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Demand Responsive Distributed Energy System Optimization Strategy: an Innovative Approach to Oilfield Energy Management

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As global demand for sustainable energy grows, so do carbon emissions from the oil and gas sector. This paper develops a comprehensive multi-objective mathematical model that incorporates supply-demand dynamics and energy storage to optimize both economic and environmental impacts. The model is designed to minimize uncertainties in annual operational costs, carbon emissions, and energy demand, providing an advanced optimization framework for the sustainable development of oilfield energy systems. Applied to an oilfield in Northeast China, the model has reduced annual operational costs and carbon emissions by 16.67 % and 18.36 %, respectively. This innovative approach based on demand response offers a promising new direction for the sustainable management of oilfield energy systems, with significant potential for widespread application and practical guidance.

1. Introduction

1.1 Background

As the global demand for sustainable energy continues to grow, the carbon emissions of the oil and gas industry also show an upward trend. According to the 2023 Carbon Dioxide Emissions Report released by the International Energy Agency, the total global carbon dioxide emissions from energy combustion and industrial processes reached 37.4 billion tons in 2023, an increase of 1.1% compared to the previous year (Ruo et al., 2023). Therefore, the rational adjustment of oil and gas resources and the optimization and upgrading of related technologies are extremely urgent.

In order to effectively reduce energy consumption and carbon emissions in the oil and gas production process, distributed energy systems (DES) provide an extremely effective strategy. The system achieves flexibility in energy conversion and supply by integrating multiple energy resources (Qin et al., 2021). In addition, DES prioritizes the use of clean, low-carbon renewable energy, greatly reducing the cost of energy distribution (Xiao et al., 2023). In view of this, energy intensive countries around the world are actively promoting the application of DES and conducting extensive research aimed at optimizing the design and operation of DES to achieve maximum environmental and economic benefits (Xiao et al., 2023).

1.2 Related work

Distributed Energy Systems (DES) can select appropriate energy types based on the resource endowment of specific regions, in order to achieve diversified supply of energy services such as electricity, gas, refrigeration, and heating. In previous studies, scholars have conducted extensive research, covering multiple aspects such as heating networks (Cortés et al., 2018) , power grids (Rn and Sgn, 2023) (Yuan et al., 2024), and heating and cooling networks (Rong et al., 2022). Moghimi et al.(2013) identified the optimal design variables and achieved multi-objective optimization by defining two objective functions: average annual total cost and efficiency.

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Compared to independent integrated energy systems, multiple subsystems located in close proximity can achieve complementary energy and voltage level support through the interconnection of microgrids. This interconnection mode can promote the comprehensive optimization and utilization of distributed energy in the region while meeting the operational goals of various subsystems (Rui et al., 2021). Mehleri and his team (2012)optimized the design of distributed energy systems (DES) by integrating heating pipeline networks, using binary variables to facilitate the connection of pipeline segments.
The introduction of demand response mechanism aims to solve the problems of energy supply imbalance and system stability, and further improve energy utilization efficiency (Dzyuba et al., 2023). Jia et al. (2020) considered optimizing the configuration of grid connected optical storage microgrids in response to demand side effects. They used an improved particle swarm optimization algorithm to solve the constructed model and analyzed the impact of demand side effects on the economic benefits and energy storage configuration of the system (Yubin et al., 2020).

1.3 Research gap and contribution

Traditional oilfield DES face inefficiencies due to decentralized energy facilities and lack of energy flow. A strategy that integrates subsystem interconnection with demand response can optimize DES, balancing load peaks, improving energy efficiency, and reducing costs and emissions while enabling users to better manage their energy use. The main academic contributions of this paper are as follows:

- Constructed a multi-objective mathematical programming model that considers supply-demand relationships and energy storage mechanisms, aiming to minimize annual costs, carbon emissions, and energy demand deviations for a win-win in both economic and environmental benefits.
- Applies interconnection theory to DES, enabling independent operation and energy sharing with other areas through microgrids or pipelines for optimized resource use.
- Demand response technology is used to adjust energy demand. Through reasonable arrangement of adjustable load, energy system efficiency is improved, cost and carbon emissions are reduced, and DES operation is optimized.

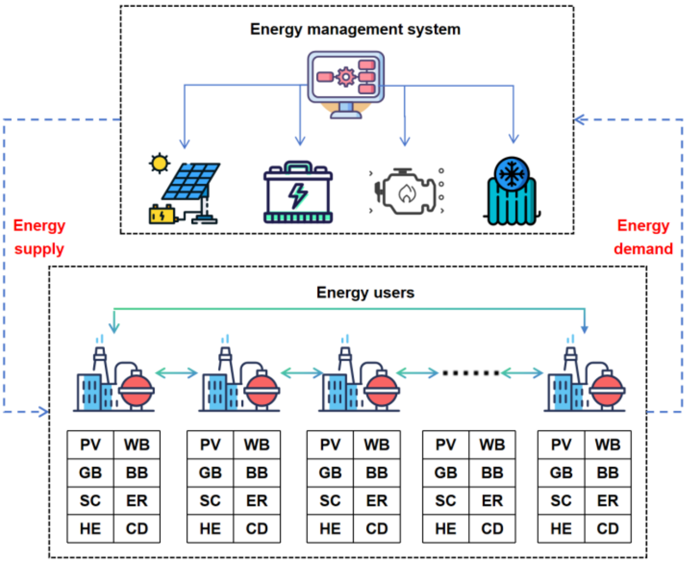

Figure 1: Technical route

2. Methodology

In order to effectively reduce energy consumption and carbon emissions in the oil and gas production process and ensure the green and low-carbon operation of the oil field, this chapter constructs a three-objective mixed integer linear programming (MILP) model. The model not only considers the two traditional objective functions of minimizing annual cost and carbon emissions, but also incorporates the minimization of energy demand deviation caused by demand response participation. The model takes energy supply, technology installation and operation, and energy balance as constraints to ensure the optimal design and operation scheme.

2.1 Objective function

Objective function

Formula (1) shows the calculation model of economic indicators, which divides the annual total cost into three parts: total capital cost, total operating cost, and total maintenance cost.

$$min\, F_1 = f_1 + f_2 + f_3 \tag{1}$$

The second side to be addressed is the environmental factor, represented by the total annual carbon emission. Eq(2) gives the calculation of carbon emission caused by different energy carrier consumption.

$$min\, F_2 = \sum_d \sum_t \sum_i \sum_e P_{d,t,i,e}^{ENEC} c_{d,t,e}^{EMIS} t_d^{YEAR} t_t^{DAY} \tag{2}$$

The user satisfaction indicator is expressed in terms of total annual energy demand deviation. Maximizing user satisfaction means minimizing energy demand deviation.

$$min\, F_3 = \sum_d \sum_t \sum_i \sum_z |d_{d,t,i,z}^{USER} - (d_{d,t,i,z}^{FIX} + D_{d,t,i,z}^{SHIFT})| + \sum_d \sum_t \sum_i \sum_z |\frac{D_{d,t,i,z}^{SHIFT}}{d_{d,t,i,z}^{USER}} - \frac{D_{d,t-1,i,z}^{SHIFT}}{d_{d,t-1,i,z}^{USER}}| \tag{3}$$

Energy carrier constraints

Solar energy is affected by solar irradiance at different times and PV panel size in different subsystems, as described in Eq(4).

$$P_{d,t,i,SOL}^{ENEC} = S_{i,PV}^{TECH} r_{d,t,i}^{SOL} \tag{4}$$

Take Eq(5) as an example, the input of energy conversion technologies is equal to the total consumption of energy carriers.

$$P_{d,t,i,SOL}^{ENEC} = P_{d,t,i,PV}^{TEIN} \tag{5}$$

Technology constraints

Take the energy conversion technology as an example. As displayed in Eq(6)(7), if an energy conversion technology is selected for installation, the size must be lower than its upper bound, upper than its lower bound Moreover, the output during operation cannot exceed the size of corresponding energy conversion technology, as shown in Eq(8).

$$S_{i,m}^{TECH} \le B_{i,m}^{TEIN} UB_{i,m} \tag{6}$$

$$B_{i,m}^{TEIN} LB_{i,m} \le S_{i,m}^{TECH} \tag{7}$$

$$P_{d,t,i,m}^{TOUT} \le S_{i,m}^{TECH} \tag{8}$$

According to Eq(9), if an energy conversion technique is not selected for operation, the corresponding output is equal to zero. However, if an energy conversion technique is selected for operation, the corresponding output must be upper than the minimum value, as shown in equation (10).

$$P_{d,t,i,m}^{TOUT} \le M_1 B_{d,t,i,m}^{TEOP} \tag{9}$$

$$S_{i,m}^{TECH} \gamma_m \le P_{d,t,i,m}^{TOUT} + M_1 (1 - B_{d,t,i,m}^{TEOP}) \tag{10}$$

Energy balance constraints

The adjusted energy demand is equal to the sum of the fixed energy demand and the removable energy demand. It must meet a rational upper and lower bound and the total energy demand keeps constant in a day, seen in Eq(11) and Eq(12).

$$d_{d,t,i,j}^{MIN} \le d_{d,t,i,j}^{FIX} + D_{d,t,i,j}^{SHIFT} \le d_{d,t,i,j}^{MAX} \tag{11}$$

$$\sum_t D_{d,t,i,j}^{SHIFT} + \sum_t d_{d,t,i,j}^{FIX} = \sum_t d_{d,t,i,j}^{USER} \tag{12}$$

Take the power balance for example, the electricity balance is given in Eq(13).

$$P_{d,t,i,PV}^{USER} + P_{d,t,i,GT}^{USER} + E_{d,t,i}^{MG} + P_{d,t,i,GR}^{ENEC} + P_{d,t,i,ELEC}^{SOUT} - P_{d,t,i,ELEC}^{STIN} - P_{d,t,i,ER}^{TEIN} = d_{d,t,i,ELEC}^{FIX} + D_{d,t,i,ELEC}^{SHIFT} \quad (13)$$

3. Cases and Results

3.1 Background description

The model is universal and can be set according to specific conditions. This study takes an oil field in Northeast China as an example to verify the effectiveness of the model. The oilfield uses electric heating technology to maintain the appropriate process temperature of the medium and prevent the solidification of crude oil pipelines. It consists of 30 wells, 5 valve groups, 1 oil station and 1 combined treatment station. It is divided into 7 independent working areas, each of which includes a gas station and its affiliated oil wells.

There are significant differences in energy demand across different seasons throughout the year. For example, in winter, due to low temperatures, in order to prevent crude oil from solidifying, it is necessary to increase the heating temperature, which leads to a sharp increase in the demand for electricity in electric heating pipelines; In summer, electricity demand is relatively reduced. The joint station where W7 is located is responsible for oil, gas, and water treatment, with a variety of equipment, resulting in a higher demand for multiple energy sources. The W1-W5 work area is mainly composed of valve groups and their managed wellhead, with a relatively single work nature and no steam demand throughout the year. Considering the low winter temperatures in the area where the oil field is located, the demand for electricity, cooling, heating, and steam in each work area fluctuates significantly with seasonal and temperature changes.

On the basis of comprehensive consideration of various factors, this study selects the carbon emission coefficient of electricity as 890 g CO_2 / kWh and natural gas as 900 g CO_2 / kWh. Since solar power generation does not involve the combustion process, its carbon emission coefficient is determined to be 0, highlighting the environmental advantages of solar energy as a zero-emission renewable energy source. According to the actual working ability and infrastructure of different working areas, the selected equipment installation capabilities of the seven areas are different. Table 1 summarizes the working hours, efficiency, and cost of various types of equipment:

Table 1 Equipment running time and efficiency

Device Name	Device life (a)	operating efficiency (%)	Fixed capital cost (CNY)	Linear capital cost
PV	30	17	250000	2,800 CNY/m²
GT	30	33	100000	1,500 CNY/kW
GB	20	83	20000	850 CNY/kW
BB	25	85	50000	600 CNY/kW
ER	25	430	150000	1,640 CNY/kW
SC	25	133	100000	970 CNY/kW
HE	20	98	70000	210 CNY/kW
WB	15	78	12000	1,200 CNY/kW
ES	15	90/85	150000	950 CNY/kWh
HS	20	90/85	80000	90 CNY/kWh
CS	20	90/85	80000	190 CNY/kWh

3.2 Running results

GUROBI 10.0.2 is used to solve the model.In the single objective function analysis, the annual cost (F1) is 8.12 × 106 CNY, the annual carbon emission (F2) is 1.37 × 103 t, and the annual energy demand deviation (F3) is 2.97 × 103 kWh. In order to ensure environmental friendliness and energy supply stability, the ε-constraint method is used to balance the three objectives, with F1 as the optimization objective and F2 and F3 as constraints. F1 and F2 are divided into different intervals, forming a multi-combination parameter set. The optimization results shown in Figure 2 show that all 20 schemes achieve Pareto optimality. Among all schemes, the ninth scheme achieves an equilibrium among the three objectives. Although it is not optimal for each objective, it is considered to be the most consistent choice with the preferences of current decision makers. Figure 2 shows the final linearization metrics for the three objectives in the 20 scenarios, where the red bar represents F1, purple represents F2, and orange represents F3. Figure 3 shows the relationship between annual cost and energy demand deviation, which provides a reference for decision makers to formulate more comprehensive pricing measures and incentives. In the ninth scheme, the energy demand deviation can be reduced by 168.71 × 103 kWh.

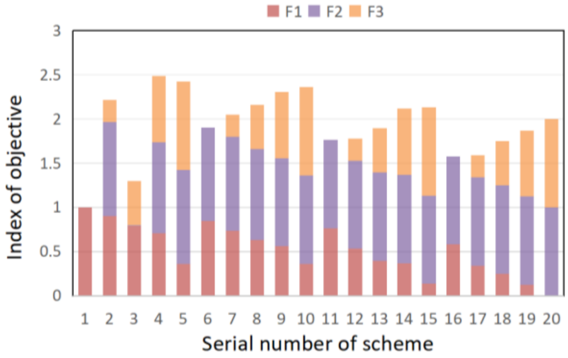

Figure 2: Linearization indexes of different targets in 20 schemes.

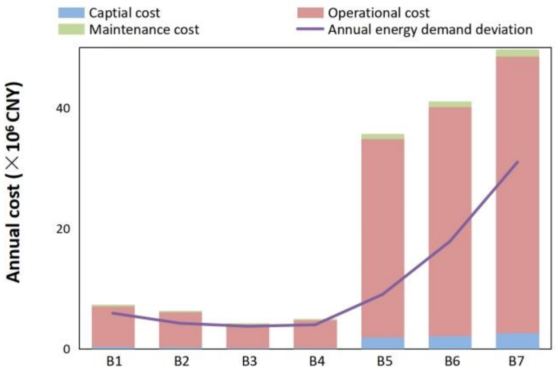

Figure3: The cost and energy demand deviation in Scheme 9.

After optimization, the capacity of each equipment is reduced, reflecting the original excess energy configuration of the oilfield, indicating that there is additional energy that can be stored. The difference of installed capacity before and after optimization is shown in Table 2, and the details of energy storage state are shown in Table 3.

Table 2 The difference of installed capacity before and after optimization

Device Name	PV	GT	GB	BB	ER	SC	HE	WB	ES	HS	CS
W1	0	900	269.39	0	833.68	357.59	0	900	1500	1500	645.03
W2	0	900	534.7	0	870	681.36	260	900	1500	1500	565.45
W3	0	900	875.61	0	839.22	864	594.1	900	1500	1500	1430.96
W4	0	900	696.28	0	869.39	778.08	418.36	900	1500	1500	1186.52
W5	0	6000	147.16	0	5510.38	4600	2264.21	6000	0	0	6651.74
W6	0	6000	2471.94	0	5100	3800	3072.5	6000	444.23	2607.97	8000
W7	0	6000	1033.445	0	5648	5179.02	2525.18	6000	1138.82	3482.36	8000

Table 3 Energy storage situation

Item	W1	W2	W3	W4	W5	W6	W7
Electric storage	0	0	0	0	385.3001	300.7242	285.6198
Thermal storage	0	0	0	0	222.0138	101.964	43.373
Cold storage	20495.47	15363.79	2064.36	4829.037	49.5862	0	0

The optimization scheme performs better in economy, which is 16.67 % lower than the original scheme, and the carbon emission is reduced by 18.36 %, which significantly promotes the green and low-carbon operation of the oilfield. The specific comparison details are shown in Table 4.

Table 4 Economic situation comparison

Comparative item	Installation costs （$\times 10^6$CNY)	Operating costs （$\times 10^6$CNY)	Maintenance costs （$\times 10^6$CNY)	Carbon emissions （$\times 10^3$t/year)
Original plan	4.02	3.37	1.86	1.6
Optimized plan	3.60	2.80	1.60	1.35
Reduce the proportion（%）	11.7	20.5	16.3	15.52

4. Conclusion

This research contributes a novel approach for optimizing sustainable energy management in oilfields, leveraging the synergy of demand response and distributed energy systems. A rigorous multi-objective mathematical programming model is formulated to concurrently minimize annual costs, carbon emissions, and energy demand deviation. The model encapsulates constraints pertaining to energy supply, technology, interconnection, and demand response, thus enabling the system to flexibly adapt energy management and optimize the design and operation of distributed energy systems. The application of the model to an oilfield case study in Northeast China resulted in a remarkable18.36 % reduction in annual operational costs and a 16.67% decrease in carbon emissions. This innovative optimization framework, underpinned by demand response, promises significant potential for enhancing sustainable energy management practices in oilfields, showcasing its broad applicability and substantial practical significance in the field.

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