absorption cooling system with a layered heat storage tank, and the system was optimized and applied in Hong Kong.

To achieve improved economy, enhancing energy system efficiency, SHC system requires scientific calculation and analysis according the architectural features. In this paper, building and system models have been established for hourly simulation of energy consumption. With verified models, SHC system has been optimized considering the solar contribution and economy index.

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2. Method

2.1. Contribution rates

Similar to solar fraction, contribution rates of solar heating and cooling systems in building energy-saving means the proportion of building heating and cooling demands meet by solar energy. The calculation method is as follows:

$$f_s = \frac{E}{Q} \qquad \text{(eq. 1)}$$

Where, f_s is the contribution rates in building energy-saving; E is building heating and cooling demands meet by solar energy; Q is total heating and cooling demands.

2.2. Optimization method

Contribution rate of SHC systems is affected by many factors. To achieve an optimal contribution rate, building and system models have been established first. Then hourly energy consumption and system performance have been simulated. During the simulation, Effects of climate, building type, and SHC system type have been considered, as shown in Fig. 1. With simulation results, the system contribution rates in building energy-saving could be determine considering following key indicators:

- *Indoor temperature*, *heating and cooling capacity*: the indoor temperature, system heating and cooling capacity have to meet the design requirements;
- *Energy saving*: reduction rate of primary energy consumption as the main index;
- *Economy*: payback period as the main index.

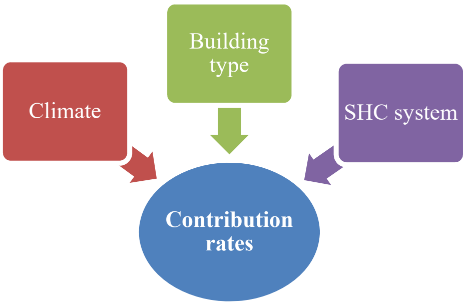


Fig. 1: Affect factors on contribution rate

3. Modeling

3.1. Building model

An office building model and an inpatient building model have been established to analyze the heat and cooling demands in different building types. Construction dimensions of both models are determined according to the design drawings of actual buildings. Building envelope conditions meet requirements of the *Design standard for energy efficiency of public buildings* (GB 50189-2015) in China. Operation time of the office building and inpatient building is different: the office building is used from 08:00 to 18:00 during workdays while the inpatient building is used 24 hours all year round.

As the actual buildings is still under construction, another office building is selected and modeled to verify the building and system models. Brief information of three buildings are shown in Tab. 1.

To analyze the effect of climates on contribution rates, heating and cooling loads of both office building and inpatient building have been calculated according the climates of different locations, results shown in Tab. 2.

Tab. 1: Building Information

Building	**Height**	**Floors**	**Gross floor area (m^2)**
office building	18.6 m	4 floors above ground 1 floor under ground	6144
inpatient building	24.9 m	6 floors above ground	5904
office building for validation	11.8 m	2 floors above ground	1850

Tab. 2: Heating and cooling loads of the office building and inpatient building in different locations

Location	Building	Cooling		Heating	
		Load (kW)	Annual demand (MJ)	Load (kW)	Annual demand (MJ)
Beijing (Northeast China)	office building	512	254,715	580	93,340
	inpatient building	504	348,776	456	146,808
Turpan (Northwest China)	office building	644	274,512	494	110,243
	inpatient building	625	374,172	381	141,172

3.2. System description

Based on investigation and analysis of practical projects, three types of SHC systems are summarized and compared with the conventional system. The SHC systems and conventional system are listed in Tab. 3.

Tab. 3: The SHC systems and conventional system

System			**Heating and Cooling Souce**
SHC systems	System I：Solar absorption cooling + Water cooled chiller + Gas boiler	Cooling	Solar collectors＋WFC + Water cooled chiller
		Heating	Solar collectors＋Gas boiler
	System II：Solar absorption cooling+ WSHP + Gas boiler	Cooling	Solar collectors＋WFC＋WSHP
		Heating	Solar collectors＋WSHP＋Gas boiler
	System III: Optimized SHC system	Cooling	Solar collectors＋WFC＋WSHP
		Heating	Solar collectors＋WSHP＋Gas boiler
Conventional system	Water cooled chiller + Gas boiler	Cooling	Water cooled chiller
		Heating	Gas boiler

WFC: Hot water fired absorption chiller WSHP: Water source heat pump

System I: Solar absorption cooling + Water cooled chiller + Gas boiler

The main components of this system include the Solar collectors, an Hot water fired absorption chiller (WFC), a Heat storage tank, Cooling towers, a Gas boiler and a Water cooled chiller for summer cooling. The system schematic is showed in Fig. 2.

Cooling mode:

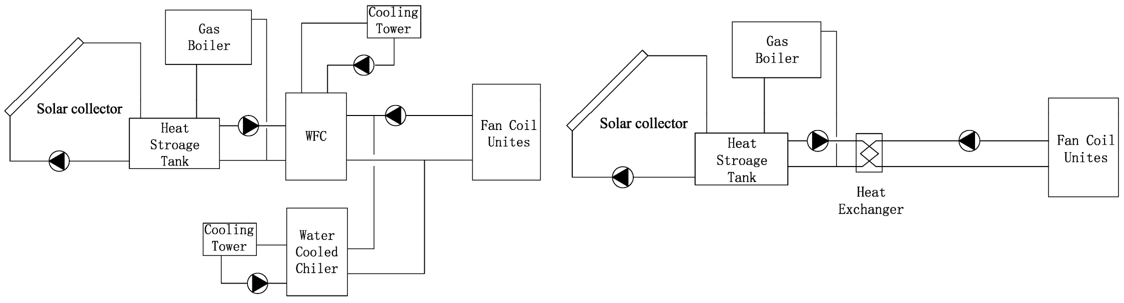
1. When the heat storage tank temperature is higher than the set point, WFC is used in priority to meet the cooling demand. When WFC cooling capacity can not meet the cooling demand, Water cooled chiller starts.

2. If the heat storage tank temperature is below the set point, Water cooled chiller is used to meet the cooling demand.

Heating mode:

1. If the heat storage tank temperature is higher than the heating requirement in winter, heating demand is satisfied directly by solar.

2. If the heat storage tank temperature is lower than the requirement, Gas boiler starts to satisfy the heating demand.



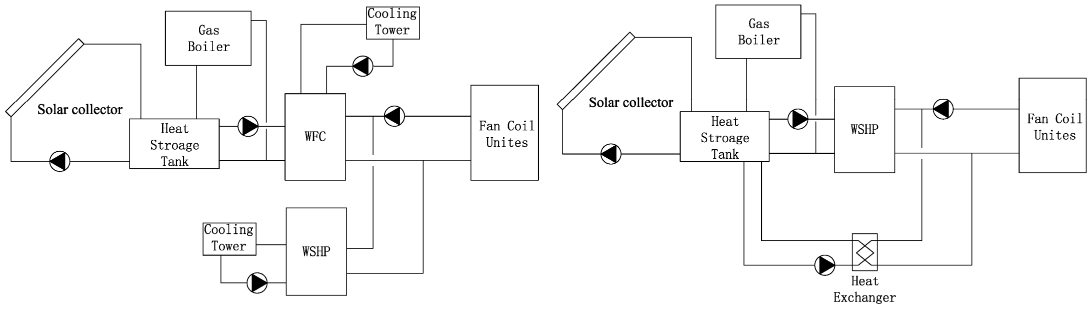
(a) cooling mode

(b) heating mode

Fig. 2: Schematic of System I

System II: Solar absorption cooling+ WSHP + Gas boiler

The main components of this system include the Solar collectors, an Hot water fired absorption chiller (WFC), a Heat storage tank, Cooling towers, a Gas boiler and a Water source heat pump (WSHP) for both heating and cooling. The system schematic is showed in Fig. 3.



(a) cooling mode

(b) heating mode

Fig. 3: Schematic of System II

Cooling mode:

1. When the heat storage tank temperature is higher than the set point, WFC is used in priority to meet the cooling demand. When WFC cooling capacity can not meet the cooling demand, WSHP starts.

2. If the heat storage tank temperature is below the set point, WSHP is used to meet the cooling demand.

Heating mode:

1. If the heat storage tank temperature is higher than the heating requirement in winter, heating demand is

satisfied directly by solar.

2. If the heat storage tank temperature is lower than the requirement, but higher than WSHP's requirement, WSHP starts to satisfy the heating demand.

3. System could also provide heating by Gas boiled directly.

Main difference between System I and System II is that the WSHP could provide heating by lower temperature water. Solar contribution rate could be increased in winter.

System III: Optimized SHC system

The main components of this system is same as System II. Main difference between System III and System II is that the heating capacity of WSHP can fully satisfy the heating load, but the cooling capacity is not required to meet the cooling load. So, the system could use a WSHP with lower volume to improve the economy indexes.

When cooling in summer, if the heat storage tank temperature is below the set point, WSHP co-works with WFC to meet the cooling demand.

3.3. System model

With TRNSYS software, all systems have been modeled and simulated based on typical meteorological year (TMY) weather data and building data of both Beijing and Turpan. The TRNSYS model of System I is shown in Fig. 4. The TRNSYS model of System II & System III is shown in Fig. 5.

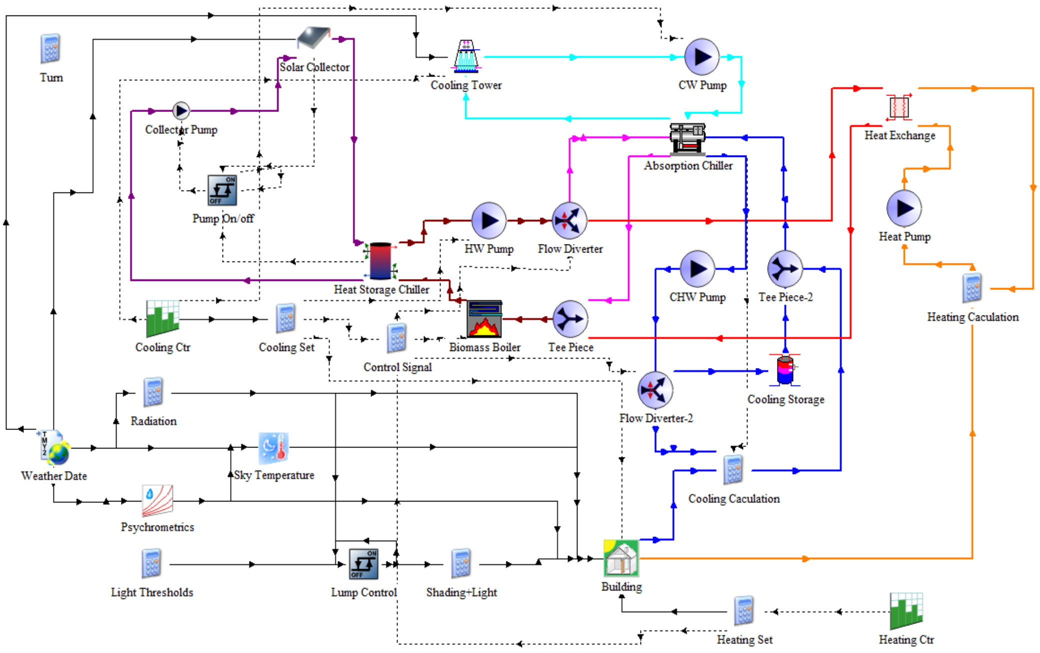


Fig. 4: The TRNSYS model of System I

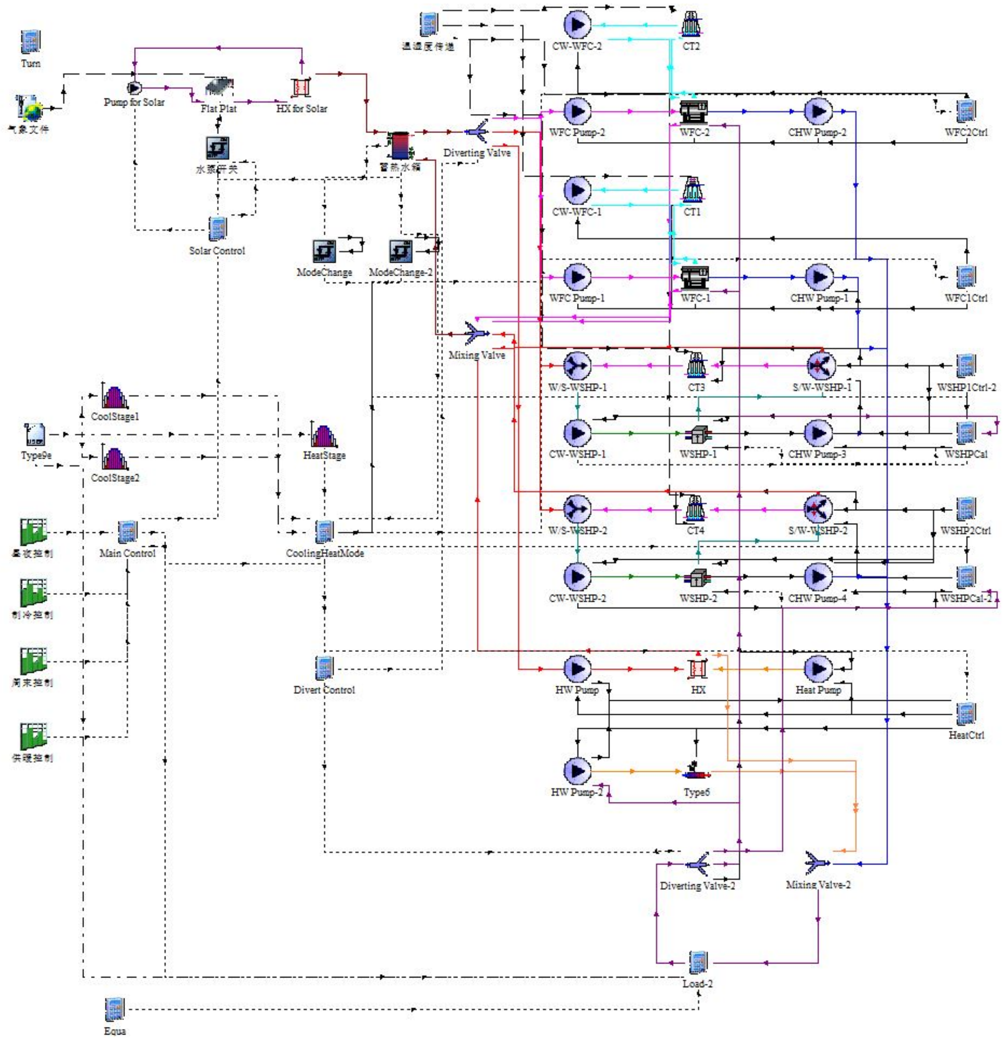


Fig. 5: The TRNSYS model of System II & System III

4. Model Validation

In this study, an office building with SHC system in Beijing is selected and modelled. Simulated and measured results are compared to verify the system model.

This two floors office building is located in Beijing, China. The SHC system applied for space cooling and heating is same as System I. Building and system information is published in previous study (He et al. 2014). The system had been tested during the summer of 2013 by China Academy of Building Research. There were 4 days selected to test the system performance under typical weathers. The solar irradiation levels of the 4 days were respectively very good, good, medium and poor.

To verify the system model, measured data of environmental parameters was integrated into the weather data of TRNSYS model of System I. Then Several operating data, such as tank temperature, flow rate, had been used to set the initial simulate conditions. Tested COP and solar fraction were compared with simulated results, as shown in Fig. 6.

Comparison of tested and simulated results show that the deviation of tested and simulated solar fraction and system COP is about 5%. It shows that the system model is accurate enough to caculate system performance.

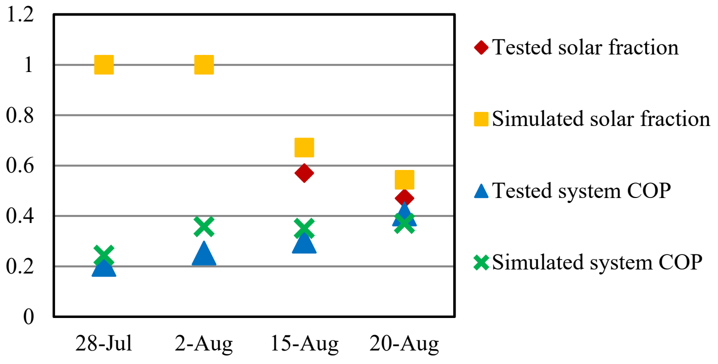
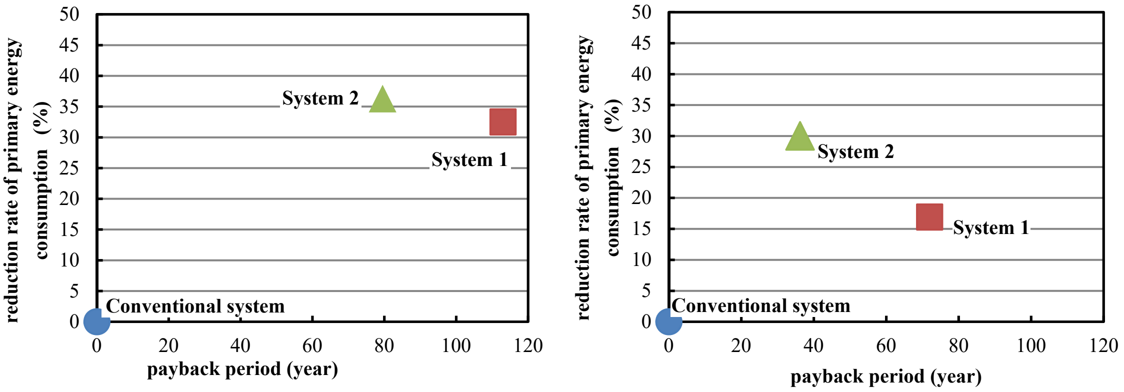


Fig. 6: Comparison of tested and simulated results

5. Optimization

5.1. Simulation results

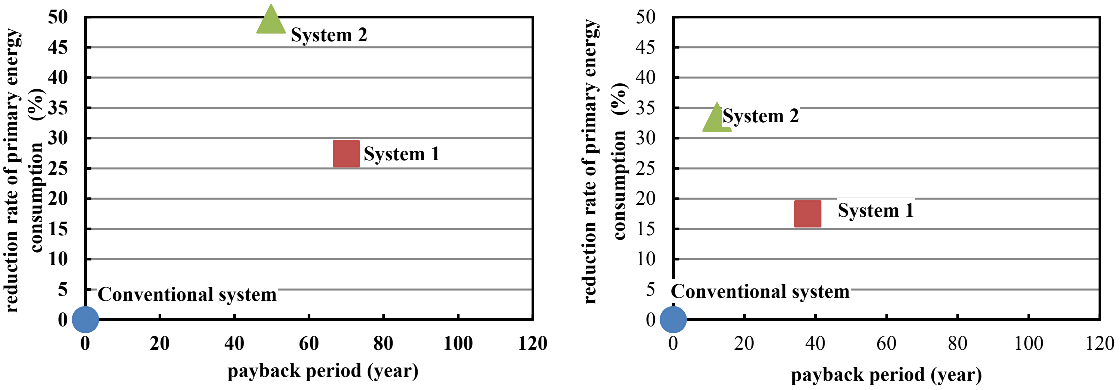
In this study, Solar contribution rates of System I and System II applied in different building types and climates have been simulated separately. Results is shown in Fig. 7 to Fig. 8.



(a) Turpan (Northwest China)

(b) Beijing(Northeast China)

Fig. 7: Simulated results of System I and System II in office building



(a) Turpan (Northwest China)

(b) Beijing(Northeast China)

Fig. 8: Simulated results of System I and System II in inpatient building

Results shows that the reduction rate of primary energy consumption of System II is larger than 30% in all buildings. In the inpatient building, the primary energy consumption could be reduced by 50%. It indicates the

SHC system has significant effect in energy-saving. But nearly all payback periods are more than 30 years, except the System II applied in inpatient building in Beijing. These unacceptable payback periods show the optimization of SHC system needs to focus on enhancing the economic performances.

5.2. System optimization

Based on System II, System III is proposed to improve the economic performances of SHC systems. Compared with System II the optimization includes:

- The heating capacity of WSHP can fully satisfy the heating load, but the cooling capacity is not required to meet the cooling load. The system could use a WSHP with lower volume to reduce initial cost.
- When cooling in summer, if the heat storage tank temperature is below the set point, WSHP co-works with WFC to meet the cooling demand.
- Increasing system scale, solar contribution rate of solar district heating and cooling system in regional heating and cooling has been simulated.

Tab. 4 shows the simulated results of System III applied in a district heating and cooling project in Turpan. The simulated results indicates that the economic performance of System III has been improved while the energy-saving effect is still significant (Reduction of primary energy consumption is more than 30%). After system optimization, the contribution rate of System III in energy-saving is about 36.8%.

Tab. 4: Simulated results of System III applied in a district heating and cooling project in Turpan

		System III	**Conventional system**
Summer	Cooling capacity (kW)	4269.4	4357
	Heat gain by collectors (MJ)	6.75E+06	0
	Cooling load (MJ)	1.21E+07	1.21E+07
	Solar contribution	40%	0%
Winter	Heat gain by collectors (MJ)	3.38E+06	0.00
	Heating load (MJ)	1.02E+07	1.02E+07
	Solar contribution	33%	0%
Electricity (kW/h)		**841431**	**1173764**
Gas consumption (m^3)		**206015**	**308216**
Reduction rate of primary energy consumption		**30.8%**	**-**
Increased investment (thousand Yuan)		**6311.9**	**-**
Reduction of operation cost (thousand Yuan)		**343.2**	**-**
Payback period (Year)		**18.4**	**-**

6. Conclusion

With the increased emphasis on building energy-saving in China, solar heating and cooling (SHC) has become one of the best promised technologies to achieve ultra-low energy consumption. To achieve improved economy, enhancing energy system efficiency, SHC system requires scientific calculation and analysis according the architectural features.

In this paper, building and system models have been established to simulate the contribution rate of different SHC systems in energy-saving. Effects of climate, building type, and SHC system type have been considered during simulation. Results show that:

- The deviation of tested and simulated solar fraction and system COP is about 5%. The system model established in this paper is accurate enough for design and optimization of SHC systems.

- Traditional SHC system has significant effect in energy-saving, but the economic performance needs to be enhanced.
- After the system scheme and configuration optimization, SHC system applied in office building in Turpan can be achieved in the solar contribution of more than 30%. Meanwhile, the payback period could be reduced to less than 20 years.

7. Acknowledgement

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