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Research on Optimal Distributed Power Supply Configuration under Air Pollution Prevention

Meng Li, Yi Lin, Zhangsui Lin, Wei Wu

State Grid Fujian Economic Research Institute, China

Abstract. Scientific planning and development of new energy resources has become the key to solve air pollution. How to optimize the allocation of distributed generation (DG) is the premise of effective development and utilization of distributed energy. In order to solve the problem of air pollution, this paper chooses the optimal allocation index of distributed generation, establishes the objective function and constraints, and optimizes the allocation of distributed generation. The results of numerical examples verify the validity of the proposed model and provide a reference for effectively solving the problem of air pollution.

1. Introduction

Scientific planning and development of distributed energy resources (DER) is the key to solve the haze weather. On the one hand, as a new way of energy utilization, distributed generation has the advantages of flexibility, high efficiency, energy saving and low carbon compared with centralized power supply. It can be a good complement to large power supply and large energy base. On the other hand, the efficiency and absorption level of distributed energy will continue to improve, and it will become an important way to develop and utilize new energy in the future.

In order to promote the distributed development and utilization to solve the pollution problem, this paper considers the economic, technological and environmental benefits separately, and constructs the optimal allocation index of distributed generation. On this basis, it establishes the objective function and constraints, and optimizes the allocation of distributed generation based on the COA-EO algorithm. Finally, the distributed combined cooling and power (DCCHP) system is taken as an example to illustrate the distributed energy demonstration project in a certain area.

2. Optimal Distributed Generation Configuration for Air Pollution Prevention and Control

2.1. Distributed Generation Optimal Configuration Index

2.1.1. Economic benefits. The economic benefit of DG optimal allocation can be reflected by the cost index of unit electricity. If the social benefit of distributed generation is greater than the social cost, and only the cost of capital is considered when calculating the production cost of distributed generation. The unit power cost of DG can be expressed as:



$$C = \frac{r(1+r)^n}{(1+r)^n - 1} \times \frac{C_{\text{inv}}}{87.6k} + C_{\text{ope}} + C_{\text{ful}} \quad (1)$$

In order to improve the operation performance of power system, different DG units are usually combined into a combined power generation system. The unit generation cost of DG can be expressed as:

$$C_{\text{union}} = \sum_{i=1}^m \varsigma_i \left(\frac{r(1+r)^{n_i}}{(1+r)^{n_i} - 1} \times \frac{C_{\text{inv}}}{87.6k_i} + C_{\text{ope},i} \right) \quad (2)$$

In the formula, C_{inv} is the installation cost of DG, C_{ope} is the operation and maintenance cost of DG, C_{ful} is the fuel cost of unit electricity, n is the reimbursement period for investment, r is the fixed annual interest rate, k is the average capacity coefficient, and ς_i is the proportion coefficient of the i th DG for all electricity costs.

2.1.2. Technical Benefits. When the distributed generation is connected to the power grid, it will change the size and direction of power flow in the distribution network, and then affect the voltage stability of the power system. The technical benefits of optimal allocation of distributed generation can be reflected by several indicators for evaluating distribution network voltage.

2.1.2.1. Comprehensive loss voltage index. This index takes into account the network loss U_{loss} and voltage quality of distribution network U_{qual} . The integrated loss voltage of DG can be expressed as:

$$U_{\text{wsdy}} = U_{\text{loss}} + \mu U_{\text{qual}} = \sum_{j=1}^{n-1} I_j^2 R_j + \mu \sum_{i=1}^n (u_i - u_{\text{rat}})^2 \quad (3)$$

In the formula, n is the total number of distribution network nodes, μ is the proportional coefficient, u_i is the bus voltage amplitude, I_j is the j th branch current, R_j is the j th branch resistance, and u_{rat} is the rated voltage amplitude.

2.1.2.2. Static voltage stability index. This index quantifies the effect of DG on improving the static voltage stability of power system after DG is connected to distribution network. The static voltage stability index of DG can be expressed as:

$$U_{\text{jtdy}} = \frac{4P_j z \cos \theta}{[u_i \cos(\theta - \delta)]^2} \quad (4)$$

In the formula: $\delta = \delta_i - \delta_j$, $u_i \angle \delta_i$ and $u_j \angle \delta_j$ are the voltage at the head and the end, respectively; $P_j + jQ_j$ is the power at the injection node j .

2.1.2.3. Voltage improvement index. This index refers to the ratio of the voltage index after DG is connected to the distribution network to the voltage index without DG. The voltage improvement index of DG can be expressed as:

$$F_{ubi} = \frac{F_{uoi}}{F_{unoi}} \quad (5)$$

In the formula, F_{unoi} and F_{uoi} are the voltage indices before and after DG access, respectively expressed as voltage indices (if the power system node is i , the voltage amplitude is u_i , the node load is L_i , and the weight value of each node is α_i , then the voltage indices can be expressed as $F_{ui} = \sum_{i=1}^n u_i L_i \alpha_i$).

2.1.3. Environmental Benefits. The environmental benefits of DG optimal allocation can be reflected by environmental improvement indicators. This index refers to the ratio of the i th pollutant emission before and after DG installation. The environmental improvement indicators of DG can be expressed as:

$$EIRI_i = \frac{PE_h}{PE_q} = \frac{\sum_{j=1}^N (EG_{Tj} \times TE_{ij}) + \sum_{k=1}^M (EDG_k \times TE_{ik})}{\sum_{j=1}^N (EG_j \times TE_{ij})} \quad (6)$$

In the model, PE_q and PE_h are the emission of the i th kind of polluted gas before and after DG installation, respectively; EG_{Tj} and EG_j are the active contribution of the i th thermal power unit before and after DG installation, respectively; TE_{ij} is the emission of the i th kind of polluted gas when the unit of the j th thermal power unit works; TE_{ik} is the emission of the i th kind of polluted gas when the unit of the j th DG generating unit works; EDG_k is the active contribution of the k th DG unit; N is the total number of thermal power units; M is the total number of DG units.

2.2. Distributed Generation Optimal Configuration Model

2.2.1. Objective function. The electricity cost, voltage improvement index and environment improvement index are selected as the multi-objective problems of DG optimal allocation. The comprehensive benefit index can be expressed as follows:

$$\max F_{obj} = \max(-C, F_{ubi}, EIRI_i) \quad (7)$$

2.2.2. Constraints. The objective function needs to satisfy the constraints of node voltage, conductor current, capacity of distributed generation and total access of distributed generation. Specifically:

(1) *Node voltage constraints:* $U_{i\min} \leq U_i \leq U_{i\max}$, $i = 1, 2, \dots, n$. Among them, U_i is the voltage of the i th node; $U_{i\max}$ and $U_{i\min}$ are the upper and lower limits of the node voltage, respectively.

(2) *Conductor current constraint:* $I_i \leq I_{i\max}$, $i = 1, 2, \dots, n$. I_i is the current of the i th node, and $I_{i\max}$ is the upper limit of the current of the i th node.

(3) *Distributed power supply capacity constraints*: $P_{DGj} \leq P_j, \sum P_{DGj} \leq P_{\max}$. Among them, P_{DGj} and P_j are the installed capacity and node load of the j th distributed power supply, respectively; $P_{\max}$ is the maximum allowable access capacity of the system.

(4) *Distributed Power Access Total Constraints*: $P_{DG} \leq P_n \times 20\%$. Among them, P_{DG} is the total installed capacity for distributed power generation and P_n is the total added load.

This paper takes DCCHP system as an example to analyze the example, so DCCHP system needs to meet its own equipment operation constraints (such as natural gas internal combustion engine units, refrigerators, heating boilers and energy storage equipment) and system operation constraints (such as electricity, heat balance).

3. COA-EO Solution Algorithms

3.1. EO algorithm

Extremal optimization (EO) is a heuristic algorithm for local search. The object of study of EO algorithm is a single individual or a single chromosome, and the components within the individual are genes or gene fragments. EO algorithm constantly improves itself by changing the worst fitness components of the individual, so that the individual always evolves towards the optimal structure. At the same time, by changing the components adjacent to the worst components, the structure of the individual is constantly optimized, so that the whole system can co-evolve, so as to search for the approximate optimal solution or optimal solution. EO algorithm has the characteristics of fast convergence, strong local search ability and no adjustable parameters, so it is easy to design and implement when it is used in optimization problems, but it is easy to fall into local optimum. In order to avoid falling into local optimum easily in solving combinatorial optimization problems, many experts and scholars have proposed improved optimization algorithms.[7]

3.2. COA algorithm

Chaos is a form of motion of a non-linear dynamic system in a certain form. It is a random behavior of the system in the non-equilibrium process. Because chaos is ergodic, chaotic variables are more advantageous than blind random search. Chaos optimization algorithm (COA) avoids the disadvantage that other optimization algorithms are easy to fall into local optimum, and it has strong robustness and is easy to integrate with other algorithms, so as to improve the optimization performance of the algorithm.[8]

3.3. Hybrid COA-EO Algorithms

In this paper, COA algorithm and EO algorithm are combined to form a COA-EO optimization model. COA-EO model takes advantage of COA algorithm's strong global search ability and fast approximation to the optimal solution, which makes up for the shortcoming that EO algorithm is easy to fall into local optimum. At the same time, EO algorithm has strong local search ability to help COA jump out of local optimum and avoid premature convergence of COA. In addition, the EO algorithm will increase the computation time of COA algorithm and weaken the fast convergence ability of the original algorithm. It is necessary to set the time interval (i.e. the Q th generation) to ensure the fast convergence ability of the algorithm, while jumping out of the local optimum. Therefore, mutation operator plays an important role in the performance of EO algorithm. Therefore, this paper uses adaptive Lévy mutation as mutation operator. The probability distribution of Lévy function is as follows:

$$L_{\tau, \gamma}(y) = \frac{1}{\pi} \int_0^{\infty} e^{-\gamma t^{\tau}} \cos(yt) dt \quad (8)$$

In the formula, γ is the scale factor and satisfies; when $\gamma > 0, 0 < \tau < 2$, if and only then, $\tau=1$, the distribution function is Cauchy distribution; then, when $\tau \rightarrow 2$, the distribution is close to the Gauss distribution. The flow chart of hybrid COA-EO algorithm is as follows:

- 1) Initialization, setting control error ε ; initial chaotic vector x_0 ; let xiteration= 0.
- 2) Mapping chaotic variables to $x_{k+1} = \lambda x_k (1 - x_k)$; initially, $k = 0$, then $x_1 = 4x_0 (1 - x_0)$, let $x^* = x_1, f^* = f_1$.
- 3) Chaotic variables are iteratively searched to get x_{k+1} and f_{k+1} ; if $f_{k+1} < f^*$, the optimal value is updated: $f^* = f_{k+1}, x^* = x_{k+1}$.
- 4) If $x_{\text{iteration}} \bmod Q = 0$, turn to the EO subroutine; otherwise, proceed to the next step.
- 5) Let xiteration= xiteration + 1, if $|f_{k+1} - f_k| < \varepsilon$, end the loop; otherwise, continue with step 3.

4. Distributed Power Generation Case Optimization

4.1. Basic Data

In this section, DCCHP system is taken as an example to analyze the distributed energy demonstration project in a certain area. The relevant data of these are shown in tables 1 and 2[9].

Tab.1 The energy price of DCCHP system

Season	Peak valley period	Electricity purchase price (yuan /kWh)	Internet tariff (yuan /kWh)	Natural gas price (yuan /m3)
Summer	Peak hours 06:00-22:00	1.097	1(Distributed Photovoltaic Subsidies: 0.42) 2(Local subsidies: 0.25) 3(Benchmark price of coal-fired power generation: 0.4359)	3.23
	Valley time 22:00-06:00	0.539		
	Peak hours 06:00-22:00	1.062		
winter	Valley time 22:00-06:00	0.504		

The typical daily load curves of DCCHP system in summer and winter are shown in Fig. 1 and Fig.2.

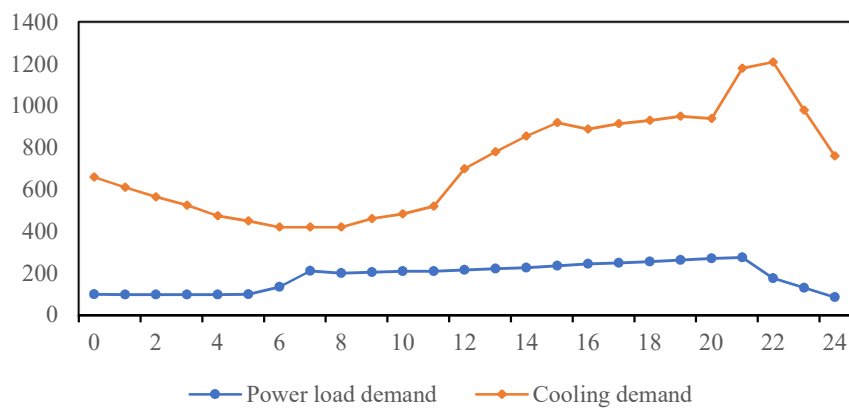
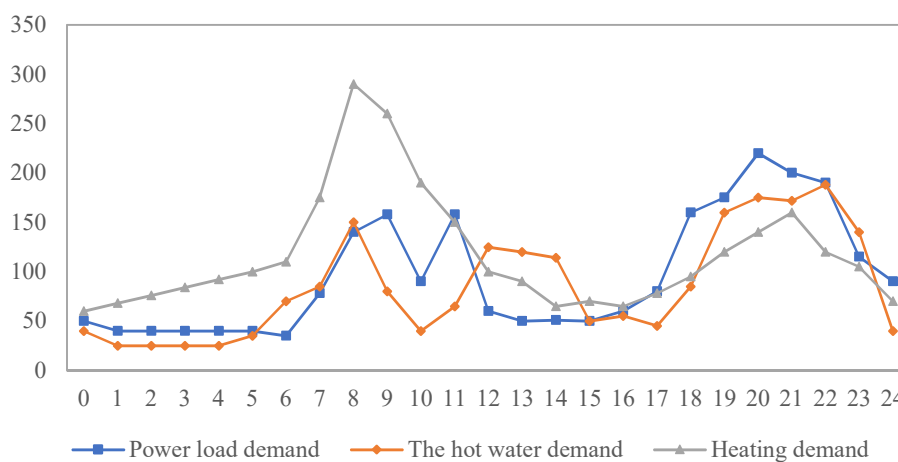
1) Seen from the distribution of electric load, the electric load increases gradually after 7:00, reaching the peak at 8:00-10:00 and 18:00-22:00 respectively. In addition, the distributed demonstration project belongs to the industrial park, so the electricity load at night is also stable.

2) Seen from the distribution of cooling load, the demand is mainly concentrated in summer, and the demand for cooling load is high from 12:00 to 24:00, while the demand for cooling load is low from 0:00 to 12:00.

3) From the point of view of heat load distribution, the heat load in winter is large. On the one hand, it is used for heating supply and demand, on the other hand, it is used for hot water supply in industrial production.

Tab.2 The technical parameters of DCCHP equipment

Device name	Equipment fee/(RMB/kWh)	Operating expenses/(RMB/kWh)	Electric efficiency /%	Thermal efficiency /%	Life cycle/year
gas turbine	8100	0.064	30	55	30
power grid	-	-	37	-	-
PV unit	21300	0.013	12	-	25
Solar Hot Water Boiler	1600	0.005	-	52	20
Natural Gas Boiler	865	0.002	-	91	20
Absorption Refrigerator	1030	0.0008	-	103	20
Electric refrigerator	1600	0.0097	-	-	-
heat exchanger	220	0.002	-	97	20

**Fig.1** The typical daily load demand in summer**Fig.2** The typical daily load demand in winter

4.2. Example Analysis

Combined with the relevant data of DCCHP system and the characteristics of typical daily load demand, the COA-EO algorithm is used to solve the results of DCCHP system in summer and winter, and the optimal configuration scheme of DG is given. The optimization results are shown in Figure 3-7 below.

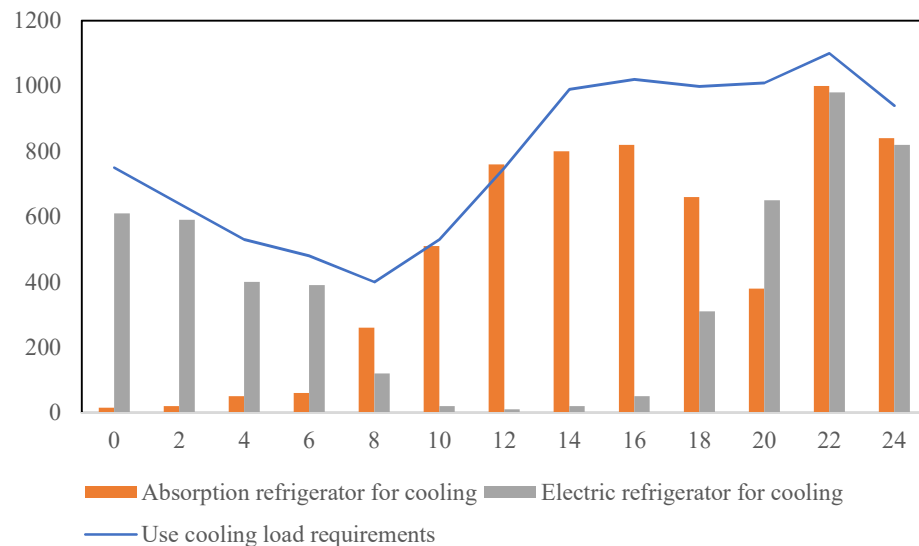


Fig.3 Optimization results of cold load supply in summer

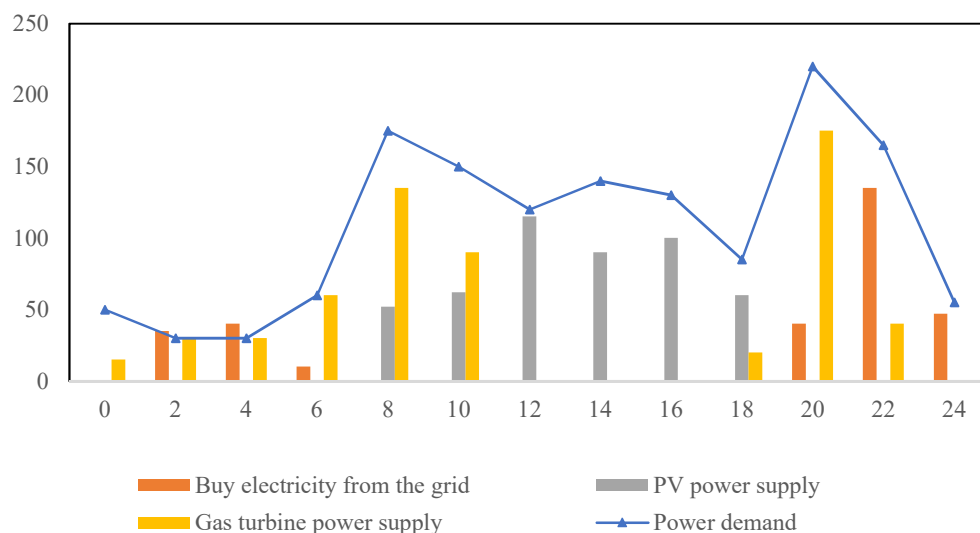


Fig.4 Optimization results of power supply in summer

From Figure 3 and Figure 4, we can see that the summer power load demand is supplied by gas turbines and photovoltaic power generation. If the power is insufficient, we need to purchase electricity from the grid. Since the valley period of summer electricity price is from 22:00 to 06:00 the next day, power purchases from power grids are often made to meet the demand of power load. In addition, the lighting conditions between 7:00 and 19:00 are better, and the power demand in this period is mostly supplied by distributed photovoltaic power generation. The cooling load demand in summer is supplied

by electric refrigerators and absorption refrigerators. The peak period of 7:00-19:00 is mainly supplied by absorption refrigerators. The cooling load supply of electric refrigerators is mostly carried out in the valley period at night.

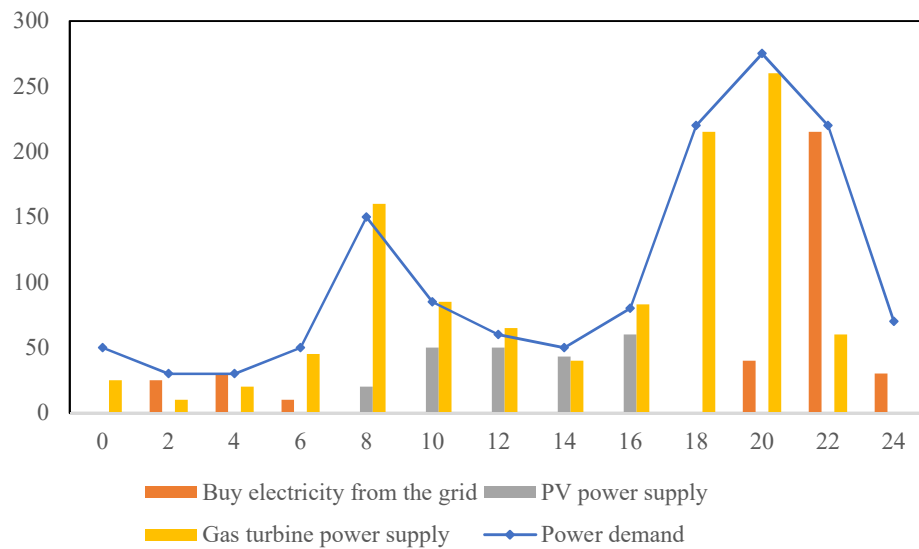


Fig.5 Optimization results of power supply in winter

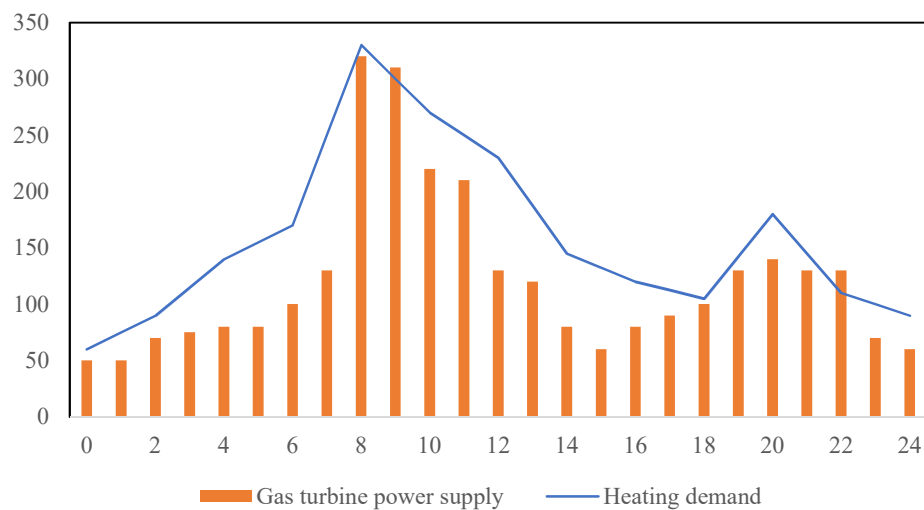


Fig.6 Optimization results of heating supply in winter

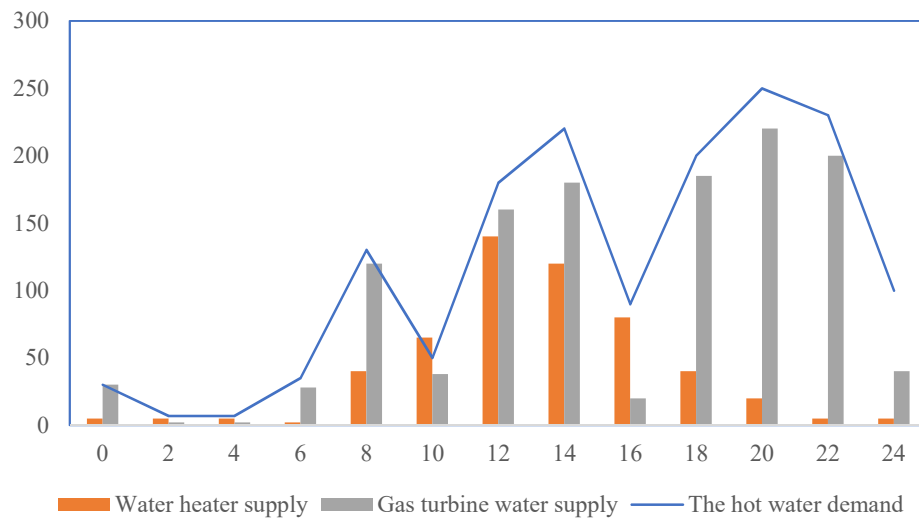


Fig.7 Optimization results of hot water supply in winter

From Figure 5 to Figure 7, it can be seen that the demand for electricity load in winter is mainly supplied by gas turbines and distributed photovoltaic power generation. If there is insufficient electricity, it is also necessary to purchase electricity from the grid. Since the period from 22:00 to 06:00 the next day is the valley period of winter electricity price, during this period, many power purchases are made from the power grid to meet the demand of power load in the system. In addition, 8:00-17:00 illumination conditions are good, and the power demand in this period is mostly supplied by distributed photovoltaic. In winter, hot water demand is supplied by gas turbines and solar collectors, while heating is mainly supplied by gas turbines. During the peak period of 8:00-17:00, the demand for hot water is mainly supplied by solar water heaters and gas turbines are used to meet the demand at night.

With the help of COA-EO algorithm, the annual cost of the system, energy saving rate of primary energy consumption and CO₂ emission reduction rate are optimized, as shown in Table 3.

Tab.3 Target optimization value of DCCHP system

Target optimization		Summer		winter	
		DCCHP system	Separate supply system	DCCHP system	Separate supply system
cost	System cost/10,000 yuan	65.4	93.5	77.2	118.6
analysis	System fee reduction/%		30.1		34.9
Energy	Energy consumption/kW	3530.1	4378.5	3590.3	4765
saving	Energy efficiency /%		19.4		24.6
analysis					
Emission	CO ₂ emissions/kg	229.6	401.1	272.3	538.4
reduction	CO ₂ emission reduction		42.8		49.4
analysis	rate/%				

Table 3 shows that DCCHP system achieves economic operation benefits in summer and winter, and achieves the effect of energy saving and emission reduction. Compared with summer, the optimal value in winter is greater than that in summer in terms of system cost reduction ratio, primary energy saving rate and CO₂ emission reduction rate. The main reason is that the external temperature in winter is low, the thermal efficiency is relatively low, and the intensity of light is relatively weak, the consumption of primary energy is more and the cost is higher.

Specifically:

1) DCCHP system uses high temperature flue gas and hot water generated by gas turbine power generation as the heat source of lithium bromide unit, realizes the step utilization of energy, reduces the input of primary energy of the system, and reduces the system cost accordingly.

2) DCCHP system uses distributed photovoltaic to provide power for the system, and uses solar collector to realize hot water supply, which reduces the input of primary energy and realizes energy saving and emission reduction.

5. Conclusions and suggestions

In order to solve the problem of air pollution and promote the scientific and effective development and planning of distributed energy, this paper proposes an optimal allocation method of distributed generation based on COA-EO algorithm. Firstly, considering the benefits of economy, technology and environment, the optimal allocation index of distributed generation is constructed. Secondly, the objective function and constraints are established, and the optimal allocation of distributed generation is carried out based on the COA-EO algorithm. Finally, by selecting a distributed energy demonstration project in Beijing, Tianjin and Hebei as an example, the DCCHP system is taken as an example to illustrate the effectiveness of the proposed model.

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