Operational optimization of integrated energy systems considering demand-side flexibility

Yongli Wang\textsuperscript{1a}, Minhan Zhou\textsuperscript{1b}, Yanan Wang\textsuperscript{1c}, Chengcong Cai\textsuperscript{1d}, Xu Han\textsuperscript{1e}, Xin Chen\textsuperscript{1f}, Kunpeng Zhao\textsuperscript{2a}

\textsuperscript{1}School of Economics and Management North China Electric Power University
Beijing, China
\textsuperscript{2}State Grid Corporation Customer Service Tianjin, China
\textsuperscript{a}18830251935@163.com

Abstract—In order to solve the operation optimization problem of integrated energy system considering the demand side, this paper takes the integrated energy system of industrial park as the research object and proposes an optimal scheduling model considering the comprehensive demand response. Algorithm analysis shows that RIES containing multiple energy storage devices fully consider the comprehensive demand side response.

1. Introduction
As energy demand continues to increase, integrated energy systems can connect the grid, heat and gas networks into a unified and efficient energy management platform \cite{1}. The integrated energy system generally consists of electric energy sub-grid, thermal energy sub-grid and gas energy sub-grid. Compared with the traditional form of single power supply in the form of microgrid or distribution network, the integrated energy system can meet the demand for diversified energy supply.

The optimal operation model of integrated energy systems has become an important topic. Currently, several studies have been conducted in the literature on the optimal operation of integrated energy systems. On the one hand, a more objective optimal operation model has been developed by considering more realistic factors with respect to the characteristics of the integrated energy system operation. Literature \cite{3} considers the water-end coordination of the system and improves the level of onshore wind energy in the region by introducing demand management techniques. In reference \cite{4}, Build integrated energy system optimization model, which takes into account the mutual conversion of electric and thermal energy and solves the uncertainty of the system. The regional model \cite{5} was established to optimize the coordination of the source and load of the integrated energy system, and to effectively improve the capacity of wind power generation by taking wind power into account. Finally, \cite{6} the design of integrated energy system and the model of complementary characteristics of electric power and heat system are introduced.

2. INTEGRATED ENERGY SYSTEM DEMAND-SIDE RESPONSE
Comprehensive demand side response mainly includes power demand response, thermal demand response and natural gas demand response. Power demand response can be divided into price response and incentive response. Price response refers to a way that users use energy actively through price signals in different periods.
Integrated energy systems integrate sources, such as refrigerators, electricity, natural gas and thermal energy in the region, so the energy grid is interconnected. As the scale of decentralized energy sources, such as wind and photovoltaics, continues to rise, the increased intermittency of electricity generation poses a threat to the stable operation of the grid, and clean energy is extremely difficult to use. By involving the demand community in grid management, the client side can be involved, which plays an important role in improving the load curve and optimizing the grid design. With the continuous development of integrated energy system, the traditional power demand response is also gradually developed into integrated demand response. Compared with the traditional power demand response which is simply time shifting and energy use reduction in the horizontal direction, IDR updates the response behavior as a combination of energy use type conversion (vertical) and time shifting (horizontal).

The introduction of energy storage batteries into the regional energy system provides favorable conditions for new energy production systems and multifunctional operations between multiple pressures, and enhances the resilience of the energy system. Based on the inclusion of wind turbines, PV arrays, micro-combustion turbines, heat storage electric boilers, storage batteries and P2G devices, we further consider three types of demand-side responses, electricity, heat and gas, and establish a RIES economic dispatch model with the lowest system economic cost and environmental protection cost as the objective function to analyze seven different scenarios, and invoke the Cplex optimizer in the MATLAB environment. The results show that considering the comprehensive demand side response in RIES can improve the absorption capacity and reduce the phenomenon of wind and light abandoning, which plays a role of peak cutting and valley filling, and brings better economic and environmental benefits in the operation of the system.

3. RIES OPERATION OPTIMIZATION MODEL CONSIDERING IDR

3.1. Objective function

The operational optimization objectives of RIES include the cost of gas consumed by micro-combustion turbines, the cost of electricity purchased, the cost of turbine and photovoltaic waste, and the cost of treatment of emissions from micro-combustion turbines. In this article, the most optimistic calculation time is 24 hours, one hour clockwise, each of which is the goal of the Lille economy:

$$\min C = \min (C_1 + C_2 + C_3 + C_4 + C_5)$$  \hspace{1cm} (1)

$$\min F = F^X + F^{wp} + F^e + F^g + F^{em}$$  \hspace{1cm} (2)

$$F^{wp} = C_i^{wt} \sum_{j=1}^{wj} P_{i,j}^{wp} \Delta t + C_i^{pv} \sum_{j=1}^{pv} P_{i,j}^{pv} \Delta t$$  \hspace{1cm} (3)

$$F^e = \sum_{t=1}^{T} C_i^e P_{i,t}^{net}$$  \hspace{1cm} (4)

$$F^g = \sum_{t=1}^{T} C_i^g P_{i,t}^{net}$$  \hspace{1cm} (5)

$$F^{em} = \alpha \lambda L_{i,t}^{em}$$  \hspace{1cm} (6)

Where $F$ is the total operating cost of the power plant, $F^X$ is the maintenance cost of the power plant, $F^{wp}$ is the total cost of wind turbines and photovoltaic disposal within a cycle, and $F^e$ is the cost of purchasing power within a cycle.; $F^g$ is the gas purchase cost during the cycle; $F^{em}$ is the carbon gas treatment cost.
during the cycle; $C_{T}^{w}$ is the price per unit of wind disposal in time period $t$; $C_{T}^{p}$ is the price per unit of light disposal in time period $t$; $C_{T}^{e}$ is the wind disposal power of the i-th turbine in time period $t$; $C_{T}^{p}$ is the disposal power of the j-th turbine in time period $t$ is the discarded power of the j-th PV unit at time $t$; $C_{T}^{g}$ is the grid electricity price at time $t$; $C_{T}^{g}$ is the gas price at time $t$; $P_{t}^{net}$ is the purchased power from the grid at time $t$; $G_{t}^{net}$ is the purchased gas quantity from the gas grid at time $t$; $\alpha_{gL}$ is the discounted cost of carbon gas emission; $\lambda_{L}$ is the emission factor of carbon gas emission from microcombustion turbines; $P_{t}^{MT}$ is the power generated by microcombustion turbines.

3.2. Binding Conditions

3.2.1 Energy conversion equipment constraints

The CHP constraint consists mainly of micro-combustion engines and bromine chillers. Waste heat power plant mainly consists of microbial engine and refrigeration machine. Small internal combustion engines burn natural gas to generate electricity and use a heating engine to concentrate the hot gas in hot water. The cogeneration model is:

$$H_{t}^{CHP} = \frac{\eta_{i}^{MT} \delta_{CHP}^{OPH} P_{t}^{MT} (1 - \eta_{i}^{MT} - \eta_{i}^{H})}{\eta_{i}^{MT}}$$  \hspace{1cm} (7)$$

where: $H_{t}^{CHP}$ is the residual heat at time $t$; $\eta_{i}^{MT}$ is the power generation efficiency engine at time $t$; $\eta_{i}^{H}$ is the heat loss rate; $\delta_{CHP}^{OPH}$ is the heat factor of bromine cooler; $\eta_{i}^{B}$ is the flue gas recovery rate.

1) Electric boiler restraint.

$$H_{t}^{EB} = \eta_{i}^{EB} W_{t}^{EB}$$  \hspace{1cm} (8)$$

$$H_{t}^{EB, min} Z_{i}^{EB} \leq H_{t}^{EB, max} Z_{i}^{EB}$$  \hspace{1cm} (9)$$

$$H_{t}^{EB} - H_{t-1}^{EB} \leq H_{t}^{EB, max} \left(1 - Z_{t}^{GT} \right) + \lambda_{t}^{EB, UR} Z_{t-1}^{EB} + H_{t}^{EB, min} \left(Z_{t}^{EB} - Z_{t-1}^{EB} \right)$$  \hspace{1cm} (10)$$

$$H_{t}^{EB} - H_{t-1}^{EB} \leq H_{t}^{EB, max} \left(1 - Z_{t-1}^{EB} \right) + \lambda_{t}^{EB, LR} Z_{t}^{EB} + H_{t}^{EB, min} \left(Z_{t-1}^{EB} - Z_{t}^{EB} \right)$$  \hspace{1cm} (11)$$

Where: $H_{t}^{EB}$ is the heating capacity of electric boiler at time $t$; $W_{t}^{EB}$ is the electricity consumption of electric boiler at time $t$; $\eta_{i}^{EB}$ is the heating efficiency of electric boiler; $H_{t}^{EB, min}$ and $H_{t}^{EB, max}$ are the minimum heating power and maximum heating power of electric boiler respectively; $Z_{t}^{EB}$ is the start-stop status of electric boiler at time $t$, where 1 means start and 0 means stop; $\lambda_{t}^{EB, LR}$ and $\lambda_{t}^{EB, UR}$ are the lower and upper climbing rates of micro-combustion engine respectively.

2) P2G device constraints.

$$Q_{t}^{P2G} = \eta_{t}^{P2G} P_{t}^{P2G}$$  \hspace{1cm} (12)$$

$$P_{t}^{P2G, min} \leq P_{t}^{P2G} \leq P_{t}^{P2G, max}$$  \hspace{1cm} (13)$$
Where: \( Q_{t}^{p2g} \) is the natural gas output at time \( t \); \( P_{t}^{p2g} \) is the input power at time \( t \); \( \eta_{p2g} \) is the electricity to gas efficiency; \( P_{p2g,min}^{p2g} \) and \( P_{p2g,max}^{p2g} \) are the minimum and maximum power of the P2G equipment operation respectively.

3.2.2 Electricit, heat and gas storage constraints

Electricity, heat and gas storage equipment for energy storage at low prices, which can effectively improve system flexibility and operating costs.

\[
E_{ES,min} \leq E_{t} \leq E_{FS,max}
\]  
\[
H_{HS,min} \leq H_{t} \leq H_{HS,max}
\]  
\[
G_{CS,min}^{ES} \leq G_{t}^{CS} \leq G_{CS,max}^{CS}
\]  
\[
C_{ES,min} \leq C_{t}^{ES} \leq C_{ES,max}
\]  
\[
C_{CS,min} \leq C_{t}^{CS} \leq C_{CS,max}
\]  
\[
C_{ES}^{Es} = (1 - \lambda_{ES}) C_{t-1}^{FS} + E_{t}^{GS} \Delta t
\]  
\[
C_{HS}^{HS} = (1 - \lambda_{HS}) C_{t-1}^{HS} + H_{t}^{HS} \Delta t
\]  
\[
C_{GS}^{GS} = (1 - \lambda_{GS}) C_{t-1}^{GS} + C_{t}^{GS} \Delta t
\]

Where: \( E_{t}^{ES}, H_{t}^{HS}, C_{t}^{CS} \) are the storage/discharge, thermal and gas power at time \( t \), where positive values indicate storage and negative values indicate discharge; \( E_{ES,min}^{FS}, E_{FS,max}^{FS} \) are the minimum and maximum storage/discharge power of the battery; \( H_{HS,min}^{HS}, H_{HS,max}^{HS} \) are the minimum and maximum storage/discharge thermal power of the heat storage tank; \( G_{CS,min}^{CS}, G_{CS,max}^{CS} \) are the minimum and maximum storage/discharge power of gas storage device; \( C_{ES,min}^{ES}, C_{ES,max}^{ES} \) are the minimum and maximum storage capacity of battery; \( C_{CS,min}^{CS}, C_{CS,max}^{CS} \) are the minimum and maximum storage capacity of heat storage tank; \( C_{GS,min}^{GS}, C_{GS,max}^{GS} \) are the minimum and maximum storage capacity of gas storage device; \( \lambda_{ES}, \lambda_{HS}, \lambda_{GS} \) are the self-consumption rates of electric, thermal, and gas storage devices, respectively.

3.2.3 Interaction with network power constraints.

\[
P_{in,min}^{in} \leq P_{t}^{in} \leq P_{in,max}^{in}
\]  
\[
G_{in,min}^{in} \leq G_{t}^{in} \leq G_{in,max}^{in}
\]

Where: \( P_{in,min}, P_{in,max} \) are the minimum and maximum purchased power; \( G_{in,min}, G_{in,max} \) are the minimum and maximum purchased power; \( P_{t}^{in}, G_{t}^{in} \) are the purchased power and purchased gas power at time \( t \) respectively.
3.2.4 Energy balance constraint.

(1) Electric load balance constraint.

\[ P_{\text{wind}}^t + P_{\text{pv}}^t + P_{\text{CHP}}^t + P_{\text{net}}^t = P_{\text{load}}^t + P_{\text{load}^2}^t + P_{\text{EB}}^t + \left( \frac{P_{\text{ES}}^t}{\lambda_{\text{ES}}} \right) \]  

where \( P_{\text{load}}^t \) is the demand-side electrical load at time \( t \).

(2) Thermal load balance constraint.

If the heat transmission is delayed and the heating comfort is ambiguous, the temperature is within a certain range. The constraints are as follows.

\[ H_{\text{CHP}}^t + H_{\text{EB}}^t = H_{\text{load}}^t + \left( H_{\text{Hs}}^t / \lambda_{\text{Hs}} \right) \]  

Where, \( H_{\text{load}}^t \) is the demand-side heat load in time period \( t \).

(3) Gas load balance constraint.

\[ Q_{\text{net}}^t + G_{\text{net}}^t = G_{\text{CHP}}^t + G_{\text{load}}^t + \left( G_{\text{Gs}}^t / \lambda_{\text{Gs}} \right) \]  

where \( G_{\text{load}}^t \) is the demand-side gas load at time \( t \).

4. EXAMPLE ANALYSIS

Consider the effects of electric power generation, electric GHG technology, forbearance, storage and storage, and the benefits of using electric power generation to influence gas demand in comparison with the following.

Option 1: Covers cogeneration installations only. Scheme 2: add storage thermoelectric boilers. Scheme 3: add P2G equipment and gas storage device. Option 4: Add batteries on the basis of Option 3. Option 5: Calculate the response to electricity demand according to option 4 Scenario 6: Consider the response to thermal energy demand on the basis of scenario 5. Option 7: The response to natural gas demand is taken into account on the basis of option 6. The cost characteristics of each option are shown in Table 3.

| Scenes | Total electricity abandoned from wind and light/(kW·h) | Electricity purchase/(kW·h) | Amount of gas purchased/(kW·h) | Carbon Treatment Costs/yuan | Total cost/million yuan |
|--------|-------------------------------------------------------|-----------------------------|-------------------------------|---------------------------|----------------------|
| 1      | 40.25                                                 | -                           | 58.64                         | 296                       | 1.01                 |
| 2      | 10.72                                                 | 0.22                        | 25.33                         | 68                        | 0.75                 |
| 3      | 3.86                                                  | 0.22                        | 20.73                         | 68                        | 0.62                 |
| 4      | 2.52                                                  | 0.22                        | 20.21                         | 63                        | 0.56                 |
| 5      | 1.48                                                  | 0.20                        | 19.56                         | 60                        | 0.53                 |
| 6      | 0.45                                                  | 0.20                        | 19.22                         | 58                        | 0.48                 |
| 7      | 0.42                                                  | 0.19                        | 18.68                         | 55                        | 0.45                 |

As Table 1, the regenerative electric boiler is added on the basis of Scheme 1. Natural gas consumption is 33.31KW-h, carbon emission is 29.53KW-h, and the total operating cost is reduced by RMB 0.2,600. The addition of P2G equipment in scheme 2 can generate natural gas, reduce gas purchase by 4.60 KW-h, reduce wind and light abandonment by 6.86 KW-h, and reduce the total operating cost by 0.1,300 yuan. In scheme 3, batteries were added and charged and discharged at different times, which reduced natural gas purchase volume by 0.52 KW-h, wind and light abandonment volume by 1.34 KW-h, and total operating cost by 6,000 yuan. Considering the power demand side response on the basis of scheme 4, the amount of wind and light abandoning is reduced by 1.04 KW-h, the purchased gas and purchased electricity are also reduced, and the total operating cost is reduced by 30,000 yuan. On the basis of scheme 5, the response of multiple load demanders is considered. Compared with the response of single load demander, the wind abandoning, light abandoning, gas purchasing, electricity purchasing and total operating costs are all reduced. In summary, it can be seen that plan 7 is the best operation mode.
5. Conclusion
In order to analyze the impact of integrated demand side response on the operation of RIES systems with electric, heat and gas loads and storage/capacity equipment, a multi-storage RIES operation optimization model considering IDR was proposed, and its validity was verified by a case study.

1) Adding different energy storage devices in sequence can effectively reduce wind and light abandonment and improve reliability and economy of RIES compared to a single energy storage device.
2) Considering responses has the effect of peak clipping and valley filling and reduces the operating cost.

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