Research on Multi-Objective Operation Optimization of Integrated Energy System Based on Economic-Carbon Emission

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Abstract. The development of an integrated energy system (IES) is an important way to improve energy utilization, link renewable energy consumption and protect the environment. In this paper, physical modeling and analysis of the key equipment of IES, with economic costs and carbon emissions as the goal, established a multi-objective operation optimization model of the integrated energy system, and used particle swarm optimization to solve practical problems. Finally, taking a typical summer day as an example, the analysis illustrates the optimization results and verifies the feasibility of the model and algorithm.

1. Introduction

The dual pressures of energy crisis and environmental pollution have promoted the rapid development of integrated energy systems (IES), forming a complex energy structure that includes a variety of energy sources, including cold, hot, and electrical sources. The development of an integrated energy system can effectively manage and dispatch different forms of energy flow, significantly reduce system operating costs, and improve environmental benefits.

The optimization of integrated energy system operation is an important technical support for the efficient operation of the energy internet. Many scholars have conducted in-depth research on the optimization of the operation of integrated energy systems. The large-scale integration of various energy sources has led to the energy system often failing to balance economic efficiency and environmental protection, and insufficient capacity to optimize operation. Therefore, how to optimize the integrated energy system and take into account the economic and environmental protection of the system operation has become a problem to be solved[1]. Ref.[2-3] considered carbon emissions and renewable energy consumption issues, and proposed a new hybrid power flow calculation method to ensure the economic and stable operation of the constructed combined heat and power microgrid. In recent years, scholars have applied multi-objective optimization methods to various aspects of power systems. Ref.[4] established a multi-objective dynamic reactive power optimization model considering short-term voltage stability and transient stability; Ref.[5] established a dynamic reactive power distribution model based on a multi-objective mixed integer programming method.

The objective function and constraint conditions are established based on the optimal system economy and environmental protection. The operation optimization model of IES is established. The
improved particle swarm algorithm is used to solve the system optimization model. The system's operating results under a single target and simultaneous consideration of multiple targets provide a reference for the later collaborative planning of IES.

2. Modeling of key equipment in IES

2.1. Gas Turbine (GT)

\[
\begin{align*}
Q_{GT}(t) &= P_{GT}(t)(1 - \eta_{GT} - k) / \eta_{GT} \\
Q_{WH}(t) &= Q_{GT}(t)COP_{GT} \\
Q_{SH}(t) &= Q_{GT}(t)COP_{GT}\eta_{WH}
\end{align*}
\]

(1)

In the formula, \(Q_{GT}(t)\) is the heat generation power and electricity generation power of the gas turbine at any time \(t\), kW; \(\eta_{GT}\) is the power generation efficiency of GT,\%; \(k\) is 0.03 for the heat loss of the gas turbine; \(Q_{WH}(t), Q_{SH}(t)\) are the heat generation power of GT at any \(t\) Heating power, kW; \(COP_{GT}\) is heating coefficient, value 1.2; \(\eta_{WH}\) is waste heat recovery rate,\%.

2.2. Photovoltaic (PV)

\[
P = \frac{P_0G[1 + k(T - T_0)]}{G_0}
\]

(2)

In the formula, \(P\) is PV output power, kW; \(P_0\) is rated power, kW; \(G, G_0\) are actual light intensity and standard light intensity, Lx; \(T\) is actual temperature, °C; \(T_0\) is reference temperature, °C.

2.3. Gas Boiler (GB)

\[
\begin{align*}
L_{GB}(t) &= \eta_{GB}\lambda_{gas}P_{Gb}(t) \\
L_{GB,min} &\leq L_{GB} \leq L_{GB,max}
\end{align*}
\]

(3)

In the formula, \(L_{GB}(t)\) is the heating power of GB at any time \(t\), kW; \(\eta_{GB}\) is the heating efficiency of GB,\%; \(\lambda_{gas}\) is the conversion efficiency of GB,\%; \(P_{Gb}(t)\) is the consumption rate of gas at any \(t\). \(L_{GB,min}, L_{GB,max}\) are the lower limit and upper power limit of GB.

2.4. Heat Pump (HP)

\[
\begin{align*}
Q_{PH} &= E_pCOP_p \\
Q_{PC} &= E_pCOP_p
\end{align*}
\]

(4)

In the formula, \(Q_{PH}, Q_{PC}\) are the heating capacity and cooling capacity of HP, kWh; \(E_p\) is the power consumption of HP, kWh; \(COP_p\) is the coefficient of performance of HP.
2.5. Energy Storage Battery (ES)

\[
E_s(t + 1) = \begin{cases} 
E_s(t) + \Delta t \frac{P_{c,s}}{\eta_c} & \text{if } E_s(t) + \Delta t \frac{P_{c,s}}{\eta_c} \leq E_s^{\text{max}} \leq E_s^{\text{min}} \leq E_s(t) - \Delta t \frac{P_{d,s}}{\eta_d} \\
E_s(t) - \Delta t \frac{P_{d,s}}{\eta_d} & \text{otherwise}
\end{cases}
\]  

(5)

In the formula, \( P_{c,s}, P_{d,s} \) are the charge and discharge power of the energy storage battery at time \( t \), kW; \( \eta_c, \eta_d \) are the charge and discharge power of the energy storage battery; \( E_s^{\text{min}}, E_s^{\text{max}} \) are the lower limit and upper limit of ES; and \( E_s^{\text{in}}, E_s^{\text{out}} \) are the charging and discharging mark of the battery. 0 is charging, and 1 is discharging. The same goes for Ice storage (IS) / Thermal storage (TS).

2.6. Electric Refrigeration (EC)

\[
Q_{ec} = E_{ec} \cdot COP_{ec}
\]  

(6)

In the formula, \( Q_{ec}, E_{ec} \) are the cooling capacity and power consumption of EC, kWh; \( COP_{ec} \) is the cooling coefficient of EC.

2.7. Lithium Bromide Refrigerator (Br)

\[
Q_{Br,c} = Q_{Br,h} \cdot COP_{Br}
\]  

(7)

In the formula, \( Q_{Br,c}, Q_{Br,h} \) are the cooling capacity and waste heat absorption capacity of Br, kWh; \( COP_{Br} \) is the refrigeration coefficient of Br, and the value is 0.8.

3. Optimization Model

This article proposes to establish a IES optimization model that takes into account both economic and environmental aspects, and establishes a construction objective function for the system's daily operating costs and carbon emissions.

3.1. Objectives

3.1.1. Economic objective function

\[
C_{op} = \sum_{i=1}^{34} \left( C_{op} + Q_{\text{gas,grid}} \cdot C_{\text{gas,grid}} + E_{\text{grid,grid}} \cdot C_{\text{grid,grid}} + E_{\text{grid,solar}} \cdot C_{\text{solar,grid}} \right) + C_{ss}
\]

\[
C_{ss} = \sum_{i=1}^{l} \left( u_{it}(1 - u_{i,t-1}) \right) SU_i
\]

(8)

In the formula, \( C_{op} \) is the total daily operating cost of the system, $; \( C_{op} \) is the equipment operating cost, $; \( Q_{\text{gas,grid}} \) is the natural gas consumption, kWh; \( E_{\text{grid,grid}} \) is the price of natural gas, $ / kWh; \( E_{\text{grid,solar}} \) is the amount of electricity purchased from the large grid, kWh; \( C_{\text{grid,grid}} \) is the price of the large grid, $ / kWh; \( E_{\text{grid,solar}} \) is the PV power generation, kWh; \( C_{solar,grid} \) is photovoltaic power subsidies, $ / kWh; \( C_{ss} \) is equipment start-stop costs, $; \( u_{it} \) is a 0-1 variable, where 0 means that the state of equipment i is closed at time t, 1 means The state of device i at time t is on; \( SU_i \) is the start-stop cost of device i, and \( l \) is the number of devices in the system.
3.1.2. Carbon emission objective function

\[ Q_{co2} = 24 \sum_{i=1}^{24} \left( Q_{dh, gas} \lambda_{gas} + M_{dh, coal} \lambda_{coal} \right) \]  

(9)

In the formula, \( Q_{co2} \) is the total daily carbon emission of the integrated energy system; \( \lambda_{gas} \) is the carbon emission coefficient of natural gas; \( M_{dh, coal} \) is the consumption of standard coal for the purchase of electricity from the grid; and \( \lambda_{coal} \) is the emission coefficient of standard coal.

3.2. Constraints

3.2.1. Supply and demand balance constraints

Supply and demand balance constraints include cold system balance constraints, thermal system balance constraints, and electrical system balance constraints. The cooling system mainly includes Br, EC, HP, and IS. The heat system mainly includes GT, GB, HP and TS. Electricity systems mainly include PV, GT, power grids, and ES. Among them, HP and EC are power-consuming equipment. The supply-demand balance constraint is expressed as:

\[
Q_{ec} + Q_{PC} + Q_{ic, out} = Q_{c} + Q_{sc, in} + Q_{c, loss} \\
Q_{MT} + Q_{GB} + Q_{PH} + Q_{sh, out} = Q_{h} + Q_{sh, in} + Q_{h, loss} \\
E_{MT} + E_{solar} + E_{s, out} + E_{grid} = E + E_{p} + E_{s, in} + E_{loss}
\]  

(10)

In the formula, \( Q_{c, loss}, Q_{h, loss}, E_{loss} \) respectively represent the cold loss, heat loss and electric loss of the system; \( Q_{c}, Q_{h}, E \) respectively represent the cold load, heat load and electric load of the system.

3.2.2. Equipment operation constraints can be seen in Chapter 2.

3.3. Algorithm

Figure 1 the flow of particle swarm algorithm

Figure 1 is the flow of particle swarm algorithm. Operation optimization is a nonlinear problem, so particle swarm optimization is used for optimization. Suppose there is a particle swarm composed of \( M \) particles, and the number of optimization variables is \( D \), then the search space of the particle swarm is \( D \) dimension.
4. Optimization Model

4.1. Background
This article takes an IES project as an example. The number of particle swarms is 100, and the number of iterations is 100. The load curve and energy price curve of various energy sources on a typical summer day are shown in Figures 2 and 3.

![Figure 2 Energy load curve](image1)

![Figure 3 Energy price curve](image2)

4.2. Optimization Results
Considering the large demand for cooling load in summer, HP provide cooling for the day, and no heat load is provided. The cooling load is satisfied by the Br, and HP and EC are selectively turned on according to the electricity price. When the gas turbine cannot meet the heat load, GB is the main heating equipment. Consider the self-loss coefficient of energy storage equipment and charge and discharge efficiency constraints to control the number of start and stop. The results of the day's operation optimization are shown in Figure 4, Figure 5, and Figure 6.

![Figure 4 Optimization results of electrical system](image3)

![Figure 5 Optimization results of heat system](image4)

![Figure 6 Optimization results of cold system](image5)

It can be seen from Table 1 that the total cost of system operation is 39209.36 $, including equipment operating cost 37973.70 $, start-stop cost 431.82 $, energy consumption cost 1416 $, and deducting photovoltaic power subsidy 612.16 $. The total carbon emission of the system is 72201.95 kg, which includes the carbon emission of the purchased electricity converted into standard coal is 45050.25 kg, and the natural gas carbon emission is 27151.70 kg.

| Description                     | Cost   |
|---------------------------------|--------|
| Equipment operating cost / $    | 37973.70|
| Start and stop costs / $        | 431.82 |
| Energy cost / $                 | 1416.00|
| Photovoltaic subsidies / $      | 612.16 |
| **Total**                       | **39209.36** |
Compared with the results before the system optimization, the optimized operating cost was saved by 29.58%, and the carbon emission reduction was achieved by 24.24%. This shows that the IES operation optimization model established in this paper can effectively reduce the system operation cost and carbon emissions, and is of great significance for improving efficiency and protecting the environment.

Table 2 Comparison of operating costs and carbon emissions

|                           | After optimization | Before optimization | Degree of improvement |
|---------------------------|--------------------|---------------------|-----------------------|
| Total operating cost / $  | 39209.36           | 55677.29            | 29.58%                |
| Carbon emission / kg      | 72201.95           | 95306.57            | 24.24%                |

5. Conclusion
In this paper, with economics and carbon emissions as the goal, a IES operation optimization scheduling model is established, and a real-time complementary daily energy operation strategy for a typical summer day of a project is analyzed. The results show that the scheduling strategy based on real-time interaction between energy supply and demand can make full use of the coupling relationship between the energy network and energy equipment, effectively reduce operating costs and carbon emissions, and improve system efficiency and effectiveness.

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