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MULTI-OBJECTIVE OPTIMAL DESIGN OF A SOLAR HEATING SYSTEM UNDER WEATHER UNCERTAINTY AND SYSTEM RELIABILITY

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ABSTRACT

In the design of renewable energy capacity, due to the existence of weather uncertainty, the conventional design method can easily lead to overdesign or unsatisfactory performance in order to ensure the system is completely reliable. Most existing solar heating system (SHS) design optimization studies are based on deterministic data or information. However, weather uncertainty is one of the key factors affecting the reliability of the system and the rationality of design results. Therefore, this study proposed a multi-objective optimal design method for SHS considering the uncertainty of the weather and reliability of the system. Taking a SHS of an office building in Tianjin as an example, based on the actual meteorological parameters of 20 years, the uncertainty of the performance of buildings and equipment are simulated by TRNSYS and EnergyPlus. Multi-objective optimization under economic, environment and reliability of the system are considered in optimization algorithm. The optimization results show that compared with the conventional f-chart method, total annual cost and CO_2 emissions are respectively reduced by 8.3% and 2.5%. Compared with the exhaustive method, it can shorten the calculation time by 98.5%, which can greatly improve the efficiency of optimization.

Keywords: solar heating system, optimization, weather uncertainty, reliability

NONMENCLATURE

Abbreviations	
SHS	Solar Heating System
TRNSYS	Transient System Simulation Program
TAC	Total Annual Cost
CRF	Capital Recovery Factor
HOIH	Hours of Insufficient Heating
ROHS	Reliability of the Heating System
GPSPSOCCHJ	Generalized Pattern Search Algorithm with Particle Swarm Optimization with Construction Coefficient and Hooke-Jeeves Algorithm
Symbols	
A_{sc}	solar collector area (m^2)
C_{aux}	auxiliary heater capacity (kW)
F_{CO2}	CO_2 emission factor
G_C	mass flowrate of pumps (kg/m^3)
H_C	head of pumps (m)
L_C	total running time of pumps (h)
m_{CO2}	CO_2 emissions (kg)
P_e	price of electricity ($/kWh)
Q_l	heat demand(kW)
Q_s	heat supply(kW)
R_c	initial cost($)
R_i	installation cost ($)
R_{op}	operating cost($)
R_m	maintenance cost ($)
R_p	operating cost of pumps ($)
R_{aux}	operating cost of auxiliary heater ($)
T	total running time (h)
V_{st}	tank volume (m^3)
η_p	pump efficiency
η_m	motor efficiency
λ	set weight values

1. INTRODUCTION

Renewable energy is easily affected by meteorological parameters such as solar radiation, temperature and wind speed. Its real-time production becomes obvious uncertainty, which leads to a big challenge in the renewable energy planning. Accurate assessment of renewable energy capacity is critical to the long-term planning of the system.

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In the planning and design of solar heating system (SHS), in order to simplify the design procedure, the mean substitution value of meteorological data was used to calculate the solar collector area in the conventional design method [1]. Furthermore, in order to ensure the reliability of the system, the auxiliary heater capacity was designed based on the determined design heating load [2]. However, it can lead to system oversized and a significant increase in production and environmental costs. Therefore, more and more studies focus on the multi-objective optimization design of the SHS under economic and environmental issues. Based on the 3E(Economy/ Energy/ Environment) concept, Victor Tulus et al. considered to optimize central solar heating plants with seasonal storage capacity design under different climatic conditions and heat demand conditions [3]. Jose M. Cardemila et al. optimized the solar water heating system design parameters from the perspective of government incentive policies, with tax rebate schemes and time-sharing electricity prices as optimization targets [4]. However, the above optimization methods are deterministic design method, and did not consider the influence of uncertainty factors. Therefore, Singiresu S. Rao proposed to consider the solar factor, typical daily load and other design variables as normal distributions. The optimization design of the flat-plate collector under these uncertain conditions was carried out and proved to be more accurate [5].

However, the above methods neglected the basic requirements of the system, the hourly energy balance between the supply and the demand. The uncertainty of the meteorological parameters will greatly affect the reliability of the system. Therefore, this paper proposes a SHS planning and design method based on reliability assessment under weather uncertainty. 20 years of measured data is used to express meteorological uncertainty changes, and TRNSYS and EnergyPlus are combined to simulate the hourly energy supply and heating load. Multi-objective optimization design of solar heating systems are conducted through economic, environmental and reliability constraints. Finally, a hybrid algorithm is used for multi-objective optimization and the results of f-chart method and optimization method are studied and compared.

2. METHODOLOGY

2.1 Optimization objective functions

- Economic indicators

The annual life cycle cost is used to evaluate the economy of SHS. The economic indicator is expressed as the total annual cost (*TAC*) [6, 7], including the total initial cost (R_c), operating cost (R_{op}) and maintenance cost (R_m), as shown in Eq. (1).

$$TAC = R_c + R_{op} + R_m \tag{1}$$

R_c includes the purchase and installation cost of all equipment (R_i), and R_i is 2% of the purchase cost [8].The operating cost (R_{op}) includes the energy consumption cost (R_p and R_{aux}) of pumps and the auxiliary heater during the operation time and the maintenance cost (R_m). R_m is 2% of the initial cost, expressed by Eq. (2) - (4).

$$R_{op} = R_p + R_{aux} + R_m \tag{2}$$

$$R_p = P_e \rho g H_C G_C L_C / (3.6\eta_p \eta_m) \tag{3}$$

$$R_{aux} = \sum_{t=0}^{N} P_e q_{aux}(t) \tag{4}$$

Where P_e is the price of electricity, H_C is the head of pump, G_C is the mass flowrate of the pump, L_C is the total running time of the pump, η_p is the pump efficiency and η_m is the motor efficiency.

- Reliability indicators

In order to meet the heating load, it is necessary to match the relationship between heating load and the heat supply of system. Based on the energy balance, two definitions of reliability indicators are proposed to evaluate the reliability of SHS in this paper. The first one is the hours of insufficient heating (*HOIH*), defined as the total hours when the heat demand (Q_l) is greater than the heat supply (Q_s). When judging at the hour (t), it can be given in the Eq. (5), and T hours in total can be expressed in the Eq. (6).

$$Prob\{Q_s(t) < Q_l(t)\} = \begin{cases} 0 & (Q_s(t) \ge Q_l(t)) \\ 1 & (Q_s(t) < Q_l(t)) \end{cases} \tag{5}$$

$$HOIH = \sum_{t=0}^{T} Prob\{Q_s(t) < Q_l(t)\} \tag{6}$$

The second definition is the reliability of the heating system (*ROHS*), which represents the reliability of the SHS in operation, that is, the reliability of the system in T hours, which can be computed by Eq. (7).

$$ROHS = \frac{HOIH}{T} \times 100\% \tag{7}$$

- Environmental indicators

Conventional energy sources (such as gas boilers and electric boilers) can cause an increase in CO_2 emissions during operation. Therefore, the addition of renewable energy to conventional systems can reduce the use of conventional energy sources, thereby reducing CO_2 emissions. In the SHS, the total CO_2 emissions (m_{CO2}) are calculated as unit energy consumption, as shown in Eq. (8) [9].

$$m_{CO_2} = \sum_{j=1}^{s}\sum_{t=0}^{T}\frac{p_j(t)}{F_{CO_2}} \tag{8}$$

Where s is the total types of equipment, T is the total running time, $p_j(t)$ refers to the consumed electric power of the class j equipment at the hour t; F_{CO2} is CO_2 emission factor (0.54522 kg/kWh).

2.2 *Optimization process based on weather uncertainty*

Schemes are evaluated by using the normalized target function ($f_{obj,i}$). This function involves two goals: total annual cost (TAC_i) and CO_2 emissions (m_{CO2}). The specific optimization objective function is expressed as Eq. (9).

$$\min_x \left\{ f_{obj,i}(x) = \lambda_1 \times f_{TAC,i}(x) + \lambda_2 \times f_{m,i}(x) \right\}, \quad i = 1,2,\ldots,n$$

$$\text{s.t.} \begin{cases} x \in S \\ \lambda_1 + \lambda_2 = 1,\ \lambda_1, \lambda_2 \in \mathbb{R} \\ ROHS_i(x) \geq ROHS_{set} \end{cases} \tag{9}$$

Where $f_{TAC,i}$ means the normalized total cost of the i-th scheme, $f_{m,i}$ is the normalized CO_2 emissions, and n represents the total number of schemes. S is the feasible area mapped by the solar collector area (A_{sc}), the storage tank volume (V_{st}) and the auxiliary heater capacity (C_{aux}). λ_1, λ_2 are set weight values, and $ROHS_{set}$ is the set heating system reliability, related to building type requirement.

Combined with TRNSYS and EnergyPlus for co-simulation, the specific steps are illustrated in the flowchart, shown in Fig 2.

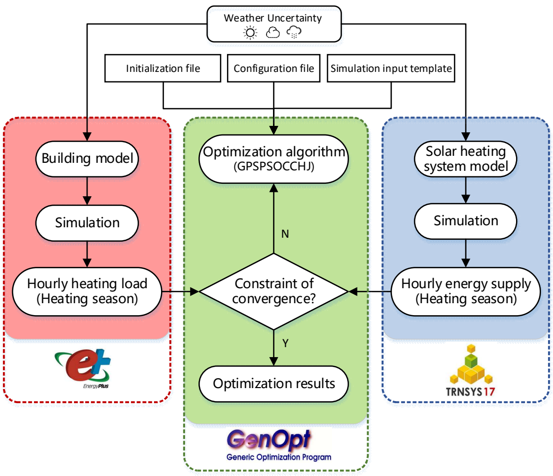

Fig 2 Simplified optimization process of SHS

3. CASE STUDY

The reference building is a typical office building in Tianjin, China, and the heating system is SHS. The heating area of this three-story building is 1,440 m^2. The heating time is ranging from 9:00 am to 17:00 pm during the heating season (November 15th to March 15th of the next year), 1,089 hours in total. Based on the 20-year meteorological parameters from 1991 to 2010 in Tianjin, EnergyPlus is used to simulate the 20-year heating load of the building. The SHS is simulated by TRNSYS, and the co-simulation diagram is shown in Fig 3.

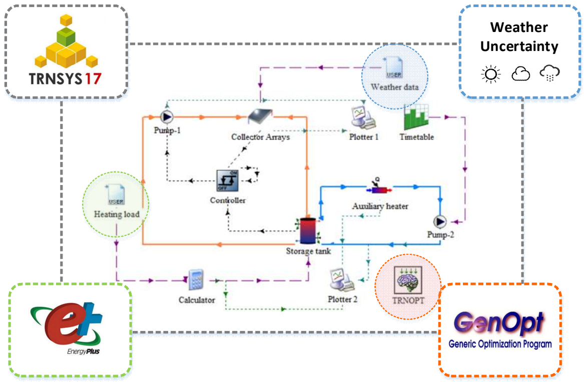

Fig 3 Simulation models of reference case in TRNSYS

The above simulation results are obtained by inputting the f-chart method results. In order to optimize based on these results, the decision variables and ranges are set in Table 1.

Table 1 Basic information for design optimization of a solar heating system

Decision variables	Range of variation of the decision variables		
	F-chart method	GPSPSOCCHJ	Remarks
Solar collector area (m^2)	255	[100-300, 5]	Total design options (N): 40×20×6 =4800
Storage tank volume (m^3)	15	[10-20, 0.5]	
Auxiliary heater capacity (kW)	105	[55-105, 10]	
	Parameters		
Weighting factor	λ_1=0.5 λ_2=0.5		$\lambda_1+\lambda_2$=1
$ROHS_{set}$ (%)	99		Ref. [1]
Range of simulation time (h)	T=20 years*1089 h		Uncertainty input

4. RESULTS AND DISCUSSION

The TRNSYS model is calculated in the GenOpt iteratively and each simulation takes about 3 seconds to obtain the deterministic optimal solution under weather uncertainty. It takes a total of 212 seconds to generate all the optimizations on a computer with an Intel Core (TM) i5-6300HQ 2.30 GHz processor and 8GB RAM. If the different schemes are calculated using the exhaustive method [10], the simulations take about 14,400 seconds, indicating that the hybrid GPSPSOCCHJ optimization algorithm can reduce the calculation time by 98.5%.

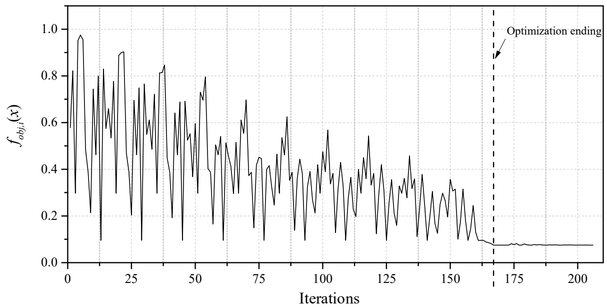

Fig 4 Evolution of objective function value during the optimization using the initial settings for GPSPSOCCHJ

The change process of the value of the objective function is shown in Fig 4. When the iteration reaches steps of 164, the objective function converges, and the total algebra of particle iteration is 8 generations. The convergence of results is shown respectively in table 2. When λ_1 and λ_2 are 0.5, compared with f-chart design result, solar collector area and the auxiliary heater capacity decreased by 5.9% and 9.5% respectively under 99% system reliability. The increase of the heat storage tank volume (16.7%) can improve the storage of solar energy, which can make full use of renewable energy.

Overall, compared with the traditional design scheme, the optimized scheme can reduce the system reliability by only 1%, but the carbon emission can be reduced by 2.6% and *TAC* by 8.3% after considering the uncertainty of weather over 20 years.

Table 2 Result of contrast after optimization using GPSPSOCCHJ

	Unit	F-chart method	GPSPSO CCHJ	Relative error (%)
Solar collector area (A_{sc})	m^2	255	220	-5.9
Storage tank volume (V_{st})	m^3	15	17.5	16.7
Auxiliary heater capacity (C_{aux})	kW	105	95	-9.5
TAC	$	8338.2	7647.3	-8.3
mCO_2	kg	3.54×10^5	3.45×10^5	-2.5

5. CONCLUSIONS

In this paper, the hybrid GPSPSOCCHJ algorithm is used to solve the multi-objective optimization problem of capacity design of SHS. Several conclusions can be drawn: The total calculation time of 4800 schemes is about 212 s, which can shorten the conventional calculation time by 98.5%.

Compared with the commonly used f-chart design method, the *TAC* and CO_2 emissions are reduced by 8.3% and 2.5% respectively under 99% set reliability of SHS.

It should be pointed out that when considering the optimization under weather uncertainty, the capacity value provided by solar energy can be quantified by using reliability indicators as constraints, so as to calculate the planning and design results including uncertainty. This multi-objective optimization can be extended to more different types of buildings and renewable energy systems, thus bringing broader application prospects.

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