Optimal Operation Model of Park Integrated Energy System Considering Uncertainty of Flexible Electrical, Thermal and Gas Load

Peifeng Li¹, Wei Wang¹, Jun Wei¹, Da Li¹, Chuan Long¹ and Wenyue Chen²,*

¹ State Grid Sichuan Economic Research Institute, Chengdu, China
² Chengdu Henghua Electric Power Science and Technology Consulting Co., Ltd., Chengdu, China

*Corresponding author email: cwy_henghua@163.com

Abstract. Flexible Load (FL) of electricity, heat and gas can improve the operation economy, flexibility and reliability of PIES. Aiming at the uncertainty of FL in the actual operation of the park integrated energy system (PIES), an optimal operation model of PIES with uncertainty of FL is proposed. Firstly, the uncertainty models of shiftable electric load and transferable load response are established, respectively. And then an adjustable heat load response model considering the uncertainty of solar radiation intensity is established. On this basis, an optimal operation model of PIES considering the uncertainty of the FL with the goal of maximizing the total revenue is constructed and is solved by the enhanced-interval linear programming method. Simulation indicate that FL can improve the operating economy of PIES and renewable energy consumption.

Keywords: Park integrated energy system (PIES); Flexible Load; Uncertainty; Enhanced-interval linear programming; Optimal operation.

1. Introduction

The traditional demand response (DR) is gradually developing to integrated demand response (IDR) [1-5]. IDR can promote the cascade utilization of energy in different energy systems and improve the overall energy efficiency of the system [3].

Most of the research on IDR in the park integrated energy system (PIES) are based on the optimal planning. An optimal scheduling model of regional integrated energy system considering the demand response of electricity, gas and heat is proposed in reference [6]. In reference [7], a multi-objective day-ahead comprehensive optimal dispatch model of energy hub is established. It is verified that the flexible load can reduce the economic cost and carbon emission of the system.

At present, there are still some deficiencies in the research of IDR in PIES. There is seldom research on IDR uncertainty[8-11]. 2. It is difficult to determine the subjective fuzzy membership function and random distribution function when Fuzzy theory and probability theory are used[12].

In view of the above deficiencies, considering the uncertainty of IDR in PIES, this paper adopts interval optimization method to model IDR. Firstly, the uncertainty of IDR is analysed. Then, considering consumer psychology, the demand response uncertainty models of transferable and replaceable loads are established. Next, this paper constructs the optimal operation model of PIES considering the uncertainty of IDR and uses the enhanced interval programming method to solve it. Finally, an example is given.
2. Uncertainty Analysis of IDR

2.1. Uncertainty of Transfer Load Response

The structure of PIES and the implementation process of IDR are shown in Figure 1. In the system, cold, heat and electricity are converted into each other. And there are corresponding production and conversion equipment. The uncertainty of peak valley transferable load response based on the principle of consumer psychology is shown in Figure 2.

\[ \lambda_{pv}^a = \begin{cases} 0 & 0 \leq \Delta p_{pv} \leq a_{pv}^a \\ \frac{\Delta p_{pv} - a_{pv}^a}{b_{pv} - a_{pv}^a} & a_{pv}^a \leq \Delta p_{pv} \leq b_{pv}^a \\ \lambda_{pv,\text{max}} & \Delta p_{pv} \geq b_{pv}^a \end{cases} \]

\[ \lambda_{pv}^d = \begin{cases} 0 & 0 \leq \Delta p_{pv} \leq a_{pv}^d \\ \frac{\Delta p_{pv} - a_{pv}^d}{b_{pv}^d - a_{pv}^d} & a_{pv}^d \leq \Delta p_{pv} \leq b_{pv}^d \\ \lambda_{pv,\text{max}} & \Delta p_{pv} \geq b_{pv}^d \end{cases} \]

\( \Delta p_{pv} \) denotes peak-valley electricity price difference; \( a_{pv}^a, a_{pv}^d, b_{pv}^a \) and \( b_{pv}^d \) respectively represent the upper and lower limits of the peak to valley transition dead zone threshold and saturation zone threshold interval of end users. \( \lambda_{pv,\text{max}}^a \) and \( \lambda_{pv,\text{max}}^d \) indicate the upper and lower limits of the maximum peak-to-valley load transfer rate range.

\[ L_{e,t}^{\pm} = \begin{cases} L_{e,0}^{\pm} + \lambda_{pv}^{\pm} L_p - \lambda_{pv}^{\pm} L_t & t \in T_p \\ L_{e,0}^{\pm} + \lambda_{pv}^{\pm} L_p - \lambda_{pv}^{\pm} L_t & t \in T_e \\ L_{e,0}^{\pm} + \lambda_{pv}^{\pm} L_p - \lambda_{pv}^{\pm} L_t & t \in T_v \end{cases} \]

\( T_p, T_e \) and \( T_v \) represent peak, average, and valley periods, respectively. \( L_{e,0}^{\pm} \) and \( L_{e,t}^{\pm} \) respectively represent the predicted load and fitting load of \( t \) period before and after the implementation of Time of Use price (TOU price). \( \lambda_{pv}^{\pm}, \lambda_{pv}^d \) and \( \lambda_{pv}^a \) represent the interval numbers of peak valley, peak flat and valley load transfer rate. \( \overline{L_p} \) and \( \overline{L_t} \) are the average value of peak load and period load before the implementation of TOU.

Figure 1. Structure diagram of PIES and implementation process of IDR.

Figure 2. Schematic diagram of peak-valley shiftable electric load uncertainty based on consumer psychology principles.

Figure 3. Schematic diagram of transformable load uncertainty based on consumer psychology principles.
2.2. Uncertainty of Alternative Load Response

As can be seen from Figure 3, the expressions of the limit value of the electric load substitution rate curve are calculated by Equation 4 and 5:

\[
\lambda_{ge} = \begin{cases} 
-\lambda_{ge,max} & \Delta p_{ge} \leq -b_{ge} \\
-\lambda_{ge,max} - b_{ge} + a_{ge} (\Delta p_{ge} + a_{ge}) & -b_{ge} \leq \Delta p_{ge} \leq -a_{ge} \\
0 & -a_{ge} \leq \Delta p_{ge} \leq a_{ge} \\
\lambda_{ge,max} (\Delta p_{ge} - a_{ge}) & a_{ge} \leq \Delta p_{ge} \leq b_{ge} \\
\lambda_{ge,max} & \Delta p_{ge} \geq b_{ge}
\end{cases}
\] (4)

\[
\lambda_{ge} = \begin{cases} 
-\lambda_{ge,max} & \Delta p_{ge} \leq -b_{ge} \\
-\lambda_{ge,max} - b_{ge} + a_{ge} (\Delta p_{ge} + a_{ge}) & -b_{ge} \leq \Delta p_{ge} \leq -a_{ge} \\
0 & -a_{ge} \leq \Delta p_{ge} \leq a_{ge} \\
\lambda_{ge,max} (\Delta p_{ge} - a_{ge}) & a_{ge} \leq \Delta p_{ge} \leq b_{ge} \\
\lambda_{ge,max} & \Delta p_{ge} \geq b_{ge}
\end{cases}
\] (5)

\(\Delta p_{ge}\) is the price difference between power and gas. \(a_{ge}^+, a_{ge}^-, b_{ge}^+, \text{ and } b_{ge}^-\) represent the limit value of the threshold of electrical substitution dead time and saturation zone, respectively. \(\lambda_{ge,max}^+\) and \(\lambda_{ge,max}^-\) indicate the limit value of the maximum load replacement rate.

The actual response quantity of the incentive type replaceable load can be calculated by Equation 6-8:

\[
\Delta L_{et,i} = -\eta_{ge} \Delta L_{et,i}^0 \] (6)

\[
\Delta L_{et,i}^min \leq \Delta L_{et,i}^+ \leq \Delta L_{et,i}^max \] (7)

\[
\Delta L_{et,i}^min \leq \Delta L_{et,i}^- \leq \Delta L_{et,i}^max \] (8)

\(\Delta L_{et,i}^+\) and \(\Delta L_{et,i}^-\) indicate the load increment of electricity and gas. \(\eta_{ge}\) represents the conversion coefficient of equal calorific value of electric energy and natural gas.

To sum up, the \(t\)-period fitting electric load and gas load after considering the uncertainty of alternative load response can be calculated by Equation 9 and 10:

\[
L_{et,i}^+ = L_{et,0} + \lambda_{ge}^+ L_{et,0} + \Delta L_{et,i}^+ \] (9)

\[
L_{et,i}^- = L_{et,0} + \lambda_{ge}^- L_{et,0} + \Delta L_{et,i}^- \] (10)

\(L_{et,0}, L_{et,2}, L_{et,0}^+\) and \(L_{et}^-\) represent electric load and gas load in \(t\) period before and after electrical replacement.

2.3. Uncertainty of Adjustable Heat Load Response

Considering the heat inertia of heating buildings and the dynamic change process of room temperature, this paper uses interval number to describe the uncertainty of solar radiation, and establishes the uncertainty model of adjustable heat load, as shown in equations 11 to 14.

\[
T_{n+1}^e = (C_e)^{-1} \left[ T_{n+1}^e + \sum_{n=1}^{N} \left( \frac{T_{n+1}^e - T_{n+1}^w}{R_w} + Q_{s,n}^e - Q_{c,n}^e - Q_{c,n}^+ \right) \alpha_{nt} \right] \cdot \Delta t \] (11)

\[
T_{n+1}^w = (C_w)^{-1} \left[ T_{n+1}^w + \left( \frac{T_{n+1}^w - T_{n+1}^w}{R_w} + \frac{T_{n+1}^e - T_{n+1}^w}{R_w} + r_a \alpha_{nt} G_{n+1}^e \right) \cdot \Delta t \right] n \in \mathbb{N} \] (12)
\[ Q_{ci,t}^+ = 0.278 \cdot N_{ai} V_{ci} \rho_{ci} (T_{ci,t}^+ - T_{en}^+) \]  
\[ Q_{en,t}^- = 0.278 \cdot V_{en} \rho_{en} (T_{en,t}^- - T_{ci,t}^-) \]  
\( T_{ci,t}^+ \), \( T_{en,t}^- \) and \( T_{en,t}^+ \) represent the indoor and outdoor temperature in \( t \) and the temperature of the \( n \) wall, respectively. \( Q_{ci,t}^+ \), \( Q_{en,t}^- \) and \( Q_{en,t}^+ \) represent the heat supply of the system, the heat loss of cold air infiltration and ventilation in \( t \), respectively. \( \Delta t \) indicates the unit scheduling time, \( \Delta t = 1 \). \( R_n \) is a binary variable, if the \( n \) wall is exposed to solar radiation, it is 1, otherwise it is 0. \( A_n \), \( \alpha_n \) and \( G_n \) indicate the area, radiation absorption coefficient and the light intensity of the \( n \) wall. \( N \) is the total number of walls. \( R_n \), \( C_n \) and \( C_t \) are wall heat resistance, heat capacity and room heat capacity. \( N_{ai} \) and \( V_{en} \) are the number of air changes per hour and the ventilation rate. \( V_t \) represents the volume of a heating building. \( c_p \) is specific heat capacity of cold air. \( \rho_{en} \) represents the outdoor air density in time \( t \).

### 3. Optimal Operation Model of PIES with IDR Uncertainty

#### 3.1. Objective Function
Taking the maximum total income as the optimization objective, which is expressed by Equation 15 to 20, including income from energy sales \( C_{in}^+ \), reduced purchasing cost \( C_{out}^+ \), operating cost \( C_{om}^+ \), the cost of carbon emissions \( C_{ce}^+ \), cost of abandoned wind turbine (WT) and photovoltaic (PV) \( C_{ab}^+ \) and compensation cost \( C_{IDR}^+ \).

\[ \text{max } C^+ = C_{in}^- - C_{out}^+ - C_{om}^+ - C_{ce}^+ - C_{ab}^+ - C_{IDR}^+ \]  
\[ C_{in}^+ = \sum_{t=1}^{T} \left( c_{e,t} P_{e,t}^+ \Delta t + c_{g,t} P_{g,t}^+ / L_{NG} \right) \]  
\[ C_{out}^+ = \sum_{t=1}^{T} \sum_{j=1}^{J} c_{om,j} P_{j,t}^+ \Delta t \]  
\[ C_{ce}^+ = \xi \cdot \sum_{t=1}^{T} \left( \mu_e P_{e,t}^+ \Delta t + \mu_g P_{g,t}^+ \Delta t \right) \]  
\[ C_{ab}^+ = \pi \cdot \sum_{t=1}^{T} P_{ab,t}^+ \Delta t \]  
\[ C_{IDR}^+ = \gamma_{e,\text{max}} \left| P_{e,\text{max}}^+ \Delta t \right| + \gamma_{e,\text{max}} \sum_{t=1}^{T} \left| \Delta L_{e,\text{max}}^+ \right| \Delta t \]

\( T \) is the total operation hours, \( T = 24 \). \( k = e, h, g \) are electricity, heat and gas respectively. \( c_{e,t} \) and \( L_{NG} \) are the selling price and selling energy of \( k \) energy in \( t \) period respectively. \( c_{e,t} \) and \( c_{g,t} \) are the price of power and gas respectively. \( P_{e,t}^+ \) and \( P_{g,t}^+ \) represent the power purchase and gas purchase in \( t \) period respectively. \( L_{NG} \) is low calorific value of natural gas. \( c_{om,j} \) is the operating cost of the \( j \) equipment unit. \( P_{j,t}^+ \) is the output of \( j \) in \( t \) period. \( \xi \) is the treatment cost per unit mass of CO2. \( \mu_e \) and \( \mu_g \) represent the equivalent carbon emission coefficients of electricity purchase and gas purchase respectively. \( \pi \) is the cost of abandoned WT and PV. \( P_{ab,t}^+ \) is the amount of abandoned WT and PV. \( P_{e,\text{max}}^+ \) is the reserved power
consumption increment of alternative load. $\gamma_{et,cap}$ and $\gamma_{et}$ represent the unit capacity cost and unit energy cost of the replaceable load.

### 3.2. Constraints

(1) Energy balance constraints are shown in Equation 22-24:

\[
P_{MT,t} + P_{PV,t} + P_{WT,t} + P_{ES,ch,t} + (P_{ES,dis,t} - P_{P2G,t}) - P_{GB,t} = E_{t}^e,
\]

(23)

\[
P_{GB,t} + P_{P2G,t} - P_{MT,t} - P_{T2G,t} = L_{t}^e,
\]

(24)

$E_{t}^e$, $L_{t}^e$, and $I_{t}^e$ indicate electricity, heat and gas load demand in $t$ period. $P_{MT,t}$, $P_{PV,t}$, and $P_{WT,t}$ represent the output of Microturbine (MT), WT and PV in $t$ period respectively. $P_{ES,ch,t}$ and $P_{ES,dis,t}$ indicate power charged and released of electric storage (ES) in $t$ period. $P_{P2G,t}$ and $P_{EB,t}$ represent power consumption of power to gas (P2G) and EB in $t$ period respectively. $P_{MT,t}$, $P_{GB,t}$ and $P_{T2G,t}$ represent the heat production of MT, GB and EB in $t$ period respectively. $Q_{T2G,t}$ and $Q_{T2G,dis,t}$ represent the charging and discharging power of heat storage (HS) in $t$ period. $P_{MT,t}$ and $P_{P2G,t}$ represent gas used by MT and GB in $t$ period.

(2) Equipment output constraint are shown in Equation 25-30:

\[
E_{m,t}^e = (1 - \mu_m)E_{m,t-1} + \left(p_{m,ch}I_{m,ch} - p_{m,dis}I_{m,dis} / \eta_m\right) \Delta t
\]

\[
0 \leq p_{m,ch} \leq I_{m,ch} \leq m_{max}^m
\]

\[
0 \leq p_{m,dis} \leq I_{m,dis} \leq m_{max}^m
\]

\[
E_{m,min} \leq E_{m,t} \leq E_{m,max}
\]

\[
0 \leq I_{m,ch} + I_{m,dis} \leq 1
\]

\[
E_{m,0}^e = E_{m,T}
\]

(30)

$E_{m,t}^e$ is the energy stored by $m$ in $t$. $\eta_{m,ch}$ and $\eta_{m,dis}$ denote the efficiency of energy storage device $m$. $\mu_m$ is the energy loss rate of $m$. $I_{m,ch,t}$ and $I_{m,dis,t}$ are binary variables, when 1 indicates the charging state of $m$ in $t$ period. $I_{m,ch,t}$ and $I_{m,dis,t}$ cannot be 1 at the same time. $m_{max}^m$ and $m_{min}^m$ represent the maximum charge and discharge energy of $m$. $E_{m,max}$ and $E_{m,min}$ represent the limit value of energy storage of $m$.

Other equipment output constraints:

\[
P_{j,min} \leq P_{j,t} \leq P_{j,max}
\]

(31)

$P_{j,t}$ is the output of $j$ in time $t$. $P_{j,max}$ and $P_{j,min}$ represent the limit value of output of equipment $j$ respectively.

(3) Tie line transmission power constraints are shown in Equation 32-33:

\[
P_{e,min} \leq P_{e,t} \leq P_{e,max}
\]

(32)

\[
P_{g,min} \leq P_{g,t} \leq P_{g,max}
\]

(33)

$P_{e,max}$ and $P_{e,min}$ indicate the limit value of power purchase. $P_{g,max}$ and $P_{g,min}$ indicate the limit value of gas purchase.

(4) Room temperature variation constraints are shown in Equation 34-35:

\[
T_{t+1}^t - T_{t}^t \leq T_{t+1}^t - T_{t}^t
\]

(34)

\[
T_{t+1}^t - T_{t}^t \leq T_{max}
\]

(35)
\( T_{mi}^{\text{max}} \) and \( T_{mi}^{\text{min}} \) represent the limit value of indoor temperature in \( t \) respectively. \( T_{\text{ch}}^{\text{max}} \) is the maximum change of room temperature in the adjacent period.

4. Model Solution

4.1. Enhanced-interval Linear Programming

In this paper, an enhanced interval linear programming (EILP) model in reference [9] are selected. The general form of EILP model are shown in Equation 36:

\[
\begin{align*}
\max & \quad Z^* = C^* X^* \\
\text{s.t.} & \quad A^* X^* \leq B^* \\
& \quad X^* \geq 0
\end{align*}
\]

\( A^* = \{ a^*_i = [a^*_i, a^*_i] : i, j \} \), \( A^* \subseteq \{ R^* \}^{m \times n} \)

\( B^* = \{ b^*_i = [b^*_i, b^*_i] : i \} \), \( B^* \subseteq \{ R^* \}^{n \times l} \)

\( C^* = \{ c^*_j = [c^*_j, c^*_j] : j \} \), \( C^* \subseteq \{ R^* \}^{l \times m} \)

\( X^* = \{ x^*_j = [x^*_j, x^*_j] : j \} \), \( X^* \subseteq \{ R^* \}^{n \times j} \)

\( R^* \) is the set of interval numbers.

EILP model assumes that when \( j=1,2,\ldots,k, c^*_j \geq 0 \), and when \( j=k+1,k+2,\ldots,n, c^*_j \leq 0 \).

1) The first sub model is shown in Equation 37:

\[
\begin{align*}
\text{max} & \quad A^* = \sum_{j=1}^{k} 0.5(c^*_j + c^*_j) x^*_j + \sum_{j=k+1}^{n} 0.5(c^*_j + c^*_j) x^*_j \\
\text{s.t.} & \quad \sum_{j=1}^{k} a^*_i x^*_j + \sum_{j=k+1}^{n} a^*_i x^*_j \leq b^*_i, \forall i; \quad x^*_j \geq 0, \forall j
\end{align*}
\]

2) The seconds sub model is shown in Equation 38:

\[
\begin{align*}
\text{max} & \quad A^* = \sum_{j=1}^{k} 0.5(c^*_j + c^*_j) x^*_j + \sum_{j=k+1}^{n} 0.5(c^*_j + c^*_j) x^*_j \\
\text{s.t.} & \quad \sum_{j=1}^{k} a^*_i x^*_j + \sum_{j=k+1}^{n} a^*_i x^*_j \leq b^*_i, \forall i \\
& \quad x^*_j \leq x^*_j, j = 1,2,\ldots,k \\
& \quad x^*_j \geq x^*_j, j = k+1,k+2,\ldots,n \\
& \quad \sum_{j=k+1}^{n} \sum_{j=k+1}^{n} \delta_x x^*_j - \sum_{j=k+1}^{n} \sum_{j=k+1}^{n} \delta_x x^*_j - \sum_{j=k+1}^{n} \sum_{j=k+1}^{n} \delta_x x^*_j - \sum_{j=k+1}^{n} \sum_{j=k+1}^{n} \delta_x x^*_j \leq 0, \forall \delta \\
& \quad x^*_j \geq 0, \forall j
\end{align*}
\]

To ensure that the optimal solution \( X^*_j, j \) is completely feasible, the following additional constraints shown in Equation 39-41 are added into Equation 38, which are emphasized to narrow the range of \( x^*_j \) by clarifying the upper and lower limits of the optimal values:

\[
\begin{align*}
\sum_{j=k+1}^{n} \delta_x [a^*_j] x^*_j - \sum_{j=k+1}^{n} \delta_x [a^*_j] x^*_j + \sum_{j=k+1}^{n} \delta_x [a^*_j] x^*_j - \sum_{j=k+1}^{n} \delta_x [a^*_j] x^*_j \leq 0, \forall \delta \\
\sum_{j=1}^{k} [a^*_j] x^*_j + \sum_{j=k+1}^{n} [a^*_j] x^*_j = b^*_j
\end{align*}
\]
\[
\begin{align*}
\alpha_{ij} & \leq 0, j = k - p + 1, \ldots, k \\
\alpha_{ij} & \geq 0, j = n - q + 1, \ldots, n
\end{align*}
\] (41)

The model is solved by CPLEX[9].

5. Case Study

5.1. Case Conditions

In this paper, an IES system in northern China is selected as an example for simulation analysis. Relative parameters are listed in Table 1~3[8-10]. Gas price is 3 yuan/m³.

**Table 1.** Parameters of devices in PIES.

| Efficiency | Unit operation and maintenance cost /yuan | Equipment | Capacity /kW | Efficiency | Unit operation and maintenance cost /yuan |
|------------|------------------------------------------|-----------|--------------|------------|------------------------------------------|
| \(\eta_e=0.35,\eta_h=0.4\) | 0.025 | GB | 500 | 0.85 | 0.027 |
| \(\eta_{e,ch}=0.94,\mu_e=0.001\) | 0.0018 | EB | 400 | 0.8 | 0.016 |
| \(\eta_{h,ch}=0.92,\mu_h=0.01\) | 0.0016 | P2G | 200 | 0.6 | 0.006 |

**Table 2.** Time of use electricity prices.

| Time Period | Electricity purchase price / (yuan/kWh) | Electricity selling price / (yuan/kWh) |
|-------------|----------------------------------------|---------------------------------------|
| Peak period: 11:00-13:00,17:00-21:00 | 0.85 | 1.00 |
| Flat period: 6:00-10:00,14:00-16:00,22:00-23:00 | 0.45 | 0.40 |
| Valley Period: 1:00-5:00,24:00 | 0.15 | 0.10 |

**Table 3.** Response parameters of shiftable and transformable load.

| Demand response type | Inflection point of dead zone (yuan/kWh) | Inflection point of saturation zone (yuan/kWh) | Upper limit of transfer rate / upper limit of replacement rate |
|----------------------|------------------------------------------|-----------------------------------------------|---------------------------------------------------------------|
| Peak to valley       | [0,0.2]                                  | [1.1,1.3]                                    | [3.5%,6.5%]                                                   |
| Peak to flat         | [0,0.2]                                  | [0.7,0.9]                                    | [2.5%,3.5%]                                                   |
| Flat to valley       | [0,0.1]                                  | [0.7,0.9]                                    | [2.5%,3.5%]                                                   |
| Electricity-gas substitution | [0,0.1]                               | [1.0,1.2]                                    | [2.5%,4.5%]                                                   |

5.2. Analysis of Example Results

Three scenarios (scenario 1 is without IDR, scenario 2 is with deterministic IDR, and scenario 3 is with IDR uncertainty) are set for simulation and comparative analysis. Forecast curve of temperature, wind turbine and photovoltaic output and electricity, gas, and heat load is shown in Figure 4.

**Figure 4.** Forecast curve of temperature, wind turbine and photovoltaic output and electricity, gas, and heat load.

**Figure 5.** Comparison of electric load curves in each scenario.
Considering the uncertainty, the gas load corresponding to the upper limit of IDR is:

\[ E_{\text{Upper, Gas}} = \text{Upper Limit of IDR} \times \text{Gas Load} \]

Considering the uncertainty, the electric load corresponding to the lower limit of IDR is:

\[ E_{\text{Lower, Electric}} = \text{Lower Limit of IDR} \times \text{Electric Load} \]

**Figure 6.** Comparison of gas load curves in each scenario.

In Figure 5 to Figure 7, the implementation of IDR can calm peaks and valleys, improve the operation economy of PIES and the level of renewable energy consumption. In Figure 5, the difference between peak and valley of the original electric load is 2297.11kw, the difference is reduced to 1942.27kw after considering the deterministic IDR, with a decrease of 15.45%. The reason is that the alternative load chooses gas instead of electricity during the peak period.

**Table 4.** Revenue of IEA in each scenario.

| Scenario | Sales income / yuan | Operation and maintenance cost / yuan | Energy purchase cost / yuan | Carbon emission cost / yuan | Cost of abandoning WT and PV / yuan | Cost of IDR / yuan | Total revenue / yuan |
|----------|---------------------|--------------------------------------|-----------------------------|-----------------------------|-----------------------------------|------------------|---------------------|
| 1        | 94385.4             | 1374.9                               | 39436.4                     | 1011.9                      | 999.0                             | 0                | 51563.3             |
| 2        | 93778.0             | 1362.6                               | 38127.9                     | 981.3                       | 0                                 | 420.0            | 52886.2             |
| 3        | [93559.9, 93979.4]   | [1341.1, 1384.7]                     | [37339.8, 39088.0]          | [947.6, 1040.5]             | 0                                 | [420.0, 489.7]   | [52089.7, 53398.1]   |

In Table 4, considering the uncertainty of IDR in scenario 3, the total income of IEA fluctuates with the range of ± 1.24%. IDR’s participation will increase the total income of IEA and the level of renewable energy consumption, while the uncertainty of IDR will make the total income of IEA fluctuate.

### 6. Conclusion

Considering the difference of consumer psychology of end users, this paper established the response uncertainty model of transferable electric load and replaceable load, and establishes the response uncertainty model of adjustable heat load.

1. IDR's participation can achieve peak load reduction and valley filling, and effectively improve the economy of the system operation and the level of renewable energy consumption.
2. Considering the uncertainty of IDR, it can more comprehensively and accurately analyse the actual effect of IDR in the process of system operation.
3. The fluctuation degree of load has a direct influence on the system operation results, and the fluctuation degree of electrical load has a great influence on the system operation and the stability of the total revenue of the integrated energy aggregators.

In the follow-up study, how to make risk decision according to the impact of IDR uncertainty on the optimal operation of PIES to reduce the risk of system operation would be studied.

### Acknowledgments

This work was supported in part by the State Grid Sichuan Economic Research Institute (item number: B7199721B021).

### References

[1] BIE Zhaohong, WANG Xu, HU Yuan. Review and prospect of planning of energy internet[J]. Proceedings of the CSEE, 2017, 37(22): 6445-6462+6757.

[2] BAHRAMI S, SHEIKHI A. From demand response in smart grid toward integrated demand response in smart energy hub[J]. IEEE Transactions on Smart Grid, 2016, 7(2): 650-658.

[3] ZENG Ming, WU Geng, LI Ran, et al. Key problems and prospects of integrated demand response in energy internet[J]. Power System Technology, 2016, 40(11): 3391-3398.
[4] XU Zheng, SUN Hongbin, GUO Qinglai. Review and prospect of integrated demand response[J]. Proceedings of the CSEE, 2018, 38(24): 7194-7205+7446.

[5] HUANG W, ZHANG N, KANG C, et al. From demand response to integrated demand response: review and prospect of research and application[J]. Protection and Control of Modern Power Systems, 2019, 4(1): 1-13.

[6] WU Yong, LÜ Lin, XU Lixiong, et al. Optimized allocation of various energy storage capacities in a multi-energy micro-grid considering electrical/thermal/gas coupling demand response[J]. Power System Protection and Control, 2020, 48(16): 1-10.

[7] WANG Q, WANG J, GUAN Y. Stochastic unit commitment with uncertain demand response[J]. IEEE Transactions on Power Systems, 2013, 28(1): 562-563.

[8] SUN Yi, PEI Junyi, JING Dongsheng. Smart home appliance control strategy considering user behavior uncertainty[J]. Power System Protection and Control, 2018, 46(17): 109-117.

[9] LUO Chunjian, LI Yaowang, XU Hanping, et al. Influence of demand response uncertainty on day-ahead optimization dispatching[J]. Automation of Electric Power Systems, 2017, 41(05): 22-29.

[10] SUN Yujun, WANG Yan, WANG Beibei, et al. Muti-time scale decision method for source-load interaction considering demand response uncertainty[J]. Automation of Electric Power Systems, 2018, 42(02): 106-113+159.

[11] HUANG Zheng. Research on the optimal scheduling strategy for combined heat and power system considering the thermal inertia[D]. Jilin: Northeast Electric Power University, 2019.

[12] DING Yifan. Research on load flexible scheduling based on value exploration[D]. Nanjing: Southeast University, 2018.