Method of Optimization and Multi-criteria Evaluation of Distributed Combined Cooling Heating and Power Energy System[1]

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Abstract. Different energy systems were developed on the basis of the major equipment of distributed energy systems (DES). According to the demand of loads, energy prices, and technical and financial information about optional technologies, using non-linear programming, an optimization model for DES was established. The optimum configuration, optimal operation scheme and evaluation criteria matrix were the results of the model. The information entropy was used to determine the weight distribution, then the multi-criteria comprehensive evaluation method was introduced. The results demonstrate that photovoltaic system is optimal scheme due to its lower cost, energy conservation and environmental protection.

Introduction

Using natural gas, renewable energy in multi-energies hybrid power systems is of great importance. The combination of Distributed Energy Systems (DES) and the centralized power generation system has also become an important future direction of power and energy industry [1].

DES contains a lot of equipment which can satisfy different kinds of cooling, heating and power loads simultaneously [2,3]; as a consequence, same kind of loads can be satisfied by different kinds of energy supplies [4]. Thus it is difficult to determine the capacity and operating mode of the equipment in an optimal way. Previous research almost focused on operational strategies developed in fixed mode, then studied characteristics of systems or determined the kind and the capacity of devices according to device parameters and energy demand [2,5].

An important factor influencing the development of the DES is an effective system evaluation method. In the previous studies, the evaluation was Primary Energy Ratio [6]. However, the only one index cannot be a reasonably accurate assessment of DES [7]. Obviously, different evaluation methods will yield different results of the evaluation, and it is difficult to determine which method is more accurate.

This paper establishes a nonlinear programming model which can optimize system configuration and operation of the program simultaneously. Considering system investment costs, annual operating costs, primary energy consumption, primary energy ratio, the annual emissions of CO_2 and NO_x and other performance criteria, that is to build the evaluation criteria system from the economic, energy and environmental aspects. According to the degree of difference between criteria, the objective weight of each criterion is determined by entropy principle.

Energy system

The most widely used DES are the internal combustion engine (gas turbine) cogeneration systems, photovoltaic systems, fuel cell systems, etc [8-10]. This paper mainly focuses on the five systems: the four mentioned before and the traditional system. These five systems are shown in Table 1.

This paper mainly focuses on grid (The average efficiency of conventional coal-fired power plants is 36% and line loss rate is 7%), internal combustion turbine, gas turbine, fuel cell, PV, gas boiler, absorption refrigeration, heat exchanger [11]. And the parameters such as equipment costs, operating costs, power efficiency and thermal efficiency can be acquired from reference books [12-14].

Table 1 Description of the energy systems

Number	Systems	System components
S1	Traditional system	Grid + Air conditioning + Gas boiler
S2	Photovoltaic system	Grid + PV panels + Air conditioning + Gas boiler
S3	Fuel cell system	Grid + Fuel cell + Air conditioning
S4	Gas turbine system	Grid + Gas turbine + Absorption refrigeration + Gas boiler
S5	Internal combustion engine system	Grid + Internal combustion turbine + Absorption refrigeration + Gas boiler

Optimization Model

Objective function

Most EDS are evaluated by economic criteria. This paper establishes an optimization model with the annual cost as the objective function. The cost covers annual investment in equipment C_{cap}, annual investment in operation and maintenance $C_{O\&M}$, annual fuel cost C_{fuel}. The objective function is (1),

$$\min C_{total} = C_{cap} + C_{O\&M} + C_{fuel} \tag{1}$$

$$C_{cap} = \sum_{tech} I_{nvtech} C_{aptech} \frac{1}{1-\left(1+I\right)^{-L_{ttech}}} \tag{2}$$

$$C_{O\&M} = \sum_{tech} O_{Mtech} \sum_{m} \sum_{h} E_{tech,m,h} \tag{3}$$

$$C_{fuel} = \sum_{m} \sum_{h} V_{gas,m,h} P_{gas,m,h} \tag{4}$$

where I_{nvtech} is the cost of each device, C_{aptech} is the optimization capacity of each device, I is discount rate, 10%, L_{ttech} is the service life of equipment, O_{Mtech} is operating costs of each device, $E_{tech,m,h}$ is hourly load of each device, $V_{gas,m,h}$ is hourly gas consumption, $P_{gas,m,h}$ is hourly gas price.

Constraints

Constraints include equality and inequality constraints. Inequality constraints are that in order to satisfy hourly cooling, heating and power load, energy supply is greater than energy demand. The inequality constraints are (5) to (7),

$$E_{des,o,m,h} + E_{ep,m,h} \geq E_{dem,m,h} \tag{5}$$

$$C_{des,o,m,h} \geq C_{dem,m,h} \tag{6}$$

$$H_{des,o,m,h} \geq H_{dem,m,h} \tag{7}$$

where subscript des, o, m, h means hourly output, ep, m, h means hourly demand, $E_{ep,m,h}$ is hourly power purchased, E, C, H mean electricity, cooling and heat.

Equality constraints are related to energy conversion and energy consumption and production. They can be demonstrated by (8) to (13),

$$\frac{V_{gas,m,h} L_{HVgas}}{3.6} = E_{gas,m,h} \tag{8}$$

$$E_{gas,m,h} = E_{des,i,m,h} \tag{9}$$

$$E_{eq,i,m,h} \alpha_{eq} = E_{eq,o,m,h} \tag{10}$$

$$H_{eq,i,m,h} \beta_{eq} = H_{eq,o,m,h} \tag{11}$$

$$C_{eq,i,m,h} C_{OPeq} = C_{eq,o,m,h} \tag{12}$$

$$H_{dem,m,h} = H_{hwl,dem,m,h} + H_{hl,dem,m,h} \tag{13}$$

where $V_{gas,m,h}$ is hourly gas consumption, L_{HVgas} is gas calorific, $E_{gas,m,h}$ is hourly heat supply, $E_{des,i,m,h}$ is input heat, α_{eq} is electricity efficiency, β_{eq} is heating efficiency, C_{OPeq} is cooling efficiency, $H_{hwl,dem,m,h}$ and $H_{hl,dem,m,h}$ are hourly hot water load and space heating load.

Evaluation Model

Economic criterion

$$C_{total} = C_{cap} + C_{O\&M} + C_{fuel} \tag{14}$$

Energy consumption criterion

Energy consumption criterion can be primary energy consumption and primary energy ratio.

Primary energy consumption Q is equal to the gas consumption of DES $Q_{des,gas}$ and the equivalent consumption of the electricity purchased $Q_{des,ep}$.

$$Q = Q_{des,gas} + \frac{Q_{des,ep}}{\eta(1-\varphi)} \tag{15}$$

where φ is average efficiency of traditional coal-fired power plant, η is loss rate of transmission line.

Primary energy ratio $P_{ER,des}$ is ratio of the output power and the primary energy consumption. The larger $P_{ER,des}$ is, the energy-saving performance is better.

$$P_{ER,des} = \frac{Q_e + Q_h + Q_c}{Q_{des,gas} + \dfrac{Q_{des,ep}}{\eta(1-\varphi)}} \tag{16}$$

where Q_e, Q_h, Q_c are hourly power, heating and cooling output.

Environmental criterion

Emissions of DES are mainly from gas turbine, gas boiler, internal combustion engine, fuel cell and electricity purchased (equivalent amount of pollutants produced by coal-fired plant). This paper focuses on the emissions of CO_2 and NO_x [15].

Multi-criteria Comprehensive Evaluation Method

Normalized criteria

Assume there are m systems to be evaluated, denoted as $\boldsymbol{Y} = [y_1, y_2, \ldots, y_m]$; there are n criteria, denoted as $\boldsymbol{X} = [x_1, x_2, \ldots, x_n]$. The criterion x_j corresponding to the system y_i is denoted as a_{ij} ($i = 1, 2, \ldots, m$, $j = 1, 2, \ldots, n$), then we have criteria matrix $\boldsymbol{A} = [a_{ij}]_{m\times n}$,

$$\boldsymbol{A} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{bmatrix} \tag{17}$$

For those criteria that we expect them large (the larger, the better), we use (18) to normalize them,

$$b_{ij} = \frac{x_i - \min x_i}{\max x_i - \min x_i} \tag{18}$$

For those criteria that we expect them small (the smaller, the better), we use (19) to normalize them,

$$b_{ij} = \frac{\max x_i - x_i}{\max x_i - \min x_i} \tag{19}$$

After the normalization, $0 \le b_{ij} \le 1$. $\boldsymbol{A}$ is normalized to $\boldsymbol{B}$, and matrix $\boldsymbol{P}$ is the normalized matrix.

$$P_{ij} = b_{ij} / \left(\sum_{j=1}^{m} b_{ij} \right) \tag{20}$$

Criteria information entropy

Information entropy has the same properties, uniqueness, additivity and extremality, as thermodynamic entropy. Larger entropy of a criterion means a larger degree of difference, and that will provide more information and play a greater role in the comprehensive evaluation, who will definitely have a larger weight. Entropy method utilizes the information entropy of criteria to define their weights.The information entropy of the criterion x_j is:

$$e_j = -k \sum_{i=1}^{m} P_{ij} \ln P_{ij} = -\frac{1}{\ln m} \sum_{i=1}^{m} P_{ij} \ln P_{ij} \tag{21}$$

Determine the entropy weights and results of comprehensive evaluation

The entropy weight of the criterion x_j is (22) and comprehensive evaluation of the system y_i is (23).

$$\omega_j = (1 - e_j) / \left[\sum_{j=1}^{n} (1 - e_j) \right] \tag{22}$$

$$v_{value,i} = \sum_{j=1}^{n} \omega_j P_{ij} \tag{23}$$

Examples

Load

Take a hotel in Shanghai as an example. Its total floor area is approximately 9600 m^2; the roof area is 1600 m^2, and since PV system occupies 6 m^2 every kilowatt, the maximum capacity of PV system can be about 260 kW. We got the data of hourly loads from DeST. Fig. 1 and Fig. 2 show the load curve of a typical winter day and a typical summer day. Since the optimization of the whole year is too complicated, we suppose each day's loads are the same in one month, and the question is simplified as 288h(12×24) instead of 8760h(365×24). The system can purchase electricity from the grid but cannot sell electricity to the grid. And the price of electricity is peak-valley price.

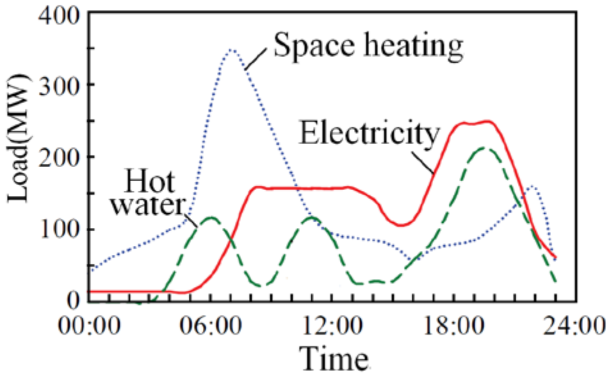

Fig. 1 Hourly load demand in January 1

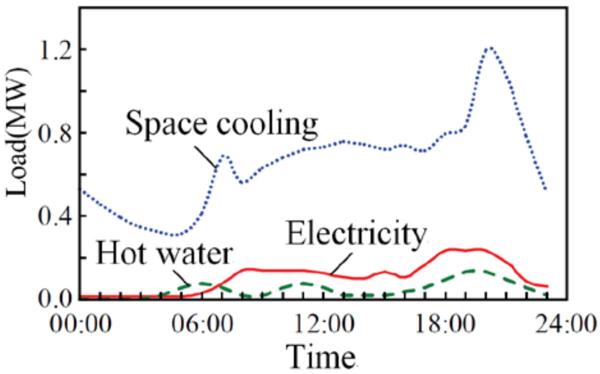

Fig. 2 Hourly load demand in July 1

Optimization results

Without knowing capacity of any device or operating strategy of S4 and S5, we used the software lingo to optimize, and we got the result that the capacity of the internal combustion engine is 180kW, the gas engine is 152kW. As for S2 and S3, since the equipment is expensive, the capacity is small, and to simplify the research, we determined the capacity of the power equipment is 150kW. The configuration is shown in Fig. 3.

Since the cooling and heating loads didn't change, the capacity of heater exchanger and refrigerator didn't change a lot. The capacity of boilers in S4 and S5 are large, and almost equal to each other, mainly because these two systems both used Lithium bromide absorption refrigeration and the cooling loads were mainly satisfied by the thermal output of systems. S3 and S2 both used electric refrigeration, so the thermal output mainly satisfied heating load, and the capacity of the boiler is small. In addition, heat can be recovered from the generator, so the capacity of the boiler in S3 is the smallest.

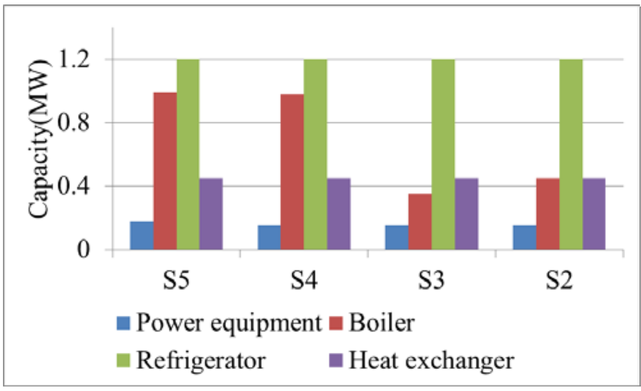

Fig. 3 Optimal configuration of DES

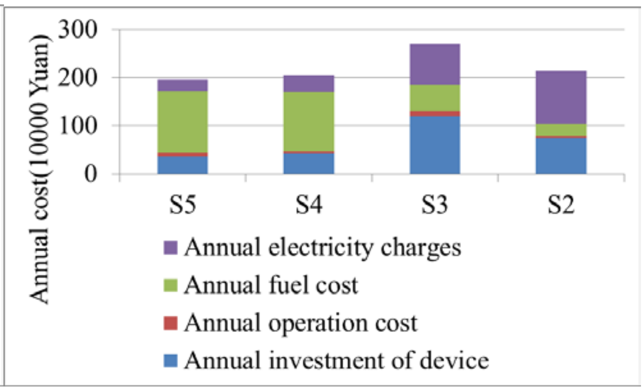

Fig. 4 Annual cost of systems

Annual cost of systems is shown in Fig. 4. The annual cost of S3 is highest because fuel cell is expensive and the cooling load is satisfied by electric refrigeration. S2 has to purchase electricity to avoid the instability of the PV. The costs of S4 and S5 have been affected a lot by the price of gas.

The calculation results of evaluation criteria

After the optimization, we calculated the value of each criterion shown in Table 2.

Table 2 The result of evaluation criteria

Number	Criterion	S1	S2	S3	S4	S5
A1	Investment(Ten thousand Yuan)	277	597	829	329	310
A2	Operation cost(Ten thousand Yuan)	189	137	159	159	153
A3	Fuel consumption(MWh)	5282	2622	3024	4684	4516
A4	Primary energy ratio(%)	66.6	1342	1163	75.1	77.9
A5	Annual emission of CO_2(t)	153.84	73.60	51.10	96.30	88.30
A6	Annual emission of NO_x(t)	4.21	1.97	1.52	1.54	1.33

The evaluation results of entropy method

Normalize all criteria in the 5 systems, and then we have distribution of all criteria shown in Fig.5. From Fig.5, we can get Fig.6. We can infer that there are huge differences between A4 of different systems, and the corresponding information entropy is smallest; the weight is biggest.

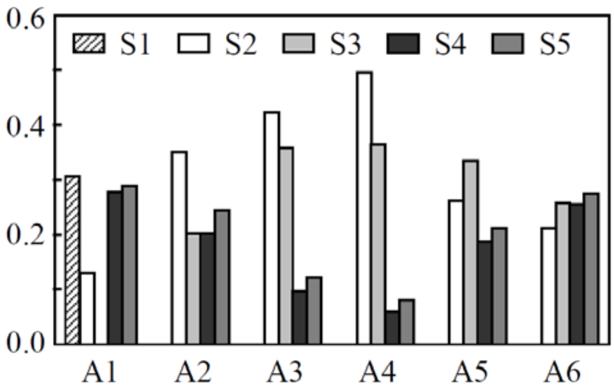

Fig. 5 The distribution of criteria

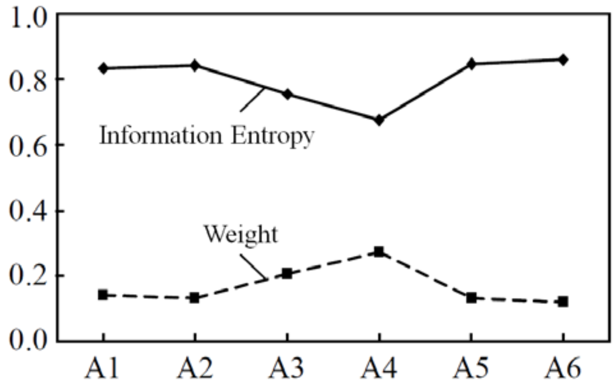

Fig. 6 Entropy and weights of criteria

According to (23), we can evaluate the 5 systems shown in Table 3. And we can come to the conclusion that S2 is the most optimized one, while S1 is the least one.

Table 3 Evaluation results

Systems	S1	S2	S3	S4	S5
Evaluation	0.04	0.39	0.30	0.12	0.15

Summary

This paper changed the optimization design and strategies into a nonlinear optimization problem. The model considered three aspects of criteria, cost, energy consumption and environmental protection. This paper evaluated five common DES and calculated six criteria and corresponding weights. Finally, these systems were evaluated. The result was that considering all three aspects, photovoltaic system is the most optimal scheme.

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