Economic Day-ahead scheduling of SOFC and biomass-based Integrated Tri-generation Energy System using artificial bee colony algorithm

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Abstract: In the process of operation, integrated energy systems encounter a series of complex optimization problems such as complex conversion of multiple types of energy, coupling of multiple types of equipment, and uneven distribution of multiple demands. In recent years and in the process of achieving the goal of "double carbon" in China, more and more problems of optimal scheduling of biomass integrated energy systems have become hot topics of research. In this paper, we propose an artificial bee colony algorithm-based operation and scheduling method for a biomass fuel cell (SOFC) cooling, heating, and power triple-supply system with the objective function of maximizing the economic profit of the integrated energy system (including fuel, operation, and maintenance costs), and the constraints of energy conservation, system safety, and operation state. The equipment included are biomass boiler and corresponding steam turbine, biogas digester, SOFC, gas storage tank, etc. The results of the algorithm include the economic benefits of using the artificial bee colony algorithm for the same load scenario. The operational scheduling results show that the artificial bee colony algorithm is able to maximize the profitability of the integrated energy system while reducing carbon emissions.

Key Words: Integrated energy system; optimal design; Biomass; Artificial Bee Colony algorithm

1. Introduction

As the total reserves of non-renewable energy sources such as oil, coal and natural gas are decreasing worldwide, and a series of environmental problems caused by the massive use of fossil energy sources, the search for new renewable and clean alternative energy sources is gradually becoming a concern of thermoelectricity in the world. Biomass energy refers to the conversion of biomass and other organic matter produced by green plants through photosynthesis into energy that can be used directly as fuel or converted into gaseous or liquid fuel carriers. As a kind of renewable, energy-saving and environment-friendly energy with great potential, biomass energy has a great role in optimizing the energy consumption structure, linking the energy supply tension, increasing agricultural income and improving environmental quality.

Biomass is organic matter produced by plants through photosynthesis and its transformation products. As an energy source with huge reserves and not yet fully utilized, biomass energy has the advantages of being renewable and zero-emission, which has received wide attention from all over the world [3]. The integrated energy system of biomass, electricity, heat, gas and fertilizer contains four types of energy: heat, electricity, gas and fertilizer, and is characterized by various types of loads and abundant energy supply equipment. It is necessary to take into account the system economy, safety, environmental protection and other objectives when scheduling, and use IOT technology and information technology to unify and implement the scheduling of all energy supply and storage equipment in the region, so as to achieve the effect of optimizing energy supply to regional thermoelectric loads and improving energy utilization efficiency [1,2]. In the vast areas of northern China, especially in Inner Mongolia and northeast China, there is a large amount of biomass resources to be developed, so the establishment of an integrated energy system with biomass as the core can promote the full and efficient utilization of biomass energy, which is of great significance to implement the national energy policy, achieve carbon peaking and carbon neutrality as soon as possible, improve the energy structure, and promote industrial restructuring and other goals.

Unlike the traditional power system problem, the energy optimization management problem of the integrated energy coordination based on biomass boilers and biogas digesters is more difficult: (1) there is a coupling relationship between heat, electricity and gas in the

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system, all of which are affected by the biomass boiler; (2) there is a certain percentage of new energy generation such as photovoltaic power generation in the system, which is easily affected by the external environment, and the form of power generation is often quite stochastic, volatile and intermittent. Therefore, high-precision scenery resources and load prediction algorithms are needed to support the energy management of the combined heat and electrical energy system. However, the accuracy of these new energy power forecasts is difficult to guarantee, especially as the time span becomes longer, the accuracy of the forecasts becomes lower, for example, the current wind power day-ahead forecasts can reach 25% to 40% error, and for intra-day forecasts may be even greater. With the continuous development of short-term and ultra-short-term forecasting technologies based on big data, and the accumulation of historical data such as renewable energy output and heat and gas load, the forecasting accuracy and speed have been significantly improved, but it is still difficult to guarantee the efficient and economic operation of combined heat and electricity energy systems.

Traditional biomass utilization is mainly by means of direct straw combustion for power generation and anaerobic fermentation in biogas digesters for biogas production. Biomass gas (CH4-containing gas produced by biomass conversion) has a high inert component, low calorific value, and unstable composition, which makes its utilization difficult, while the development of fuel cells provides an opportunity for its large-scale utilization. As a kind of electrochemical energy conversion device, solid oxide fuel cell (SOFC) has high electrical efficiency, wide fuel adaptability, no pollution, and has advantages that other kinds of fuel cells cannot match when processing biomass gas, mainly as follows: (1) SOFC can directly use the biomass gas after pollutant purification treatment, without reforming, water gas conversion and other pre-treatments. (2) SOFC has good adaptability to changes in biomass gas composition and can be used directly as a fuel even for gases with very low calorific value[4]. Therefore, SOFC has good prospects for utilization in integrated energy systems with biomass as the core.

Good matching between various energy sources and performance of integrated energy systems cannot be achieved without rational planning. There are relatively few studies on the planning of integrated energy systems including biomass, and the literature [5] proposed a user participation willingness assessment model based on improved PMV-PPD (predicted mean vote-predicted percentage of dissatisfied) index. Based on the cloud model theory, a price-based integrated demand response model considering mixed uncertainty is established. And on this basis, the optimal dispatching strategy of the integrated energy system is proposed by considering the uncertainties of various types of energy response volume boundaries and price elasticity coefficients. In [6], an optimal scheduling strategy based on integrated demand response and master-slave game is proposed for a multi-micro-grid integrated energy system containing electrical energy interaction, and an integrated demand response model containing multiple types of loads such as transferable interruptible electrical loads, transferable non-interruptible electrical loads, flexible thermal loads and cold loads is established. In [7], a deep reinforcement learning method based on a flexible actor-judge is proposed to realize the optimization of integrated electricity-gas energy dispatching in multiple scenarios through the interaction between an intelligent body and an energy system and adaptive learning of control strategies. In the literature [8], an optimal scheduling model of integrated energy system considering integrated demand response and multi-energy storage devices is constructed with the objective function of minimizing the total operating cost of integrated energy system, and the uncertainty of renewable energy output is handled by using conditional value-at-risk approach. However, the above work does not fully consider the renewable energy access, cooling/heating/electricity multi-load demand and SOFC does not supply power to the system, i.e., the above system still depends on the power supply from the external grid.

In summary, this paper proposes a scheduling optimization model for SOFC in a biomass-core electric-thermal-gas-fertilizer multi-energy flow integrated energy system, in which a biomass direct-fired generator set, SOFC as electric-thermal coupling equipment, can both generate electricity and supply heat to the outside, and there are also gas supply equipment (digester) and energy storage equipment (gas storage tank). In this paper, we firstly establish the model of each key equipment in the system, consider the energy coupling, energy balance constraint, equipment safety constraint and operation state constraint among each energy conversion equipment, and solve the system by artificial bee colony optimization algorithm with the objective of maximizing annual profit, so as to obtain the optimal scheduling scheme before the system day. Finally, the feasibility and effectiveness of the method are verified based on the analysis of calculation cases.

2. Mathematical model of biomass system equipment

The biomass-electricity-heat-gas-fertilizer cogeneration system studied in this paper is shown in Figure 1. The power generation equipment in the system includes biomass direct-fired generator set and SOFC, and the electricity generated by the system is used to meet the electric load demand of users; the heat generated by burning straw in the biomass boiler and the waste heat generated during the operation of SOFC can be used as the heat source for external heat supply; the biogas produced by the digester is transported to the storage tank after being dried, deodorized and desulfurized by the filter, gas-water separator and purification regulator through the gas transmission pipeline. On the one hand, it can supply gas to customers, and on the other hand, it can be used as fuel for SOFC operation. The heat generated by the biomass boiler in this system can be used for the heat preservation of the digester, the fly ash can be used as the PH regulator of the digester, and the combination of digestate and fly ash can be used to produce fertilizer, which not only makes the ash and waste heat of direct-

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fired power generation available, but also solves the problems of heat preservation, PH regulator and efficient utilization of digestate and digestate in the process of anaerobic fermentation.

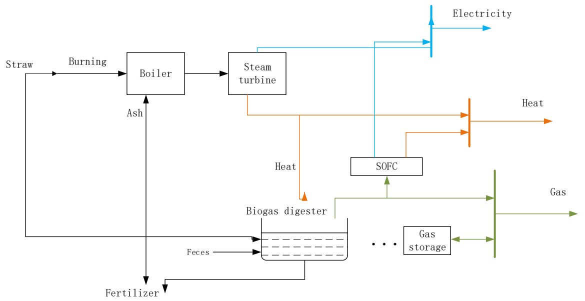


Fig.1 Flow chart of biomass electric heating and gas fertilizer polygeneration system

2.1 Biomass boilers and steam turbines

Biomass boilers can burn straw under permissible working conditions to produce heat, and their operating mode can be expressed as follows

$$Q_{BB} = \eta_h^{BB} F_{BB} \quad (1)$$

where Q_{BB} is the thermal power output of biomass boiler, FBB the calorific value input for the fuel, η_h^{BB} the thermal efficiency of biomass boiler.

The steam turbine studied in this paper is an extracted condensing turbine, and the turbine body contains a steam extraction port, which is mainly used for external steam extraction for heat supply. For the mathematical modeling of the turbine body, the input parameters are: main steam parameters(Flow D_0 ,Pressure P_0 ,Temperature T_0)、Vapor extraction parameters(Flow D_1 , Pressure P_1 , Temperature T_1), the output parameters are: Turbine power generation Pe 、Turbine heat supply Q_h [12]。

Q_h is calculated as:

$$\begin{cases} Q_h = D_1 \cdot h_1 \\ h_1 = f\left(P_1, T_1\right) \end{cases} \quad (2)$$

The power equation of the turbine is:

$$\begin{cases} Pe = \left[D_0\left(h_0 - h_1\right) + \left(D_0 - D_1\right)\left(h_1 - h_c\right)\right]\eta_m \eta_g \\ h_0 = f\left(P_0, T_0\right) \end{cases} \quad (3)$$

where h_0 is the main steam enthalpy; h_c is the exhaust enthalpy; η_m and are the mechanical drive efficiency and generator efficiency, respectively, which are determined by the system structure and generator performance and can be calculated from the heat balance data.

2.2 Biogas digester

2.2.1 Calculation of gas production and biogas fertilizer yield

Biogas fermentation, also known as anaerobic digestion, is a process in which organic materials (manure, straw, etc.) are subjected to certain conditions of temperature, humidity, pH and anaerobic conditions to produce biogas through the decomposition and metabolism of anaerobic microorganisms [13]. Biogas fermentation feedstock consists mainly of water and total solids (materials other than water, mainly manure and straw). The gas production rate of raw materials is generally expressed as the gas production per unit weight of total solids, which is inconsistent for different raw materials and varies for the same raw materials due to differences in gas production rates between species. Usually, gas production can be estimated from the data in Table 1.

Table 1 Estimation of total solid content and actual gas production rate of biogas raw materials

Material type	Total solids content (%)	Gas production rate (m^3/kg·TS)
Corn stalks	80～90	0.30
Sorghum straw	80～90	0.30
Pig manure	18～20	0.35
Human manure	18～20	0.35
Chicken manure	30	0.35

Therefore, the total feedstock solids quantity and gas production can be calculated by the following equation.

$$Y_B = \sum_i^n M_i D_i \quad (4)$$

$$V_{MG} = \sum_i^n M_i D_i \beta_i \quad (5)$$

where Y_B is the total solids quantity of raw materials, n is the number of raw material types, M_i is the weight of the fresh material of the i-th ingredient, D_i is the total solids content of the i-th raw material, V_{MG} is biogas production, β_i is the gas production rate of the i-th feedstock.

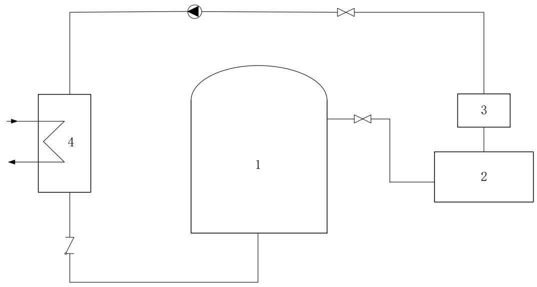
According to the conservation of mass, the mass of the remaining digestate can be calculated, assuming that 75% of the digestate can be used as organic fertilizer, the mass of organic fertilizer produced is[13]:

$$M_{MF} = (Y_B - \rho_b \times V_b) \times 0.75 \quad (6)$$

where M_{MF} is the yield of biomass fertilizer in one fermentation cycle; ρ_b is the biogas density and is taken as 0.7kg/m3 at room temperature.

2.2.2 Heat transfer modeling

The activity of bacterial flora during fermentation is affected by the temperature of the digestate, which in turn affects the efficiency of gas production in biogas digesters. The low ambient temperature in winter in northern areas of China leads to less or even no gas production in biogas digesters, and some digesters are even frozen[14]. In order to ensure the normal fermentation of biogas digesters, it is often necessary to take insulation measures for biogas digesters and to support the corresponding warming system[15].



1. Biogas digester 2. Water tank 3. Filter 4. Heat exchangers
Fig.2 Brief flow chart of biogas pool warming system

The biogas digester heating system mainly consists of digester, water tank, filter, heat exchange device and heat exchange pump. The water is stored in the tank as the heat transfer medium of the system, and absorbs the heat from the steam generated by the biomass boiler in the heat exchange device, and then flows through the internal heating coil of the digester to transfer the heat to the fermentation liquid. It is assumed that the inner wall of the digester is made of enameled steel plate and the insulation material is made of polystyrene foam board. The flow of the digester heating system is shown in Figure 2.

In this paper, the heat transfer calculation model is established by referring to the method of literature[16] for heat transfer calculation. The main heat loss of this biogas digester system comes from the heat dissipation of the digester and tank, and the heat loss of the incoming and outgoing feed liquids, and the main heat gain is the heat of biological fermentation. According to the heat balance principle, the heat balance equation can be obtained as follows:

$$Q_{sr} = Q_{zq} + Q_{sx} + Q_{ly} - Q_{sw} \quad (7)$$

where Q_{sr} is the total heat loss from the digester; Q_{zq} is the amount of heat dissipated by the biogas digester; Q_{sx} is the water tank heat dissipation; Q_{ly} is the inlet and outlet liquid heat loss; Q_{sw} is biodigestion heat.

(1)Heat dissipation from biogas digester

The digester is approximated as a cylindrical shape, and only the case where the digester is in contact with air all around is considered. Based on the available studies, it is known that the reactor heat transfer model is[17]:

$$Q_{zq} = \sum_{i=1}^{n} K_i A_i \left(t_z - t_0 \right) \quad (8)$$

where t_z is the temperature of the feed liquid in the digester and t_0 is the ambient temperature.

The heat dissipation of the digester comes mainly from the top, side walls and bottom parts. The top load factor is:

$$K_1 A_1 = \frac{A_1}{\frac{1}{h_n} + \frac{\delta_d}{\lambda_d} + \sum_{i=1}^{n} \frac{\delta_i}{\lambda_i} + \frac{1}{h_n}} \quad (9)$$

where A_1 is the heat transfer area at the top of the digester; h_n is the heat transfer coefficient of the internal top surface of the biogas digester; δ_d is the thickness of the biogas digester wall; λ_d is the thermal conductivity of the biogas digester wall; δ_i is the thickness of the i-th layer of insulation material ; λ_i is the thermal conductivity of the i-th layer of insulation material; h_w is the thermal conductivity of the i-th layer of insulation material.

The sidewall load factor is:

$$K_2 A_2 = \frac{H_f}{\frac{1}{h_{fb} \pi d_1} + \sum_{i=1}^{n} \frac{1}{2\pi\lambda_i} \ln \frac{d_{i+1}}{d_i} + \frac{1}{h_w \pi d_{n+1}}} \quad (10)$$

where H_f is the height of the material liquid in the digester; h_{fb} is the surface heat transfer coefficient of the inner wall of the biogas digester; h_w is the heat transfer coefficient on the external surface of the digester; d_1 is the internal diameter of the digester; λ_i is the thermal conductivity of the i-th layer of insulation material; d_i is the inner diameter of the i-th layer of insulation material of the digester; d_{i+1} is the outside diameter of the i-th layer of insulation material of the digester; d_{n+1} is the outside diameter of the biogas digester.

The bottom load factor is:

$$K_3 A_3 = \frac{A_3}{\frac{1}{h_{fd}} + \frac{\delta_d}{\lambda_d} + \sum_{i=1}^{n} \frac{\delta_i}{\lambda_i} + \frac{1}{h_w}} \quad (11)$$

where A_3 is the heat transfer area at the bottom of the digester; h_{fd} is the heat transfer coefficient of the inner bottom surface of the biogas digester. The inner wall thickness and thermal conductivity of the biogas digester are: δ_d =0.01m, λ_d =2.05 $W/(m^2 \cdot k)$ .The insulation thickness and thermal conductivity are as follows δ_2 =0.2m, λ_2 =0.05 $W/(m^2 \cdot k)$. Considering the fast heat and mass transfer rate of the fluid in the biogas digester, $1/(h_{fb} \pi d_1)$ and $1/h_{fd}$ are small, Ignoring these two heat transfer coefficients on the water side.

(2)Water tank heat dissipation

The water tank is used to store the hot water required to heat the digester, and only the case where it is in contact with air all around is considered. The heat dissipation from the circumferential walls of the tank is considered as a one-dimensional steady-state heat conduction problem that varies along the radius; the heat dissipation from the top and bottom surfaces of the tank is also considered as a one-dimensional steady-state heat conduction problem through the flat walls [18]:

$$Q_{sx} = \left(\frac{l}{r_1} + \frac{A}{r_2} \right) \times \left(T_{st} - t_0 \right) \quad (12)$$

where l is the height of the material in the tank; A is the sum of the area of the top and bottom of the water storage tank; r_1 is the thermal resistance of the circumferential surface thermal conductivity ; r_2 is the thermal resistance of the upper and lower bottom surface thermal conductivity; T_{st} is the water tank storage temperature.

(3)Inlet and outlet heat loss

The one-time feeding solution, after a complete fermentation cycle in the digester, will all be renewed, and the average mass flow rate will be:

$$m = \frac{M}{T} \quad (13)$$

where m is the average mass flow rate; M is the total mass of feed liquid; T is the fermentation period, where 16d is taken for calculation.

Since the heat taken away by water vapor and biogas in the feed solution is very little and is often neglected in engineering, the heat loss in and out of the feed is mainly the heat consumption required for the fermentation solution to rise from the initial temperature of the feed to the fermentation temperature, which can be derived from the heat transfer heat flow calculation formula:

$$Q_{ly} = cm\left(t_z - t_{ly}\right) \quad (14)$$

where c is the specific heat of the liquid, the liquid is approximated as water; t_{ly} is the temperature of the liquid when feeding.

(4)Anaerobic fermentation bioheat

Related studies have shown that 3% of the effective energy (16.91 kJ/kg) of the biogas fermentation stock solution is released as heat [19]. The biogas digester feed liquor will continue to generate biothermal heat during the fermentation cycle, and the average daily biothermal heat generated will be:

$$Q_{fj} = \frac{M \times 16.91 \times 3\%}{T} \quad (15)$$

According to the heat balance relationship Equation (7), the calculation results of the above sub-items are organized to obtain the total heat loss of the biogas digester . Thus the heat to be supplied to the digester by the biomass boiler is:

$$Q_h = \left(1 + \Psi\right) \cdot Q_{sr} \quad (16)$$

where Ψ is the heat pipe heat loss rate, equaling 0.1%.

2.3 SOFC Model

A fuel cell is a device that converts energy stored in fuels such as hydrogen, natural gas and oxygen into electrical energy through chemical reactions without pollution and also recovers waste heat for utilization.The electro-thermal efficiency in the SOFC model varies with the output power and the empirical relationship between its chemical reaction output electrical power and thermal power can be fitted through a large number of investigations[20] as follows:

$$\frac{\eta_E}{\eta_{E,r}} = 1.042 - 0.045\frac{P_r^{FC}}{P^{FC}} \quad (17)$$

$$\frac{\eta_T}{\eta_{T,r}} = 0.2477\frac{P^{FC}}{P_r^{FC}} + 0.8326 - 0.0757\frac{P_r^{FC}}{P^{FC}} \quad (18)$$

$$H^{FC} = P^{FC}\frac{\eta_T}{\eta_E} \quad (19)$$

where P^{FC} is the output electrical power of SOFC, η_E and η_T are the electrical and thermal efficiency of SOFC respectively, r represents the rated operating condition, and the corresponding output thermal power H^{FC} can be calculated by the energy balance principle. The coupling between P^{FC}、H^{FC}、η_E and η_T increases the complexity of SOFC model operation.

2.4 Gas storage tank

When excess biogas is generated in the integrated energy system, it is partially stored in the storage tank, which is modeled as:

$$V_{t+1,zq} = V_{t,zq} + V_{t,zq,in} \cdot \eta_{zq,in} \quad (20)$$

When the gas storage tank provides biogas, its outgassing model is :

$$V_{t+1,zq} = V_{t,zq} - V_{t,zq,out} / \eta_{zq,out} \quad (21)$$

Where $V_{t+1,zq}$ is the current gas volume of the storage tank; $V_{t,zq}$ is the gas volume at the last moment of the storage tank; $V_{t,zq,in}$ is the amount of biogas entering the storage tank; $V_{t,zq,out}$ is the amount of biogas to be supplied by the storage tank; $\eta_{zq,in}$ is the storage efficiency of the storage tank, and the value of this paper is 0.9; $\eta_{zq,out}$ is the discharge efficiency of the storage tank, and the value of this paper is 0.9.

3. Run scheduling model solving based on artificial bee colony algorithm

The structure of the day-ahead economic scheduling model based on the artificial bee colony algorithm is shown in Figure 4. The assumptions of the model are as follows: the equipment output is assumed to be a continuous variable; the equipment is fault-free during the optimized operation.

3.1 Optimization models and algorithms

3.1.1 Optimization variables

For the integrated energy system studied in this paper, the capacities of biomass boilers and digesters have been determined by the project, and the amount of boiler straw, digester straw, biogas production, gas storage, boiler power generation, boiler heat supply, electricity purchase, and gas purchase are selected as optimization variables in this study.

3.1.2 Objective function

In this paper, considering the investment cost of the system and the economy of operation, the objective function is the maximum annual profit of the system, that is $\max f = Profit - Cost$ 。

$$Profit = P_{MG} + P_{MF} + P_{PG} + P_{HS} \quad (22)$$

where $Profit$ is the annual operating income of the system, including biogas income, biogas fertilizer income, power generation income, heating income.

The total cost is the sum of the annual equivalent investment cost and the annual operating cost of the equipment.

$$\mathrm{Cos}t = C_{inv} + C_{run} \quad (23)$$

The annual equivalent investment cost of equipment is the cost value of the total investment cost of the system by equal allocation to each year of the operating cycle, which includes the annual equivalent investment cost of equipment such as digesters, SOFCs, and storage tanks. The equation for calculating the annual equivalent investment cost of equipment is shown below[22]:

$$C_{inv} = C_{inv,GS} + C_{inv,\mathrm{SOFC}} \quad (24)$$

$$C_{inv,i} = \frac{r(1+r)^n}{(1+r)^n - 1} c_{inv,i} S_{inv,i}, \quad i = GS, \mathrm{SOFC} \quad (25)$$

where $C_{inv,GS}$、$C_{inv,\mathrm{SOFC}}$ are the annual investment cost of gas storage tank and SOFC respectively; r is the discount rate; n is the full life cycle; $c_{inv,i}$ is the unit capacity investment cost of the i-th equipment; $S_{inv,i}$ is the installed capacity of the i-th equipment.

Annual operating costs include annual straw purchase cost C_{SC}, electricity purchase cost $C_{grid,e,t}$, gas purchase cost $C_{grid,g,t}$:

$$C_{run} = C_{sc} + \sum_{t=1}^{8760} \left(C_{grid,e,t} + C_{grid,g,t} \right) \quad (26)$$

3.1.3 Constraints

The constraints of the integrated biomass-based energy system day-ahead economic optimal dispatch model include power balance constraints, equipment capacity constraints, equipment operation constraints, etc.

The power balance constraints are calculated as $P_{swz}^t + P_{SOFC}^t + P_{Grid}^t = P_{Load}^t$, where P_{Grid}^t is the hour-by-hour power exchange value between the integrated energy system and the external grid; P_{Load}^t is the hour-by-hour load value; P_{swz}^t is the hour-by-hour power generation of the biomass boiler; P_{SOFC}^t is the hour-by-hour power generation of the SOFC.

For the thermal load, the power balance constraint is calculated as $H_{swz}^t + H_{SOFC}^t = \mathrm{H}_{Load}^t$, where H_{Load}^t is the hour-by-hour load value; H_{swz}^t is the hour-by-hour heat supply of biomass boiler; H_{SOFC}^t is the hour-by-hour heat supply of SOFC.

The equipment capacity and operating constraints within the integrated energy system are calculated as follows:

For biomass boiler power generation: $P_{swz}^{min} \le P_{swz}^t \le P_{swz}^{max}$

For biomass boiler heat supply: $H_{swz}^{min} \le H_{swz}^t \le H_{swz}^{max}$

For SOFC heat supply: $H_{SOFC}^{min} \le H_{SOFC}^t \le H_{SOFC}^{max}$

For SOFC power generation: $0 \le P_{SOFC}^t \le P_{SOFC}^{max}$

For gas storage equipment storage capacity: $0 \le Q_{cq}{}^t \le Q_{cq}^{max}$

For biogas digester gas production: $0 \le Q_{zq,i}{}^t \le Q_{zq,i}^{max}$

where P_{swz}^{min} and P_{swz}^{max} are the minimum power generation output and maximum power generation output of biomass boiler; H_{swz}^{min} and H_{swz}^{max} are the minimum heating output and maximum heating output of biomass boiler; H_{SOFC}^{min} and H_{SOFC}^{max} are the minimum heating output and maximum heating output of SOFC; P_{SOFC}^{max} is the maximum power generation capacity of SOFC; Q_{cq}^{max} is the maximum storage capacity of gas storage equipment; $Q_{zq,i}^{max}$ is the maximum gas production capacity of i-th biogas digester.

3.1.4 Optimization algorithm

In this paper, an artificial bee colony intelligent optimization algorithm is chosen to solve the optimal configuration of the integrated energy system. In the algorithm search process, the employing and following bees are responsible for finding the optimal solution, and the detecting bees are responsible for avoiding the situation of falling into the local optimum during the search process, and generating new nectar sources randomly once they fall into the local optimum, whose search process is mainly as follows:

(1) Initialization: Determine the number of populations, the maximum number of iterations, the problem dimension D and the search range of the solution, and generate D-dimensional random solutions in the search space (i=1,2,3,...,SN).

(2) Each hired bee generates a new random solution according to Equations (27) at the beginning of the search phase.

$$v_{ij} = x_{ij} + \rho_{ij} \cdot (x_{ij} - x_{kj}) \quad (27)$$

where $k \in \{1,2,3,\ldots,SN\}$, $j \in \{1,2,3,\ldots,D\}$ and $k \ne i$, random number $\rho_{ij} \in [-1,1]$.Calculate the fitness value fit_i corresponding to the new solution, and if fit_i is better than the old solution, then the new solution replaces the old solution. Conversely, the old solution is retained.

(3) After all hired bees complete the search, share the solution information with the following bees and calculate the probability value of each solution according to Equations (28).

$$p_i = \frac{fit_i}{\sum_{k=1}^{SN} fit_k} \quad (28)$$

Then, based on the principle of roulette, a random number is generated in the range of [-1,1]. If the probability value of the solution is greater than the random number, a new solution is generated according to Equations (27), and if the fitness value of the new solution A is better than the old one, the new solution replaces the old one. Conversely, the old solution is retained.

(4) After all following bees finish searching, if a solution is not updated for more than M times, it means that the solution falls into local optimum, and the solution is discarded. The detecting bees generate new solutions according to Equations (29),

$$x_{ij} = x_{\min i} + rand(0,1)\cdot(x_{\max j} - x_{\min j}) \quad (29)$$

where $j \in \{1,2,3,\ldots,D\}$ .Then repeat the above search process.

(5) The maximum number of iterations is satisfied and the optimal solution is output.

For this original ABC optimization algorithm, the new food source search strategy is Equations (27), in which the base solution x_{kj} selected for the neighborhood search is a random food source and the search direction is more random. However, the random food source does not always proceed in a favorable direction when leading the swarm search, therefore, this paper adopts an improved artificial swarm optimization algorithm IGABC based on a hybrid search strategy of the best nearest neighbor and the current optimal solution, and its specific search strategy is shown below.

$$v_{ij} = \begin{cases} \text{Existing best neighbor} \\ x_{ij} + \mu_{ij}\cdot\left(x_{\text{best neighbour}} - x_{ij}\right) + \psi_{ij}\cdot\left(y_j - x_{ij}\right) \\ \text{or not} \\ x_{ij} + \varphi_{ij}\cdot\left(x_{ij} - x_{kj}\right) + \psi_{ij}\cdot\left(y_j - x_{ij}\right) \end{cases} \quad (30)$$

where μ_{ij} is a random value in [0,1].

The basic principle of the IGABC algorithm search strategy is: when the best nearest neighbor exists for this food source, the hiring bee and the following bee search for a better food source through the best nearest neighbor and the current global optimal solution; otherwise, they search for a better food source through the stochastic food source and the current global optimal solution. According to the optimization process of IGABC, a two-stage stochastic planning IGABC optimal planning platform for integrated energy systems is established as shown in Figure 4.

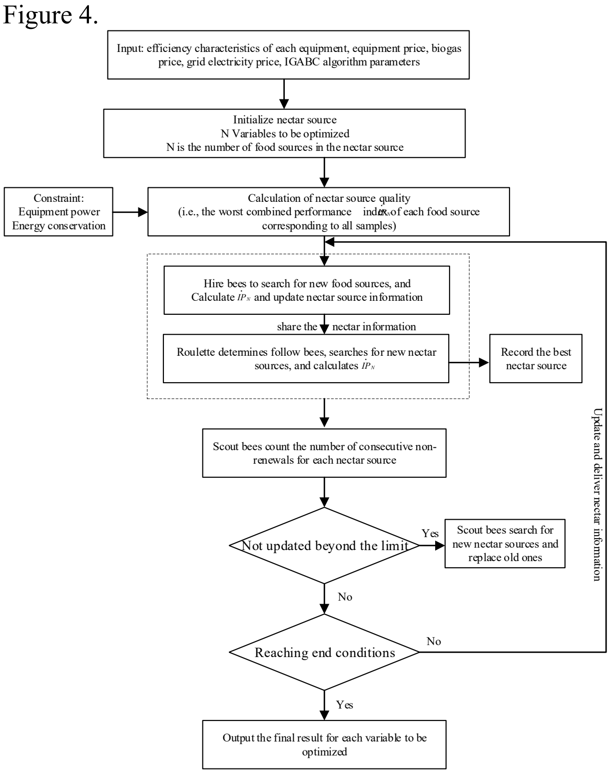


Fig.4 IGABC optimization platform for two - stage stochastic programming of integrated energy system

4. Example analysis

4.1 System Introduction

This paper is based on the example of a typical biomass-electricity-heat-gas-fertilizer co-generation system in a region of Inner Mongolia. In this integrated energy system, there are 8 biogas digesters with a diameter of 10 m and a volume of 300 m3. The raw materials entering the digesters are corn straw and pig manure, which are fermented at a high temperature of 55°C. The location of the research subject is set in an alpine region, where the equipment operates all year round. Based on the local climatic conditions, the typical days are divided into typical summer days, typical winter days and typical transitional season days based on the local historical data. The electrical load and gas load of each typical day are shown in Figure 5 and Figure 6. The gas load demand varies greatly with seasonal changes, with the highest demand in winter due to heating, the second highest in the excessive season, and the smallest in summer, with the peak of gas load occurring around 8:00 am and 10:00 pm.

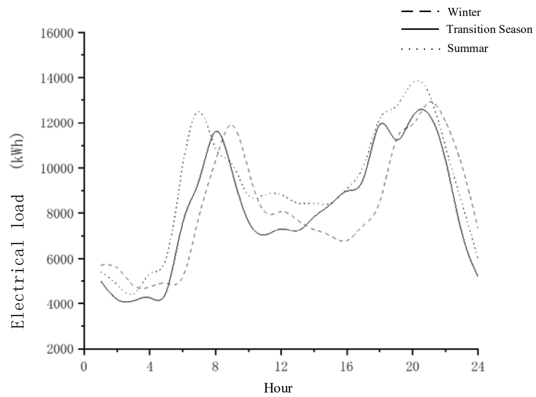


Fig.5 Typical daily electricity load

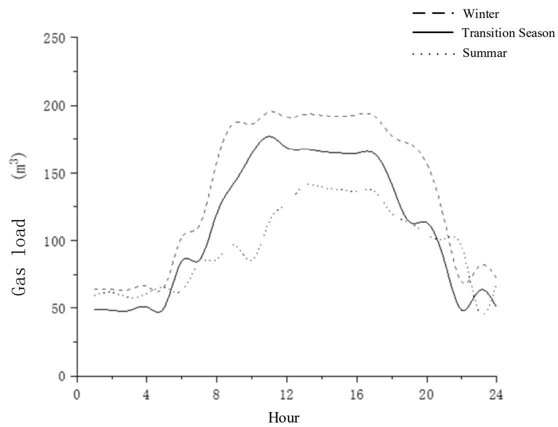


Fig.6 Typical daily biogas load

The equipment involved in the integrated energy system in this study includes biomass boilers, steam turbines, SOFC, digesters, and storage tanks. The input to the system includes straw and manure, and the output is electricity, heat, biogas, and biomass fertilizer, and some of its unit prices are shown in Table 2.

Table 2 Unit prices of some equipment and resources in the integrated energy system

Projects	Price	Source
SOFC Construction Costs	130rmb/kW	[23]
Gas Storage Tank Construction Cost	100rmb /m^3	Project Settings
Metered Heat Price	180rmb /t	Project Settings
Straw price	100rmb /t	Project Settings
Biogas fertilizer price	1000rmb /t	[13]

Since the system power generation participates in grid peaking, the electricity selling price can be obtained by referring to the peaking price in the literature[24], and the biogas price is set by the project as 1.5 rmb/m3. Electricity price and biogas price are uncertainties in the integrated energy system, and in this paper, the lower grid electricity price is set to obey a uniform distribution, and the biogas price obeys a triangular distribution, which can be obtained by Monte Carlo sampling for 100 sets of scenarios.

4.2 Analysis of optimization scheduling results

Using the above model and algorithm for calculation and analysis, Figures 7-16 give the amount of straw entering the boiler hour by hour, the amount of straw entering the digester hour by hour, the amount of gas produced by the digester hour by hour, the amount of electricity generated by the system hour by hour, the amount of heat supplied to the system hour by hour, the amount of heat purchased hour by hour, and the amount of gas purchased hour by hour, Electrical load and equipment electrical power , Heat load and equipment thermal power and Gas load and equipment gas power respectively.

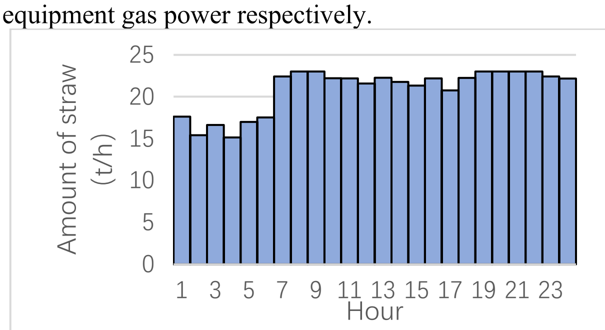


Fig.7 Amount of straw fed into the boiler

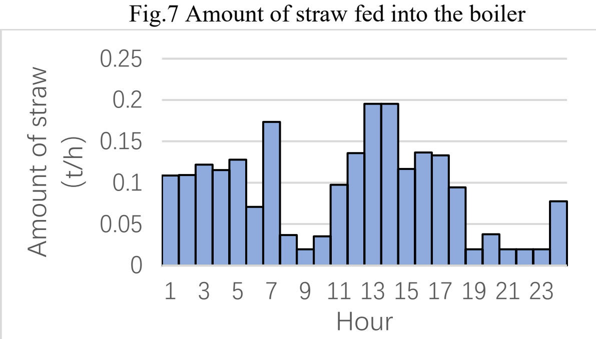


Fig.8 Amount of straw fed into the digester

From the optimization results of the previous day's operation, we can see that under uncertain conditions, the SOFC does not work for most of the time because the turbine pumping can basically meet the heat load. 9:00-10:00 time period reaches the peak heat load, and the electric load is also larger at this time, the turbine pumping is very small, and the biogas production is also smaller, so it is necessary to purchase a large amount of biogas to meet the heat load through SOFC.

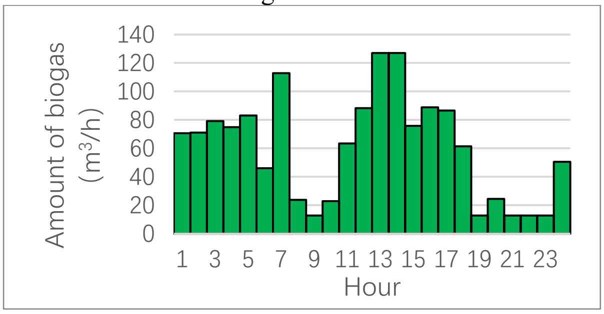


Fig.9 Amount of biogas

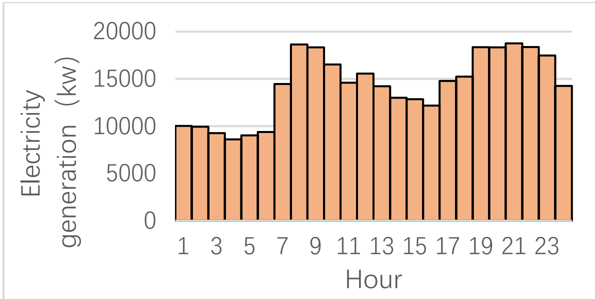


Fig.10 Electricity generation

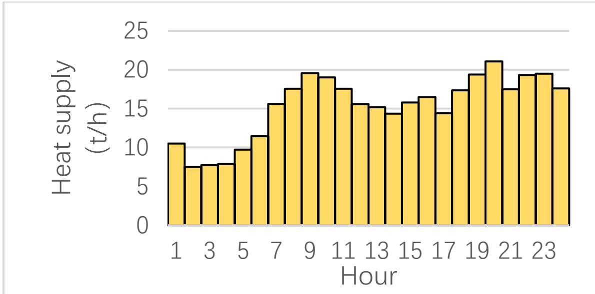


Fig.11 Heat supply

In the time period of 1:00-7:00 the electric, thermal and gas loads do not reach the peak, and the system chooses to fill the gas storage tank appropriately during this time to cope with the higher load in the subsequent moments. After 7:00 the energy storage device discharges gas to the outside, and the gas storage volume keeps decreasing until it drops to zero at 10:00. In the day-ahead dispatch, the maximum power purchase is made during the 21:00-22:00 time period, and the maximum purchase volume is made during the 9:00-10:00 time period. If the maximum power purchase is 2000kw and the maximum gas purchase volume is 100m^3/h, there are four unsatisfied points.

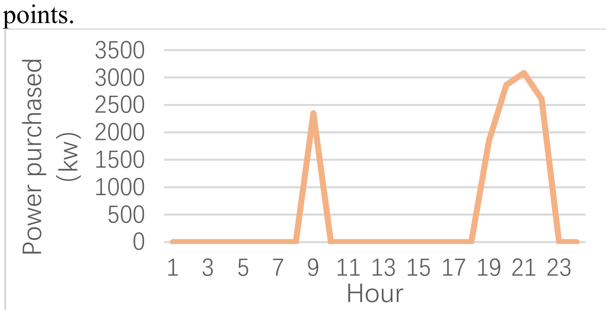


Fig.12 Power purchased

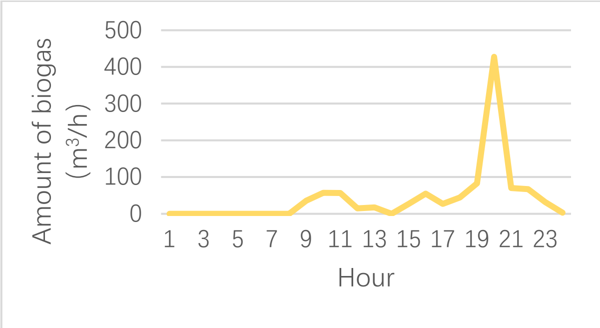


Fig.13 Amount of biogas purchased

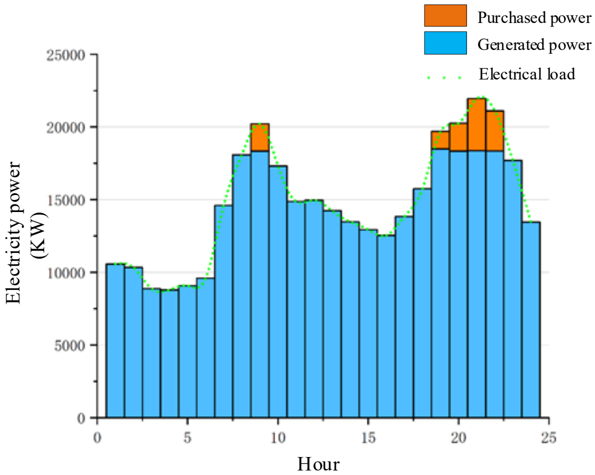


Fig.14 Electrical load and equipment electrical power

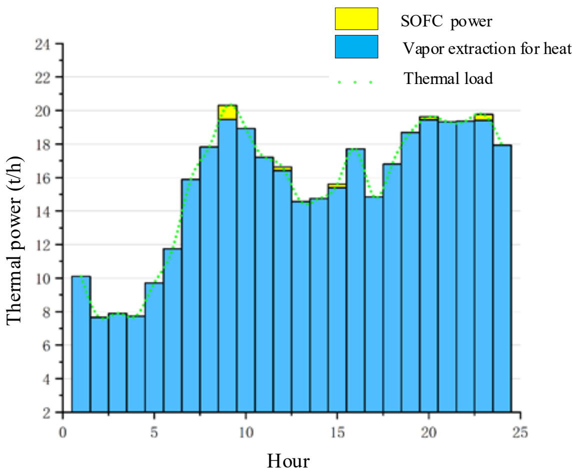


Fig.15 Heat load and equipment thermal power

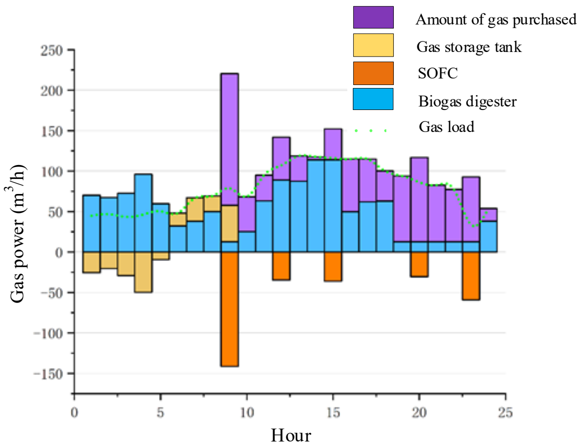


Fig.16 Gas load and equipment gas power

Under uncertain conditions, the maximum load case is larger due to the heat load, the turbine steam extraction priority heating to meet the heat load, while the amount of steam used to heat the digester is small, and the digester working at 55 ℃ is very little, so the amount of gas production is small, relying on gas purchase to meet the gas load. The amount of biogas production is relatively larger in the minimum load case, which is because there is more extraction steam available to heat the digester when the thermal load is low, and more straw fermented in the digester, more biogas fertilizer is produced, and the biogas fertilizer yield is larger, so the amount of straw entering the digester is larger, and the excess biogas produced is stored in the gas storage tank. The electricity, heat and gas loads are higher at the maximum load case, so the profit and carbon reduction are larger.

5. Conclusion

This paper proposes an economic scheduling optimization method based on an artificial bee colony optimization algorithm with the objective of maximizing annual profits for an integrated energy system including SOFC with biomass as the core. Based on the mathematical model of each energy device, the proposed method takes into account the energy balance constraint, equipment safety constraint, operation state constraint and coupling characteristics of energy sources, while taking into account the investment cost and operation cost of electricity and gas purchase, as well as the revenue of biogas and biogas fertilizer and power generation. The feasibility of the proposed method is verified by using the actual data of a typical biomass cogeneration system in Inner Mongolia. The results show that according to the proposed optimization method based on the swarm algorithm, the profit of the whole system can be greatly increased based on the reduction of carbon emission, which is a certain guidance for the production practice.

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