Optimization of capacity of CCHP system coupled with solar and biomass energy

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Abstract: The CCHP system uses renewable energy to meet the heating, cooling and power loads, improve primary energy efficiency, and reduce carbon emissions. In this paper, a biomass energy-driven and solar collector-assisted CCHP system is proposed. The mathematical model of the system is achieved. And capacity was optimized by a genetic algorithm. Further, a building in Urumqi as an example, the feasibility of the system was verified by genetic algorithm. The results demonstrate that the values of primary energy saving ratio, annual total cost saving rate and carbon emission reduction ratio are 20.94\%, 11.73\% and 40.79\%, respectively. This finding could provide a reference for biomass energy-driven and solar collector-assisted CCHP system design for buildings in the Urumqi plateau.

1. Introduction
The combined cooling, heating and power (CCHP) system, based on the principle of energy cascade utilization, can simultaneously meet the electricity, cooling, and heating loads, which improves the energy efficiency and reduces air pollutant emissions obviously\([1-3]\). However, growing energy demand has promoted the development and use of renewable energy. Solar energy and biomass could provide feasible, environment-friendly and sustainable alternatives to fossil fuel energy system. CCHP system with biomass is a means to increase energy efficiency and harness renewable energy\([4-8]\).

2. Mathematical model

2.1 Energy flow of system
The system consists of PGU, solar collector, boiler, heat exchanger, absorption chiller, electric chiller, heat recovery, mixed fermentation, which was showed in Fig. 1. The CCHP system operates following thermal demand, which is a common operation strategy. The system electrical load is supplied by the biomass-driven PGU. If the PGU cannot meet the electrical load, the grid purchase method is adopted. The cooling system consists of an electric chiller and absorption chiller. The absorption chiller unit enables efficient use of recovery heat and increases system energy efficiency.
The balance of energy in CCHP system is expressed as:

\[ E_{\text{grid}} + E_{\text{PGU}} = E_{\text{net}} + E_{\text{e}} + E_{\text{ac}} \]

where \( E_{\text{grid}} \) is electricity from grid, \( E_{\text{PGU}} \) is power generation from PGU, \( E_{\text{net}} \) is electricity demand of building, \( E_{\text{e}} \) is additional power consumption of CCHP system, \( E_{\text{ac}} \) is electric energy consumption for electric chiller providing cooling load to building. \( Q_c \) is cooling demand of building. \( Q_{ac} \) is cooling load provided by absorption heat pump. \( Q_{rec} \) is waste heat recovery from the PGU system. \( Q_h \) is heating demand of building. \( Q_{ah} \) is heat supplied to absorption heat pump.

\[ E_{\text{e}} = \frac{Q_c}{\text{COP}_e} \]

where \( Q_c \) is cooling load of building provided by electric chiller. \( \text{COP}_e \) is coefficient of performance of electric chiller.

\[ F_{\text{PGU}} = \frac{E_{\text{PGU}}}{\eta_{PGU}} \]

where \( F_{\text{PGU}} \) is biomass energy consumption of PGU. \( \eta_{PGU} \) is electrical efficiency of PGU.

Here \( x \) is defined to the ratio of cooling load provided by electric chiller to the cool load and it is expressed as:

\[ x = \frac{Q_{ac}}{Q_c} \]

\[ Q_{rec} = F_{\text{PGU}} \eta_{rec} (1 - \eta_c) \]

where \( \eta_{rec} \) is efficiency of heat recovery system.

The balance of the fuel in CCHP system is expressed as

\[ F_b = \frac{Q_h}{\eta_b} \]

where \( F_b \) is biomass energy consumption of boiler. \( \eta_b \) is efficiency of boiler.

\[ F_{in} = F_{\text{PGU}} + F_b \]

where \( F_{in} \) is biomass energy consumption of system. \( F \) is total fuel energy consumption and it is expressed as:
\[ F = F_{PGU} + F_b + \frac{E_{grid}}{\eta_e \eta_{grid}} \cdot U \]

\[ U = \begin{cases} 1, & E_{grid} \geq 0 \\ 0, & E_{grid} < 0 \end{cases} \]

\( U \) is a piecewise function. When \( E_{grid} \) is greater than 0, that is, when power is purchased from the grid, the purchased electricity is included in the total energy consumption.

The system operates following thermal demand. It is necessary to judge the boiler operation and the total biomass energy consumption of the system according to the relationship between the system heat generation and heat demand.

Text condition: \( \frac{(1-x)Q}{COP_e} + \frac{Q}{\eta_b} \geq F(1-\eta)\eta_{rec} + Q_s \)

If text condition = True then:

\[ E_{grid} = E + E_p + x \cdot \frac{Q}{COP_e} - F_{PGU} \cdot \eta_e \]

\[ F = F_{PGU} + \frac{(1-x)Q}{COP_e} + \frac{Q}{\eta_b} \cdot \frac{1}{\eta_e \eta_{grid}} \cdot U + \frac{E_{grid}}{\eta_e \eta_{grid}} \]

If text condition = False then:

Further test conditions: \( \frac{(1-x)Q}{COP_e} + \frac{Q}{\eta_b} \geq Q_s \)

If text condition = True then:

\[ E_{grid} = E + E_p + x \cdot \frac{Q}{COP_e} - F_{PGU} \cdot \eta_e \]

\[ F = \frac{(1-x)Q}{COP_e} + \frac{Q}{\eta_b} \cdot \frac{1}{(1-\eta)\eta_{rec}} + \frac{E_{grid}}{\eta_e \eta_{grid}} \]

If text condition = False then:

\[ F = \frac{E_{grid}}{\eta_e \eta_{grid}} \cdot U \]

\[ E_{grid} = E + E_p + x \cdot \frac{Q}{COP_e} \]

2.2 Evaluation criteria

(1) Primary energy savings (PES)

PES is ratio of primary energy savings of CCHP system compared to SP system, and indicate as:

\[ P = \frac{E_{PES} - F}{E_{PES}} = 1 - \frac{F}{E_{PES}} \]

(2) Annual total cost saving (ATCS)

\[ ATCS = \frac{ATC^{SP}}{ATC^{CCHP}} - 1 = \frac{ATC^{SP}}{ATC^{CCHP}} \]

Where \( C_i \) is initial investment of CCHP system. \( C_o \) is operating expenses of CCHP system. \( R \) is capital recovery factor. \( i \), \( n \) are interest rate and service life of the equipment, respectively.

(3) Carbon dioxide emission reduction (CDER)

\( \text{CO}_2 \) reductions were selected as environmental indicators for the system. Defined as follows:

\[ \text{CDER} = \frac{CDE^{SP} - CDE^{CCHP}}{CDE^{SP}} = 1 - \frac{CDE}{CDE^{SP}} \]

Where \( \mu_{CO_2,f} \) and \( \mu_{CO_2,e} \) are emission conversion factors of biomass gas and electricity from grid,
respectively. The following objective function, namely the fitness function in GA, is defined to maximize the benefits of CCHP system from energy efficiency, economy and environment:

\[
\max S_{\text{fitness}} = \alpha_1 \cdot PES + \alpha_2 \cdot ATCS + \alpha_3 \cdot CDER
\]

3. Optimization

Fig. 2 Flow chart of the optimization process in GA

In this study, genetic algorithm was implemented to solve the optimal nonlinear problems and obtain the accurate or approximate solution. The mathematical model of the CCHP system has been listed in the section 2. By in putting the building load, cost parameters, evaluation criteria, and then coding the optimization variables. The variable is iterated until the convergence condition is reached. After that, the optimization results will be obtained, including \( x \), \( S \) and \( F_{FPGA} \). The calculation process is implemented in python.

The GA optimal process is shown in Fig. 2.

4. Case study

4.1 Building description and energy demands
The genetic algorithm was used to determine the capacity and ratio of cooling load provided by electric chiller to the cool load of the CCHP system, and a park in Urumqi was used as the target building for analysis. The target building area is 40,000 m², and the total area of windows and glazing comprises about 30% of the total wall area. The park includes canteens, office buildings, dormitories and auditoriums. The average temperature is set to 20-24°C. The Dest software is used to simulate the whole year of the building. Corresponding, the electric load, heat load and cold load are shown in the figure below.
4.2 Results

The optimization results are shown in Table 1.

Table 1. Optimal results of CCHP system

| PGU (kW) | Solar collector (k·m²) | x |
|----------|------------------------|---|
| 1622     | 5.18                   | 0.59 |

Table 2. Performances of system

| PES (%)  | ATCS (%) | CDER (%) | Integrated performance (%) |
|----------|----------|----------|---------------------------|
| 18.6     | 5.64     | 81.3     | 35.21                     |

The capacity optimization results are shown in Table 1. Performances of system are shown in Table 2.

From the above data, we can note that the values of primary energy saving ratio, annual total cost saving rate and carbon emission reduction ratio are 18.6%, 5.64% and 81.3%, respectively. These values fully reflect that the optimization design method can advance the system in technical, economic and environmental. Meanwhile, the system responds to the country’s new energy policy, and if the state subsidies are examined, the economic performance will improve.

5. Conclusion

This paper presents a CCHP system driven by biomass energy and solar. The GA algorithm is utilized to optimize the capacity of the system. A building in Urumqi as an example, the feasibility of the algorithm is verified. Compared with traditional energy supply systems, the biomass energy-driven and solar collector-assisted CCHP system under the optimal ratio increases the primary energy utilization rate by 21%, the annual cost value by 3.64%, and the annual carbon emission by 81.4%.

References

[1] P. Mancarella, G. Chicco, Assessment of the greenhouse gas emissions from cogeneration and trigeneration systems. Part II: Analysis techniques and application cases, Energy, 33 (3) (2008) 418-430.
[2] H. Cho, A.D. Smith, P. Mago, Combined cooling, heating and power: A review of performance improvement and optimization, Applied Energy, 136 (2014) 168-185.
[3] W. Gu, Z. Wu, R. Bo, W. Liu, G. Zhou, W. Chen, Z. Wu, Modeling, planning and optimal energy management of combined cooling, heating and power microgrid: A review, International
Journal of Electrical Power & Energy Systems, 54 (2014) 26-37.

[4] J.-J. Wang, K. Yang, Z.-L. Xu, C. Fu, Energy and exergy analyses of an integrated CCHP system with biomass air gasification, Applied Energy, 142 (2015) 317-327.

[5] M. Ehyaei, P. Ahmadi, F. Atabi, M. Heibati, M. Khorshidvand, Feasibility study of applying internal combustion engines in residential buildings by exergy, economic and environmental analysis, Energy and Buildings, 55 (2012) 405-413.

[6] J. Xu, J. Sui, B. Li, M. Yang, Research, development and the prospect of combined cooling, heating, and power systems, Energy, 35 (11) (2010) 4361-4367.

[7] S. Gopisetty, P. Treffinger, Generic combined heat and power (CHP) model for the concept phase of energy planning process, Energies, 10 (1) (2017) 11.

[8] D. Maraver, A. Sin, F. Sebastián, J. Royo, Environmental assessment of CCHP (combined cooling heating and power) systems based on biomass combustion in comparison to conventional generation, Energy, 57 (2013) 17-23.