Introduction and Efficiency Evaluation of Multi-storage Regional Integrated Energy System Considering Optimal Operation Integrated Demand Side Response

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Abstract. With the depletion of traditional energy sources, the Regional Integrated Energy System (RIES) came into being to solve the energy crisis and the problem of consumption. The battery, the thermal storage electric boiler and the P2G equipment are added into energy system. The impact of system operation was analyzed after adding different equipment. Then, the demand side response of the electric heating and gas are considered, and the economic operation model of the regional integrated energy system is established with the minimum operating cost of the system as the objective function. Seven scenarios were set up for comparative analysis. The results show that the demand side response of electric, heating, and gas are considered in the regional comprehensive energy system with multiple energy storage devices, which not only makes the load achieve the purpose of peak load cutting and valley filling, but also reduces the phenomenon of abandoned wind and sunlight and the system operation cost.

1. Introduction
The push for renewable energy is an essential part of the energy revolution. In recent years, the National Energy Administration has issued many documents related to clean energy and diversified energy. Regional Integrated Energy System (RIES) has many energy forms, rapid demand side response and can provide various demands to loads. RIES’ consideration of energy storage and demand-side response in RIES not only improves energy efficiency, but also absorbs new energy sources and reduces operating costs. Electric energy storage has the effect of absorbing new energy. The regenerative boiler can convert the electric energy into heat energy to supply the load, and the excess heat energy can be stored, which breaks the traditional mode of fixed electricity by heat and improves the energy efficiency. Power to gas (P2G) equipment achieves the conversion between electric energy and natural gas by decomposing hydrogen and hydrogen methane generated by water, which increases the coupling between electricity and gas. Combined Heat and Power (CHP) unit can realize the cascade utilization of different energy resources, which is economically and environmentally friendly.

With the increase of energy coupling, considering various storage energy devices and comprehensive demand response is the key to system operation optimization. The combination of electric heat transfer
and heat storage equipment can be free from thermoelectric coupling constraints and operation restrictions, so that renewable energy can interact with each other and reduce the operating cost and complexity of the system. Considering demand-side response, users can change their energy use in a certain period, improve the coordination ability between energy output and load, add energy storage equipment into the coupling system, improve energy utilization rate, and reduce wind and light abandoning phenomenon to a certain extent.

Based on the literature, we established a demand-side pricing model with CCHP system and customer satisfaction as the target, so that CCHP could participate in comprehensive energy supply through price adjustment. In the literature, considering the response of electricity price, a CCHP coordination and optimization model containing wind, light, gas and electricity storage device was established, which explained the advantages of multiple clean energy sources and CCHP in complementary power generation.

Literature establishes an energy system optimization model considering demand response, and the results show that this model can effectively reduce operating costs.

In this paper, energy storage equipment is introduced into the regional energy system, which is beneficial to the coordinated operation between new energy output and various loads and enhances the controllability of the energy system.

2. Comprehensive demand side response

Integrated Demand Response (IDR) mainly includes Power Demand Response, Thermal Demand Response and Natural Gas Demand Response. Power Demand Response is divided into price response and incentive response. Among them, price-type response refers to a way in which the user takes the initiative to use energy through price signals at different periods.

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This paper adopts peak and valley electricity price and natural gas price. The elasticity matrix method of electricity price is as follows:

\[
E_{ele} = \begin{bmatrix} \eta_1 & \eta_2 & \cdots & \eta_n \\ \eta_1 & \eta_2 & \cdots & \eta_n \\ \vdots & \vdots & \ddots & \vdots \\ \eta_1 & \eta_2 & \cdots & \eta_n \end{bmatrix}
\]

\[
J^o_t = \tilde{J}^o_t + \Delta J^o_t
\]

\[
J^o_t = \begin{bmatrix} J^o_1 \\ J^o_2 \\ \vdots \\ J^o_n \end{bmatrix}
\]

\[
\Delta J^o_t = \tilde{J}^o_t \cdot E_{ele} \cdot \Delta P_t
\]

\[
J^o_t = \begin{bmatrix} J_1 \\ J_2 \\ \vdots \\ J_n \end{bmatrix}
\]

\[
\Delta P = \begin{bmatrix} \Delta P_1 \\ \Delta P_2 \\ \vdots \\ \Delta P_n \end{bmatrix}
\]
where: $\eta$ is the elasticity coefficient of power demand; $J$ is electricity quantity, $P$ is electricity quantity increment, is electricity price increment, is electricity price increment; Is the electric quantity at time $t$ before the demand response, is the electric quantity change at time $T$ after the demand response, is the electric quantity change at time $T$ after the response, is the electric price change at time $T$ after the response; Is the electric quantity in time period $T$ after response.

Natural gas and electric power are both important energy sources in today's society. Compared with the price-type electric power load, gas-price elastic matrix is adopted, which is as follows:

$$
\varepsilon = \frac{\Delta H}{H} \cdot \frac{Q}{\Delta Q}
$$

(8)

$$
E_{\text{gas}} = \begin{bmatrix}
e_{11} & e_{12} & \cdots & e_{1n} \\
e_{21} & e_{22} & \cdots & e_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
e_{m1} & e_{m2} & \cdots & e_{mn}
\end{bmatrix}
$$

(9)

$$
H_t = H_t^o + \Delta H_t
$$

(10)

$$
H_t^o = \begin{bmatrix}
H_{t1}^o & H_{t2}^o & \cdots & H_{tn}^o
\end{bmatrix}^T
$$

(11)

$$
\Delta H_t = H_t^r \cdot E_{\text{gas}} \cdot \Delta Q_t
$$

(12)

$$
H_t^r = \begin{bmatrix}
H_1 \\
H_2 \\
\ddots \\
H_n
\end{bmatrix}
$$

(13)

$$
\Delta Q_t = \begin{bmatrix}
\Delta Q_1 & \Delta Q_2 & \cdots & \Delta Q_n
\end{bmatrix}^T
$$

(14)

where, the meanings of each variable can be analogized by the power price response; gas is the gas value elastic matrix.

3. Thermal Demand Response

Thermal demand response temperature has a delay, so users will not be affected largely in a certain range. The temperature characteristics of the heating system can be obtained according to data mining or physical model. The autoregressive moving average (ARMA) model of the heating temperature is as follows:

$$
T_{t+k} = \sum_{i=0}^{l} \alpha_i T_{t+i} + \sum_{i=0}^{l} \beta_i T_{t+i}^g + \sum_{i=0}^{l} \gamma_i T_{t+i}^w
$$

$$
\eta = \frac{\Delta T}{J} \cdot \frac{P}{\Delta P}
$$

(15)

$$
T_{t+n} = \sum_{j=0}^{l} \beta_j T_{t+j}^b + \sum_{j=0}^{l} \phi_j T_{t+j}^g + \sum_{j=0}^{l} \omega_j T_{t+j}^w
$$

$$
\eta = \frac{\Delta T}{J} \cdot \frac{P}{\Delta P}
$$

(16)

Figure 1 shows RIES, including wind turbine, solar cell array, CHP unit, electric boiler, battery, gas storage equipment and heat storage tank. In winter, CHP unit output alone will easily lead to wind and light loss; while adding thermal storage electric boiler, storage battery and P2G equipment will use wind and solar surplus for power storage. Heating /heat storage, gas generation/ gas storage, and the electrical load is supplied by power grid, wind turbine, photovoltaic, CHP unit and battery.
3.1. Objective Function

The operation optimization objectives of RIES include the cost of natural gas consumed by micro gas turbine, the cost of purchasing natural gas, the cost of purchasing electricity, the cost of abandoning fan and photovoltaic, and the cost of controlling the emission of micro gas turbine. In this paper, we set the optimal scheduling period as 24 hours, and the unit time interval as 1 hour, and the response output of each equipment is in accordance with the demand side, so that the operation cost of RIES is minimized. The economic objective function of RIES is as follows:

$$\min F = F^X + F^{wp} + F^e + F^g + F^{em} \eta = \frac{\Delta J}{J} \frac{P}{\Delta P}$$

(17)

$$F^e = \sum_{i=1}^{T} C^e_i P_{wind}^i$$

(18)

$$F^g = \sum_{i=1}^{T} C^g_i G_{net}^i$$

(19)

$$F^{em} = \alpha_{g} \lambda_{e} \sum_{i=1}^{T} P_{MT}^i$$

(20)

where $F$ represents the total operating cost of the system; $F^X$ represents the maintenance cost of system equipment; $F^{wp}$ represents the total abandonment cost of fan and pv within the cycle; $F^e$ represents the electricity purchase cost within a period; $F^g$ represents the gas purchase cost within the cycle; $F^{em}$ represents the treatment cost of carbon gas emitted by micro-turbine within a cycle; $C^w_t$ represents the unit wind abandon price in time period $t$; $C^w_t$ represents the unit abandonment price in time period $t$; $P_{MT}^i$ represents the wind abandoning power of the $i$-th fan in time period $t$.

3.2. Constraints

CHP mainly includes micro gas turbine and bromine cooler. Micro gas turbine burns natural gas for power generation, and the high-temperature flue gas discharged is used for heating and domestic hot water supply through bromine cooler. Thermoelectric model:

$$H_i^{CHP} = \eta^H C_i^{CHP} P_i^{MT} \left(1 - \eta_i^{MT} - \eta^H\right) \eta = \frac{\Delta J}{J} \frac{P}{\Delta P}$$

(21)
where $H_{i}^{\text{CHP}}$ represents the residual heat of CHP unit at time period t; $\eta_{i}^{\text{MT}}$ represents the generation efficiency of micro-turbine in period t; $\eta_{i}^{l}$ represents loss rate of heat dissipation; $\delta_{i}^{\text{OPH}}$ represents the heat coefficient of bromine cooling mechanism; $\eta_{i}^{\text{b}}$ represents the recovery rate of flue gas.

\[
H_{i}^{\text{EB}} = \eta_{i}^{\text{EB}} W_{i}^{\text{EB}}
\]  
(22)

\[
H_{i}^{\text{EB}, \text{min}} Z_{i}^{\text{EB}} \leq H_{i}^{\text{EB}} \leq H_{i}^{\text{EB}, \text{max}} Z_{i}^{\text{EB}}
\]  
(23)

\[
H_{i+1}^{\text{EB}} - H_{i+1}^{\text{EB}} \leq H_{i}^{\text{EB}, \text{max}} (1 - Z_{i}^{\text{EB}}) + V_{i}^{\text{EB}} Z_{i}^{\text{EB}} +
\]
\[
H_{i+1}^{\text{EB}, \text{min}} (Z_{i+1}^{\text{EB}} - Z_{i}^{\text{EB}})
\]  
(24)

\[
H_{i+1}^{\text{EB}} - H_{i+1}^{\text{EB}} \leq H_{i}^{\text{EB}, \text{min}} (1 - Z_{i}^{\text{EB}}) + V_{i}^{\text{EB}} Z_{i}^{\text{EB}} +
\]
\[
H_{i+1}^{\text{EB}, \text{min}} (Z_{i+1}^{\text{EB}} - Z_{i}^{\text{EB}})
\]  
(25)

where $H_{i}^{\text{EB}}$ represents the heat produced by the electric boiler in time period t; $W_{i}^{\text{EB}}$ represents power consumption of electric boiler in time period t; $\eta_{i}^{\text{EB}}$ represents the heating efficiency of electric boiler; $H_{i}^{\text{EB}, \text{min}}$ and $H_{i}^{\text{EB}, \text{max}}$ represent the minimum and maximum heating power of the electric boiler respectively; $Z_{i}^{\text{EB}}$ represents the start and stop state of electric boiler in time period t, where $Z_{i}^{\text{EB}}=1$ indicates the starting stage and $Z_{i}^{\text{EB}}=0$ indicates the stopping stage; $V_{i}^{\text{EB}}$ and $V_{i}^{\text{EB}}$ represents the slope climbing rates under and above the micro gas turbine respectively.

\[
Q_{i}^{p2g} = \eta_{i}^{p2g} P_{i}^{p2g}
\]  
(26)

\[
P_{i}^{p2g, \text{min}} \leq P_{i}^{p2g} \leq P_{i}^{p2g, \text{max}}
\]  
(27)

where $Q_{i}^{p2g}$ represents the natural gas output in time period t; $P_{i}^{p2g}$ represents the input power in time period t; $\eta_{i}^{p2g}$ represents the electric-gas efficiency; $P_{i}^{p2g, \text{min}}$ and $P_{i}^{p2g, \text{max}}$ represents the minimum and maximum power of P2G equipment respectively.

Electrical, thermal and gas storage equipment can store energy in the price valley, effectively improving the system flexibility and operating cost.

\[
E_{i}^{\text{ES}, \text{min}} \leq E_{i}^{\text{ES}} \leq E_{i}^{\text{ES}, \text{max}}
\]  
(28)

\[
H_{i}^{\text{HS}, \text{min}} \leq H_{i}^{\text{HS}} \leq H_{i}^{\text{HS}, \text{max}}
\]  
(29)

\[
G_{i}^{\text{GS}, \text{min}} \leq G_{i}^{\text{GS}} \leq G_{i}^{\text{GS}, \text{max}}
\]  
(30)

\[
C_{i}^{\text{ES}, \text{min}} \leq C_{i}^{\text{ES}} \leq C_{i}^{\text{ES}, \text{max}}
\]  
(31)

\[
C_{i}^{\text{GS}, \text{min}} \leq C_{i}^{\text{GS}} \leq C_{i}^{\text{GS}, \text{max}}
\]  
(32)

\[
C_{i}^{\text{ES}} = (1 - \lambda_{i}^{\text{ES}}) C_{i-1}^{\text{ES}} + E_{i}^{\text{ES}} \Delta t
\]  
(33)

\[
C_{i}^{\text{HS}} = (1 - \lambda_{i}^{\text{HS}}) C_{i-1}^{\text{HS}} + H_{i}^{\text{HS}} \Delta t
\]  
(34)

\[
C_{i}^{\text{GS}} = (1 - \lambda_{i}^{\text{GS}}) C_{i-1}^{\text{GS}} + G_{i}^{\text{GS}} \Delta t
\]  
(35)

\[
P_{i}^{\text{in}, \text{min}} \leq P_{i}^{\text{in}} \leq P_{i}^{\text{in}, \text{max}}
\]  
(36)

\[
G_{i}^{\text{in}, \text{min}} \leq G_{i}^{\text{in}} \leq G_{i}^{\text{in}, \text{max}}
\]  
(37)
where $P_{\text{in}, \text{min}}$ and $P_{\text{in}, \text{max}}$ represents the minimum and maximum purchasing power respectively; $G_{\text{in}, \text{min}}$ and $G_{\text{in}, \text{max}}$ represents the minimum and maximum gas purchasing powers respectively; $P_t$ and $G_t$ represents power purchase and gas purchase at time period $t$ respectively.

4. Example Analysis

4.1. Basic data and scene design

In order to verify the effectiveness of the model proposed in this paper, a regional integrated energy system in China is selected. Take 24 hours a day as the scheduling time, and the unit scheduling time is 1h. FIG. 2 shows the electrical, thermal and gas load curves of the system and the predicted output curves of wind power and photovoltaic. The self-elastic coefficients of electric power and natural gas are -0.1 and -0.581 respectively, and the cross elastic coefficients are both 0.03. The peak period of users is 10:00-14:00, 17:00-21:00; The normal period is 8:00-10:00, 14:00-17:00, 21:00-22:00, and the valley period is 00:00-8:00, 22:00-24:00. Table 1 is equipment parameters, and Table 2 is peak-valley flat electricity price parameters.

**Table 1. Relevant equipment parameters of RIES.**

| Equipment           | Parameter                        | Value  |
|---------------------|----------------------------------|--------|
| Wind Turbines       | Max Power Output                 | 40KW   |
|                     | Min Power Output                 | 0      |
| Photovoltaic Array  | Max Power Output                 | 30KW   |
|                     | Min Power Output                 | 0      |
| Regenerative Boiler | Max Power                       | 50KW   |
|                     | Accumulation of heat capacity    | 100KW.h|
|                     | Max heat storage power           | 50KW   |
|                     | Max heat release power           | 50KW   |
|                     | Produce thermal efficiency       | 97%    |
|                     | Store thermal efficiency         | 95%    |
|                     | Heat releasing efficiency        | 91%    |
| P2G Equipment       | Max Power                       | 50KW   |
|                     | Max gas storage power            | 35KW   |
|                     | Max bleed power                  | 35KW   |
| Battery             | max capacity                     | 100KW.h|
|                     | Max charging power               | 20KW   |
|                     | Max discharge power              | 20KW   |
|                     | Discharge efficiency             | 90%    |
|                     | Charging efficiency              | 90%    |

**Table 2. Peak and valley electricity price parameters.**

| Time Periods     | Power purchase prices (Yuan / KW.h) | Gas Purchase price (Yuan / m3) |
|------------------|-------------------------------------|-------------------------------|
| Peak Time        | 0.95                                | 3.78                          |
| Ordinary Period  | 0.68                                | 3.00                          |
| Valley Period    | 0.43                                | 2.84                          |

In order to verify the effectiveness of electricity to heat technology, electricity to gas technology, and gas, heat and electricity storage equipment, and to consider the advantages of electricity and heat demand response, the following scenarios are set for comparison:

Scene 1: CHP unit only
Scene 2: Add a storage thermoelectric boiler to Scenario 1
Scene 3: Add P2G equipment and gas storage device on the basis of Scenario 2
Scenario 4: Add battery to Scenario 3
Scenario 5: Consider the power demand response based on Scenario 4
Scenario 6: Thermal demand response is considered based on Scenario 5
Scenario 7: Consider the natural gas demand response based on Scenario 6

4.2. Economic benefit analysis
On the basis of scenario 1, a storage thermal power boiler was added to reduce the output of the micro gas turbine. Natural gas consumption was reduced by 33.31kW·h, carbon emission was reduced, wind and light curtailment by 29.53kW·h, and the total operating cost was reduced by RMB 0.26000. To sum up, scenario 7 is the best run.

Table 3. Abandoned wind and sunlight power, purchased electricity power, purchased gas and related costs under scene 1-7.

| SCENE | Total amount of abandoned wind and the light / KW·h | Purchased Electricity/ KW·h | Purchased Natural Gas/ KW·h | Carbon Cure/ Yuan | Total FEE/thousand Yuan |
|-------|---------------------------------|-----------------|-----------------|----------------|-----------------------|
| 1     | 40.25                           | --              | 58.64           | 296            | 10.1                  |
| 2     | 10.72                           | 0.22            | 25.33           | 68             | 7.5                   |
| 3     | 3.86                            | 0.22            | 20.73           | 68             | 6.2                   |
| 4     | 2.52                            | 0.22            | 20.21           | 63             | 5.6                   |
| 5     | 1.48                            | 0.20            | 19.56           | 60             | 5.3                   |
| 6     | 0.45                            | 0.20            | 19.22           | 58             | 4.8                   |
| 7     | 0.42                            | 0.19            | 18.68           | 55             | 4.5                   |

5. Conclusion
In order to analyze the effect of the combined demand-side response on the system operation of RIES containing electrical, thermal, gas, storage/capacity equipment, an optimization model of multi-energy storage RIES with IDR in mind was proposed, and the effectiveness of the model was verified by example analysis.

Compared with a single energy storage, the addition of multiple energy storage devices can effectively reduce wind and light abandon and improve the reliability and economy of RIES; It is verified that considering multiple demand-side responses has the effect of peak load clipping and reducing operation cost compared with considering single demand-side response; Further consideration of the integrated demand-side response in RIES containing a variety of energy storage devices can increase the energy supply and reduce the power purchase, gas purchase and total system operating cost.

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