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Day-ahead Multi-objective Coordinated Optimization Strategy for Regional Scale Source Network Load Storage System

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Abstract. The regional scale source network load storage coordination system is an effective organization form to increase the proportion of clean energy and absorb distributed renewable energy. However, due to the different ownerships of various distributed resources in the system, balancing the interests of different stakeholders in the operation is an important issue to be considered. The types of distributed resources contained in the regional scale source network load and storage system and their belongingness are analyzed in different perspectives, and then the optimal operation strategy of distributed resources is proposed to balance the interests of different stakeholders. Based on this strategy, a bi-layer optimization model with energy supply cost minimization and the power consumption satisfaction maximization is established. It takes the power supply of the energy supplier and the power demand of consumer as the correlation variable of the upper and lower layer models, the analytical target cascading (ATC) theory is used to adjust the correlation variables iteratively until the power supply meets the power demand, and obtains the distributed resources trade-off operation plan satisfying different objectives. YALMIP modeling tool is used to call CPLEX solver on MATLAB platform to solve the model in parallel. An example based on the data of a regional scale source network load storage system shows that the optimization model and its solution strategy can effectively balance the optimization objectives of different stakeholders.

1. Introduction

In recent years, distributed generation, such as photovoltaic power generation, natural gas power generation, biomass energy power generation, installed capacity has increased year by year, and distributed generation has gradually become the development trend of renewable energy in the future. However, the traditional control mode of source following load can't control the distributed generation with random output such as wind power and photovoltaic, and it is difficult to ensure the safe and economic operation of distribution network. Different from the controllable microgrid that can be connected to grid or operate independently [2] and flexible aggregation virtual power plant with open system characteristics [3], as one of the core technologies to promote large-scale consumption of new energy [4], the regional scale source network load storage coordination control can realize the optimal adjustment and active management of all kinds of distributed resources in the vertical and deep layer, and give full play to the complementarity of power sources, the flexibility of power grids, the flexibility and controllability of load and energy storage system, improving the ability of distribution network to absorb new energy, and ensuring the reliability and economy of distribution network operation, have become a research hotspot in recent years.



The coordinated control technology of source network load storage has been studied at home and abroad. However, most studies only consider the coordination and optimization of some schedulable resources [6-9]. With the development of integrated energy system, energy internet and other projects, there are more types of distributed resources in the system, and the coupling relationship is more complex. Therefore, it is necessary to coordinate the coordination relationship among various distributed resources more comprehensively. Secondly, most studies take the energy supply side cost and renewable energy consumption as the optimization objectives for modeling [10-13], ignoring the power consumption feeling of the consumer side, and it is necessary to establish an optimization model to balance the interests of multiple stakeholders, so as to maximize the comprehensive social benefits. Therefore, a multi-objective optimization operation strategy of distribution system with multiple distributed resources is studied, and analytical target cascading (ATC) theory is used to balance the interest game between different stakeholders in this paper.

2. System structure analysis and optimal control strategy

2.1. System structure analysis

The traditional "source network load storage" coordination optimization mainly refers to the interactive operation among power source, power grid, load and energy storage. In the context of energy internet, "source network load storage" has derived a deeper meaning [5]. Therefore, the regional scale source network load storage system considered in this paper includes photovoltaic, wind power, CCHP unit, energy storage system, flexible load, cooling load and heat load. Aiming at the problems of fixed operation mode and poor regulation performance of the traditional CCHP unit, a "energy buffer" is built around the power and heat output of gas turbine and waste heat boiler by building heat storage device in distributed energy station, so as to realize the decoupling of heat and power in CCHP unit, improve the regulation capacity of unit and expand the consumption of distributed renewable energy, improve the autonomous operation ability of the regional source network load storage system. The energy flow relationship among distributed resources is shown in Figure 1.

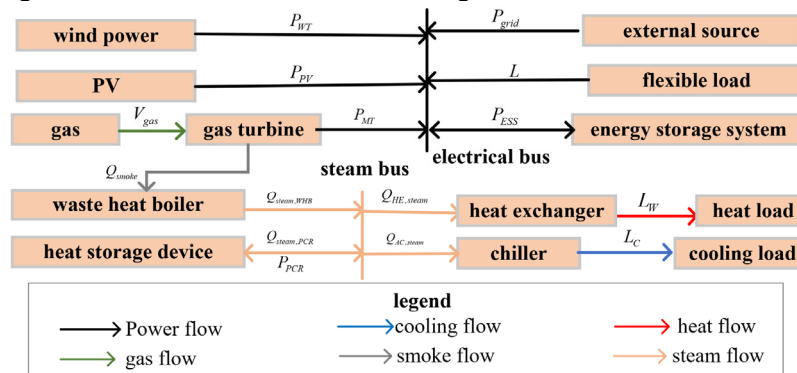


Figure 1. Bus structure of regional scale source network load storage system

2.2. Optimal control strategy

In the source network load and storage system with multiple types of distributed schedulable resources described in section 2.1, from the perspective of society, energy supplier needs to reasonably use the distributed resources in the system on the premise of meeting the basic energy demand of power, cooling and heat loads, so as to fully absorb renewable energy, reduce operation cost and save social resources; From the perspective of consumers, as an independent group, consumers need the energy supplier to meet the basic energy demand of their production or life in real time, and can adjust their own power consumption plan according to the incentive conditions of the energy supplier, but the amount of adjustment depends on their own profit. It can be seen that not all the schedulable sources in the system belong to the same stakeholder. If the whole system is centralized and optimized, although it can achieve the optimization of a certain objective of the whole system, it is not necessarily able to achieve the

benefit optimization of different stakeholders. Therefore, it is necessary to seek an operation state that can balance the benefits of multiple stakeholders in the system.

Based on the above analysis, according to the actual operation mode of the system, the system is divided into two stakeholders: energy supplier and flexible load consumer. The upper layer optimization model with the energy supply cost minimization of energy supplier and the lower layer optimization model with the power consumption satisfaction maximization of flexible load consumer are established respectively. The optimization objectives and operation constraints of different stakeholders are refined, as well as the interests game. The optimization strategy is shown in Figure 2.

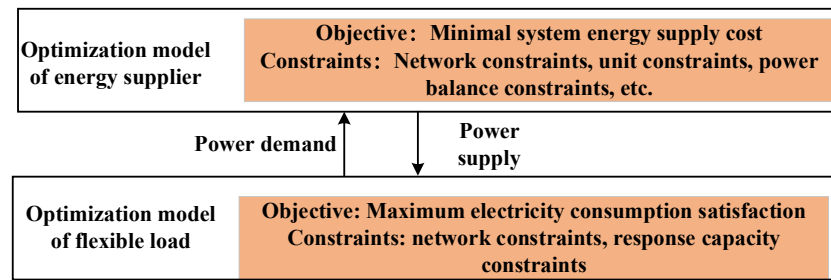


Figure 2. Schematic diagram of bilayer optimization model

In the upper layer optimization model, the input information is distributed wind power, photovoltaic day ahead output forecast, initial state of charge of energy storage system and power demand feedback from the flexible load optimization model of the lower layer. The energy supply cost minimization of the system is taken as the optimization objective. The constraints of network power flow, system power balance, upper and lower limits of unit output, ramp rate constraints and charging and discharging power constraints of energy storage system are considered. The input power of external source, generation power of CCHP unit, charging and discharging power of energy storage system, power supply to flexible load and storage / release power of heat storage device are optimized, and the total power supply power of the system is sent to the lower layer as the reference value for optimization of the lower layer. While fully absorbing renewable energy, it is also necessary to prevent it from transferring power to transmission network.

In the lower layer optimization, the consumer's daily load forecast is taken as the input, and the optimized power supply power of the upper layer is taken as the reference, and the satisfaction of the power consumption maximization is taken as the optimization objective to optimize the power demand of the flexible load, and the optimized power demand is fed back to the upper layer.

3. Optimal control model

3.1. Upper layer optimization model

The objective of the upper layer optimization is to minimize the energy supply cost of energy suppliers. The cost of wind power and photovoltaic mainly includes three parts: investment cost, operation and maintenance cost and financial expense [14,15]. These costs are fixed and hardly affected by the operation status. In this paper, the operation costs of wind power and photovoltaic are ignored. Therefore, the cost of energy supply only includes the cost of purchasing electricity from external power sources, the cost of using energy storage systems, and the cost of purchasing gas for CCHP unit. The mathematical model is as follows.

$$\min C = \min \sum_{t=1}^T (p_e(t)P_{grid}(t)\Delta t + C_{ess}(t) + C_{mt}(t)) \quad (1)$$

Where C is the energy supply cost, C_{ess} is the loss of energy storage system caused by charging and discharging, C_{mt} is the operation cost of CCHP units in Δt period, $p_e(t)$ is the time of use price of power

grid, $P_{grid}(t)$ is the exchange power with the transmission network, T is the optimization cycle, and Δt is the minimum calculation time.

$$C_{mt} = p_{gas} \frac{P_{MT}}{\eta_e R_{gas}} \Delta t \quad (2)$$

P_{MT} and η_e represent the electric power and power generation efficiency of micro gas turbine respectively, p_{gas} represents the price of natural gas, and R_{gas} represents the calorific value of natural gas combustion, generally taken as 9.7kWh/m³.

$$C_{ess} = C_{base} \frac{E_{loss}}{E_{full}} \quad (3)$$

Where C_{base} is the construction cost of the energy storage system, E_{loss} is the throughput loss caused by charging and discharging in the period of Δt , and E_{full} is the total throughput in the life cycle of the energy storage system.

3.2. Lower layer optimization model

The objective of the lower layer optimization is to achieve the satisfaction maximization with power consumption, and the evaluation index of power consumption satisfaction includes two aspects:

The first is the satisfaction of power consumption mode, which reflects the change of power consumption mode after adjustment compared with the power consumption mode predicted by the day ahead. The greater the flexible load response is, the greater the change of power consumption mode is. The satisfaction of power consumption mode φ can be expressed by equation 4.

$$\varphi = 1 - \frac{|\Delta L|}{L_0} \quad (4)$$

Where ΔL and L_0 respectively represent the response volume and the electricity consumption before the response.

The second is the satisfaction of load response benefit, which reflects the change of power charges after the consumer adjusts the power consumption mode compared with the power charges under the forecast power consumption mode. The higher the power charges, the lower the satisfaction. The response benefit satisfaction γ can be expressed by equation 5.

$$\gamma = 1 - \frac{p_e L - p_e L_0}{p_e L_0} \quad (5)$$

The comprehensive satisfaction of flexible load consumer response can be expressed as follows:

$$\begin{cases} \max F = \max(\lambda_1 \varphi + \lambda_2 \gamma) \\ \lambda_1 + \lambda_2 = 1 \end{cases} \quad (6)$$

Where, λ_1 and λ_2 represent the weights of satisfaction degree of power consumption mode and response benefit of flexible load consumer respectively.

3.3. Solving strategy of optimization model

3.3.1. ATC theory. ATC theory is a design method to solve the complex system by using the parallel idea [16]. Its basic idea is to divide the system into several subsystems step by step, continuously shunt the design indexes from top to bottom, at the same time, the response results of all layers are fed back step by step from bottom to top, and each layer system solves independently, and the solution results are fed back to each other until the convergence conditions are satisfied [17]. The mathematical model of variable optimization in the target cascade analysis method is shown in equation 7.

$$\begin{cases} \min f(x) + \pi(t_{ij} - r_{ij}) \\ s.t. \begin{cases} g(x) < 0 \\ h(x) = 0 \end{cases} \end{cases} \quad (7)$$

Where $f(x)$ is the initial objective function, $g(x) < 0$ and $h(x) = 0$ are the constraints of the system layer. t_{ij} is the design variable passed from the upper system to the lower layer; r_{ij} is the response result of the lower layer system feedback to the upper layer; $\pi(t_{ij} - r_{ij})$ is the penalty function, which has different expression forms according to different application requirements.

Corresponding to this paper, the upper layer system sends the optimized total power supply L as the design variable to the lower layer system, and the lower layer system uploads the optimized power demand L' as the feedback variable to the upper layer system. According to the penalty function setting idea of the ATC theory, the upper and lower layer objective functions need to be updated, as shown in equations 8 and 9 respectively.

$$\min C + v \sum_{t=1}^T (L(t) - L'(t))^2 \quad (8)$$

$$\max F - u \frac{\sum_{t=1}^T |L(t) - L'(t)|}{\sum_{t=1}^T L_0(t)} \quad (9)$$

Where L_0 is the load before optimization, v and u are coefficients greater than 0, and their values are determined according to C and F respectively, and should make the order of magnitude of the former and the latter two values in equation 15 and equation 16 be similar. It can be seen that after adding the penalty function, the deviation between the upper layer design variables and the lower layer feedback variables will increase the energy supply cost of the upper layer and reduce the power consumption satisfaction of the lower layer, making the current solution a non-optimal solution. By adjusting the penalty function coefficient to change its influence on the objective function, the approximation speed of the current optimization layer variable to its upper or lower layer variable can be adjusted. The optimal solution of the system is obtained by iterating until the error between the design value and the feedback value is less than the set value ε . The convergence condition of iteration is shown in equation 10.

$$\max(|L(t) - L'(t)|) \leq \varepsilon, t = 1, 2, 3, \dots, T \quad (10)$$

As the number of iterations increases, the error between design variables and feedback variables gradually decreases, and the influence of penalty function term on the objective function decreases, too. Which reduces the approximation speed between design variables and feedback variables, that is, the convergence speed of the algorithm is reduced. Therefore, a variable coefficient strategy is designed in this paper. The coefficient of penalty function increases synchronously with the increase of iteration times, so as to slow down the decrease speed of the whole penalty function term and accelerate the convergence speed of the algorithm. The coefficient updating method is shown in equation 11.

$$\begin{cases} v = k^2 v_0 \\ u = k u_0 \end{cases} \quad (11)$$

Where k is the number of iterations, v_0 and u_0 are the initial values of the coefficients.

The process of solving the day ahead optimization model of source network load storage coordination based on ATC theory is shown in Figure 3.

3.3.2. Solving tool. As a professional optimization software, CPLEX can solve complex optimization models such as linear programming, quadratic equation programming and mixed integer programming, and has been widely used in power system optimization. In this paper, the YALMIP modeling tool is used to establish the optimization model on the MATLAB platform, and the CPLEX solver is called to solve the model.

4. Example analysis

Taking the data of a regional scale source network load storage system in Jiangsu province as an example, the basic situation of the system is as follows.

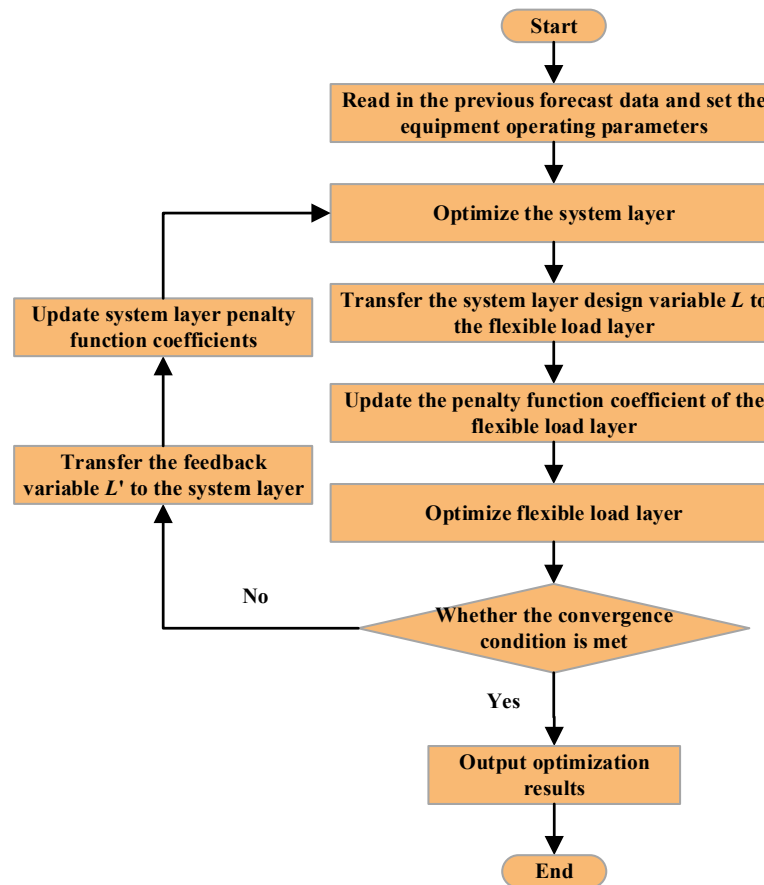


Figure 3. Model solving process

4.1. Distributed resources

4.1.1. Sources. In this area, there are 33.25 MW distributed photovoltaic power and 50 MW wind power installed capacity; The project of CCHP unit is planned to build 2×10 MW gas steam combined cycle units with power generation efficiency of 31.2%, and rated evaporation capacity of single HRSG is 19 t/h. The construction scheme of CCHP unit is shown in Figure 4. The regional system is connected with the superior power transmission network through a 220 kV substation (180 MVA). The 10 kV distribution line in the region adopts the combination of overhead and cable lines. The lines can realize mutual standby supply and achieve full coverage of distribution automation.

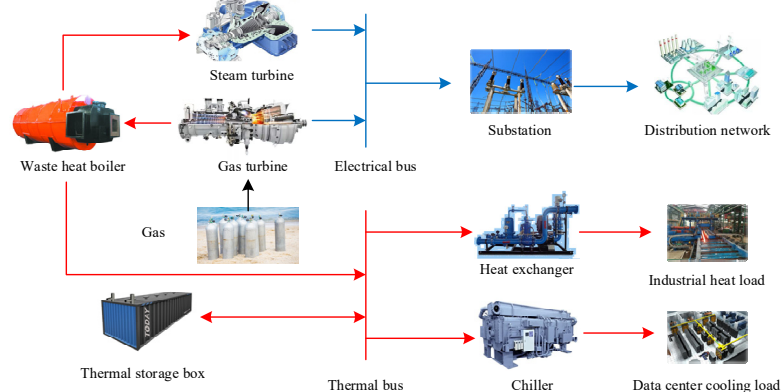


Figure 4. Construction scheme of source integration of CCHP system

4.1.2. Loads. The maximum power load in the region is 69 MW, and the maximum response in each period is 5% of the current load. The industrial heat load of 33t/h is the industrial steam for production, and the cooling load of 3.9t/h is supplied to the data center for refrigeration. Both heating and cooling loads are perennial and have nothing to do with seasonal changes. Heating load and domestic hot water heat load are not considered temporarily. The conversion method between T / h and MW is given in Reference [18].

4.1.3. Energy storage system. There are grid side energy storage power stations in the region, with the capacity of 10MW/20MWh, the construction cost of energy storage system is 16 million yuan, and the total power throughput in the whole life cycle is 115700MWh.

4.2. Electricity price

The TOU price mechanism is implemented in this region, and the price curve is shown in Figure 5.

4.3. Day-ahead forecast results of renewable energy output and load

The wind power, photovoltaic output and load of a typical day in the region is selected to simulate the day ahead forecast results, as shown in Figure 6.

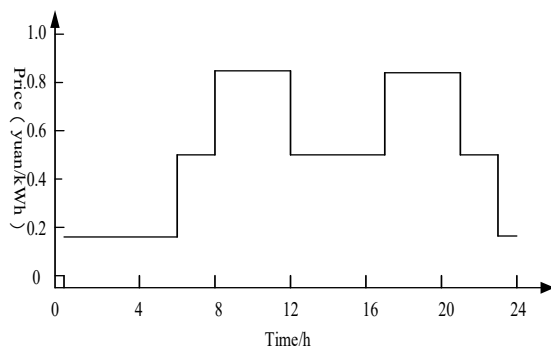


Figure 5. Electricity price curve

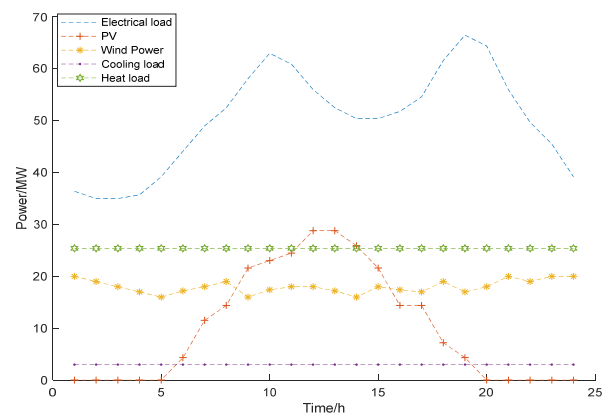


Figure 6. Day-ahead forecast results of renewable energy output and load

4.4. Model parameter setting

After preliminary calculation, the order of magnitude of the system energy supply cost (yuan) (with 10 as the bottom, the same below) is 5, the order of magnitude of power consumption satisfaction is -1, and the order of magnitude of the difference between design variable and feedback variable (MW) is 1. In order to make the penalty function in the ATC theory effectively affect the original optimization objective, the initial value of the penalty function should be close to the order of magnitude of the original objective function. Therefore, the order of magnitude of the penalty function coefficient of the upper layer is taken as 2, and that of the lower layer is -1. The specific parameter values are shown in table 1.

Table 1. Model parameter

Flexible load layer parameters		Penalty function coefficient	
λ_1	λ_2	v_0	u_0
0.6	0.4	500	0.2

4.5. Optimal scheduling results of distributed resources

The model is used to optimize the day ahead operation plan of each equipment in the energy supply system, and the output of each equipment is obtained as shown in Figure 7.

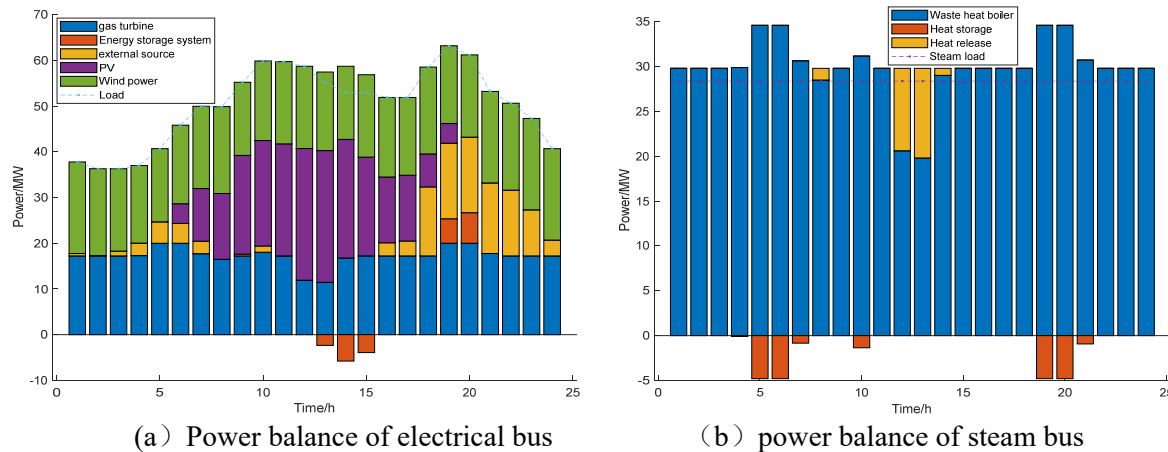


Figure 7. System equipments output

As can be seen from Figure7, during 0:00-6:00 and 17:00-24:00, due to no light or weak light intensity, the photovoltaic power generation is less, and the power supply of the system mainly comes from wind power, CCHP unit and external source. During 6:00-17:00, the light is sufficient and the photovoltaic power generation capacity is large. The power supply of the system mainly comes from wind power, photovoltaic power generation and CCHP unit, and the dependence of the system on external source is almost reduced to 0. Due to the strong correlation between the heating and power of the CCHP unit, and the cooling and heat loads are stable loads, almost unchanged, the load rate of the CCHP unit is kept at about 86% all day. However, due to the addition of heat storage device, the CCHP unit increased the power generation during 4:00-6:00 and 18:00-20:00 when the output of renewable energy was insufficient, the load rate reached 100%, and the excess heat power is stored by the heat storage device, and released in 11:00-13:00 when the renewable energy output is sufficient, which reduced the load rate of the cogeneration unit to about 58%, and reduced the primary energy consumption. At the same time, the energy storage system stores power during 12:00-15:00 when the renewable energy output is relatively sufficient, and then releases it in 18:00-20:00 when the output of renewable energy is insufficient, which reduces the purchasing power of the system to external sources during the peak load period, and plays the role of peak shaving.

It can be seen that, due to the addition of heat storage device and energy storage system, to a certain extent, it weakens the power and heat coupling characteristics of CCHP unit, improves the scheduling flexibility of CCHP unit, promotes the absorption of renewable energy, reduces the power fluctuation on the tie line between the system and external sources, and improves the security of power grid operation.

4.6. Comparison of different optimization models

In order to compare the optimization effects of different models, this paper designs three optimization models, which only take the energy supply cost minimization as the objective, only take the customer satisfaction maximization as the objective, and comprehensively consider the energy supply cost and consumer satisfaction. After solving, the energy supply cost, customer satisfaction and load curves of different optimization models are shown in table 2 and Figure 8 respectively.

In the single-layer single objective optimization, when the energy supply cost minimization is the optimization objective, the optimized load curve is almost all lower than the predicted load curve, and only at noon when the photovoltaic power generation is sufficient, the planned load curve is higher than the predicted load curve. The reason is that the model only considers the energy supply cost of the

system, and the energy supply cost of the system is related to the amount of energy supply and the types of energy supply. If the energy supply is less or the energy supply comes from renewable energy, the cost is low. Therefore, in the period when the output of renewable energy is insufficient, the system reduce the cost by reducing the energy supply, so the load operates at the upper limit of the reduced capacity in this period. However, in the period of abundant renewable energy output, the CCHP unit needs to meet the energy supply demand of cooling and heat load, and can't greatly reduce the output of CCHP unit, so the optimal load is higher than the predicted load. On the whole, the optimal load with the energy supply cost minimization as the objective is lower than the predicted load.

Table 2. Energy supply cost and customer satisfaction of different models

model	Energy supply cost (thousand yuan)	Power consumption satisfaction	Change of power consumption mode (MWh)	Change of power charges (thousand yuan)
Minimize costs	464.3	0.9952	-32.35	-19.41
Maximize satisfaction		1.0081	0	-13.63
Multi-objective	476.4	1.0058	-0.96	-9.69

Note: in the model with the satisfaction maximization, only the power consumption and electricity charge variation are considered, and the power combination is not considered, so the energy supply cost cannot be calculated.

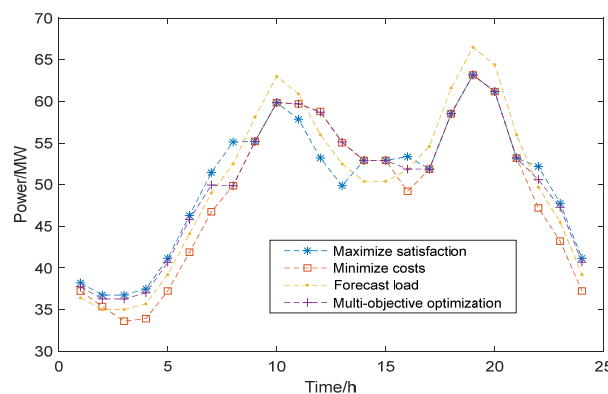


Figure 8. Load curves of different optimization schemes

The optimization model with the satisfaction maximization takes into account the changes of total power consumption and total power charges. In order to reduce the consumer's power charges and meet the power demand in one day, the model transfers the power load from peak price period to valley price period maximally, and reduces the power charges to the minimum under the condition of the total power consumption unchanged in a day.

The multi-objective optimization model finds a compromise operating point in the interest game between energy supplier seeking energy supply costs minimization and consumer seeking satisfaction maximization, which not only moderately reduces the energy supply costs of the system, but also minimize changes in the way consumer uses power.

5. Conclusion

In this paper, the distributed resources are divided into two categories with different stakeholders from different perspectives, and a multi-objective two-layer optimization model is established, which considers the energy supply cost minimization of energy supplier and the customer satisfaction maximization. The model is solved by the ATC theory, and the optimal scheduling of the regional scale source network load storage coordination system is realized. Compared with traditional multi-objective optimization strategies, such as main objective method, linear weighting method, hierarchical sequence method, etc., the hierarchical modeling and parallel solving multi-objective optimization strategy used in this article have two major advantages:

1) It can ensure the independence of different stakeholders in the interest game. Each stakeholder has no primary and secondary distinction. Except for the related variables, the optimization process and objective are independent of other stakeholders, so as to better achieve the balance of interests between different stakeholders.

2) The independent modeling strategy of each layer can simplify the modeling process of multi-objective optimization models with different objective measurement scales, refine the optimization objectives and operation constraints of distributed resources in different layers, and the selection of optimization algorithms for each layer has more flexibility.

The example shows that the model can effectively balance the interests of different stakeholders under the condition that the output of various distributed resources is reasonably allocated, the balance of power, cooling and heat is realized, and the safe and stable operation of the system is ensured. However, in the optimization strategy of this paper, only the active output of various distributed resources is considered, and the distribution of power flow in the network is not taken into account. The coordinated optimization of active and reactive power, which takes network power flow and node voltage into constraints, will be the focus of the next step. Secondly, this article has a certain subjectivity in the selection of penalty factors and weight coefficients in the model, and the principle of model parameter selection needs to be further improved.

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