Two-stage planning optimization of multi-scenarios integrated energy system considering energy reliability

Changle Yu1, Qingqi Zhao1,3, Jun Liu1, Yuanda Zhu1, Minghu Xu1, Haoran Xu1, Shuyi Gao2, Huaijian Wang2

1 State Grid Liaoning Electric Power Supply Co., Ltd, Skills Training Center, Jinzhou 121001; 2 College of Information Science and Engineering, Northeastern University, Shenyang, 110819, Liaoning, China
3 Email: Papers20202020@163.com

Abstract. The pace of economic society and globalization is accelerating, and the energy shortage and environmental pollution is increasing relatively. In order to comprehensive utilizing energy, this paper constructs an Integrated Energy System (IES) with electricity and gas in and electricity, cooling, and heat out, and solves the optimal configuration of this energy system through a two-stage planning optimization model. First, the two-stage planning optimization model based on particle swarm optimization (PSO) is established, and the capacity configuration plan of energy device is solved by the first stage. Then, Rayleigh probability distribution model is used to describe the uncertainty of wind power output, and two device reliability indicators are proposed to be added to the constraints. Finally, the objective function of the second stage is solved to obtain the optimal operation plan, and the planning optimal results of IES is obtained by repeated iterations of the two stages. Considering the energy storage devices, the Industrial and Living-official scenarios of IES are simulated and the results show that the proposed model is available to different scenarios and can reduce the costs of the energy system effectively and make sure the energy supply reliably.

1. Introduction
In order to alleviate the pressure of energy shortage and improve environmental problems, the Integrated Energy System (IES) is proposed which can organically coordinate the production, transmission, conversion, distribution, storage, and consumption of energy by the planning and operation processes. When combining different forms of energy, it is usually necessary to use two or more types of energy devices, or combined with energy storage equipment, to utilize different energy sources in IES through multi-energy complementation [1]. In terms of multi-energy planning and optimization, Swiss scholars first proposed the concept of Energy Hub (EH) [2]. The EH model describes the coupling relationship of electricity, gas, cooling, and heat in IES.

By constructing an IES that combines different forms of energy, energy storage devices and power generation systems, energy utilization efficiency can be effectively improved, and energy costs can be reduced [3]. As a result, a lot of research on the optimal planning and design of IESs carried out. [4]-[6] uses the EH model to describe the power system, constructs the mixed integer nonlinear problem of the power-natural gas coupled system joint programming, and solves it with the CPLEX solver. [7]-[9] studies the capacity planning of integrated energy systems. [10] uses planning methods and intelligent...
optimization algorithms to study the environmental, energy consumption, and economic characteristics of the regional IES with indicators, but the dispatch of energy storage in the integrated energy system methods are less involved.

The uncertainty and relevance of renewable energy output such as wind and solar brings great complexity to the system design. If these factors are ignored, sub-optimal decision-making risks will inevitably be introduced in the system planning stage [11]. [12] also considered the randomness of wind farm output and the mutual influence between different wind farms and used NSGA-II to solve a multi-objective optimization problem with minimum investment, production capacity emission cost. [13] predicts future wind, solar output and load demand scenarios, and uses sampling techniques to obtain a large number of samples and uses scene reductions to obtain typical scenarios. [14] comprehensively considers the energy procurement cost and the corresponding procurement risk in the optimization goal and uses conditional value at risk (CVaR) to describe this Procurement risk. In the current electricity-gas joint planning problem, it is generally believed that the interruption of system components is the main reason for the unreliable energy supply [15]-[16]. [17] proposed a fast analysis method to respond to the reliability assessment of the electricity-gas integrated energy system. [18] puts forward relevant indicators of system reliability. For the optimal planning considering energy reliability, relevant research mainly focuses on:

1) Analysis of the uncertainty of wind power or photovoltaic output. Most studies have been done to establish wind power or photovoltaic forecast models, and typical scenarios can be obtained through scenario reduction.

2) Analysis of the uncertainty of energy supply caused by equipment failure. Most studies have proposed related indicators to measure system instability caused by equipment failure.

However, there are few studies on the optimization of system energy capacity and operation strategy considering the uncertainty of renewable energy and the uncertainty of equipment failure at the same time.

The contributions of this paper are briefly discussed as followed: This article constructs the IES, taking the minimum cost as the first stage optimization function planning the quantity and capacity of the energy conversion and energy storage devices of the IES, and takes the annual operating cost as the optimizing function in the second stage solving the annual operating cost of the system in each typical day. A probability distribution model is used to describe the uncertainty of wind power output, meanwhile two indicators of energy shortage rate and energy supplement rate are proposed to describe the uncertainty of energy device and added to the second stage optimization model as constrains. The particle swarm algorithm and CPLEX solver are combined to solve the optimal results. The effectiveness and economy of the proposed method are verified by simulating, and the influence of reliability indicators on the system optimization results is analysed.

The rest of the paper is organized as follows: Section 2 constructs an IES including electricity, cooling, and heat, and describes the output model of each device. Section 3 proposes a two-stage planning optimization model and describes the objective function and constraints of optimization. Section 4 describes the uncertainty of wind power output, two reliability indicators describing system equipment failures are proposed at the same time. An algorithm to solve the optimal configuration model are proposed in Section 5. Section 6 sets four scenarios and analyses the simulation results to verify the effectiveness and practicability of the method proposed in this paper. Section 7 draws conclusions based on the analysis results.

2. Model of the Integrated Energy System

In this paper, considering the demand of electricity, cooling and heat energy of IES, based on the concept of EH, a system including Wind Turbine (WT), Air Conditioning (AC), Electric boiler (EB), Combined Cooling, Heating and Power (CCHP), Gas Boiler (GB) and energy storage devices ES (Electric Storage), CS (Cool Storage) and HS (Heat Storage) are shown in Figure 1.
The electricity and natural gas purchased from the local power grid and natural gas network, and output electricity, cooling and heat for users to use by the energy conversion and distribution of energy equipment in IES.

2.1. Energy conversion model of IES without energy storage devices
Without considering the electric, cooling and heat energy storage equipment, the energy conversion relationship of the system can be described as:

$$
\begin{bmatrix}
P_{ELE}^t \\
P_{COOL}^t \\
P_{HEAT}^t 
\end{bmatrix} =
\begin{bmatrix}
1 & -1 & -1 & -1 & \eta_{CCHP}^{ele} & 0 & 1 \\
0 & 0 & \eta_{CCHP}^{cool} & 0 & \eta_{CCHP}^{cool} & 0 & 0 \\
0 & 0 & \eta_{EB}^{heat} & \eta_{GB}^{heat} & \eta_{GB}^{heat} & 0 & 0
\end{bmatrix}
\begin{bmatrix}
p_{buy,ele}^t \\
p_{sell,ele}^t \\
p_{AC}^{ele} \\
p_{CCHP}^{ele} \\
p_{GB}^{ele} \\
p_{WT}^{ele}
\end{bmatrix}
$$

(1)

$p_t$ is the total output power of energy $m$ of IES during the period $t$ without considering the energy storage device, $p_{m,n} \in \{P_{ELE}, P_{COOL}, P_{HEAT}\}$, $n \in \{ele, cool, heat\}$. $\eta_n^m$ is the energy $m$ power efficiency of device $n$, $n \in \{AC, EB, CCHP, GB, WT\}$. $p_{buy,ele}^t$, $p_{sell,ele}^t$ is the electric power system purchase and sale during period $t$. $p_{m,n}^{in}$ is the input energy $m$ power of device $n$ during period $t$, $m' \in \{ele, gas\}$. $p_{WT}^{ele}$ is the power generation of WT.

The natural gas purchased by the system is converted into other forms of energy by CCHP and GB, and the relationship between the gas purchased and the gas power of CCHP and GB can be described as:

$$
V_{buy, gas}\Delta t = (p_{CCHP}^{gas} + p_{GB}^{gas})\Delta t
$$

(2)

$V_{buy, gas}$ is the natural gas purchased during period $t$, $H_i$ is the inferior calorific value of lighting natural gas, $9.73 kW \cdot h / m^3$ in this paper.

Figure 1. Structure of IES and interaction between energy devices.

2.2. Energy conversion model of IES with energy storage devices
In this paper, energy storage system is established through installing energy storage devices of electricity, cooling and heat. On one hand, energy storage is the stabilizer of the terminal of IES, which can reduce the fluctuation of renewable energy and the uncertainty of the energy demand of scattered users. On the other hand energy storage can act as an energy aggregator, concentrating resources on the production side and energy consumption side.

Considering energy storage devices, the energy charged and discharged of the energy storage devices of electric, cooling, and heat during the period $t$ can be described as:

$$
\Delta S_{m,n}^t = \begin{bmatrix}
\eta_{m}^{w} \\
\eta_{m}^{d}
\end{bmatrix} - \begin{bmatrix}
1 \\
1
\end{bmatrix}
\begin{bmatrix}
p_{buy,ele}^t \\
p_{sell,ele}^t
\end{bmatrix} \Delta t
$$

(3)
is the charging and discharging power of storage device for energy during period \( t \), \( \eta_{\text{ch}} \), \( \eta_{\text{dis}} \) is the charging and discharging efficiency of storage device for energy during period \( t \), \( \Delta S_m \) is the changing amount of storage device for energy during period \( t \), \( \Delta S_m = S_{m,t} - S_{m,t-1} \).

Considering the energy storage device, the energy output by ISE during the period can be described as:

\[
E_{m,t} = P_{m,t} \Delta t - \Delta S_{m,t} \tag{4}
\]

3. Energy reliability of the Integrated Energy System

3.1. Considering the uncertainty of wind power output

Considering the fluctuation and uncertainty of wind speed, Rayleigh probability distribution model is usually used to simulate actual wind speed [19]. The probability distribution of wind speed obeys Rayleigh distribution and the power generation of wind turbine can be described as:

\[
P_{\text{WT}}(v) = \begin{cases} 
0, & v \leq v_{\text{in}} \text{ or } v \geq v_{\text{out}} \\
\frac{v - v_{\text{in}}}{v_{\text{r}} - v_{\text{in}}} P_{\text{WT},r}, & v_{\text{in}} \leq v \leq v_{\text{r}} \\
\frac{v - v_{\text{r}}}{v_{\text{out}} - v_{\text{r}}} P_{\text{WT},r}, & v_{\text{r}} \leq v \leq v_{\text{out}} 
\end{cases} \tag{5}
\]

\( P_{\text{WT}} \) is the rated output power of WT, \( v_{\text{r}} \), \( v_{\text{in}} \), \( v_{\text{out}} \) is the rated wind speed, cut-in and cut-out wind speed.

3.2. System reliability considering equipment failure

Expectation Energy Not Supply (EENS) [20] is usually used to describe the lack of energy supply in IES due to failure caused by one-error of energy equipment.

In this paper, two reliability indicators, namely energy not supply rate and energy backup rate are established to describe the influence of energy shortage on the system, and the two indicators are considered into the constraints of the second stage optimization model.

The energy not supply rate indicates the ratio of EENS of energy \( m \) to the total load demand of IES, and can be described as:

\[
S_{\text{EENS}}^m = \frac{E_{\text{EENS}}^m}{E_{m,t}} \times 100\% \tag{6}
\]

The lower \( S_{\text{EENS}}^m \), the higher the stability of energy supply when the equipment fails.

The energy backup rate indicates the ratio that the backup energy \( m \) of system equipment can supplement the energy shortage, and can be described as:

\[
S_{\text{BENS}}^m = \frac{R_m \Delta t - E_{\text{EENS}}^m}{E_{\text{EENS}}^m} \times 100\% \tag{7}
\]

\( R_m \) is the backup power of energy \( m \) during period \( t \) . The higher \( S_{\text{BENS}}^m \), the higher the capability of the energy complement when the equipment fails.

4. Two-stage optimal model of the Integrated Energy System

When energy companies invest and build integrated energy system, in order to minimize the cost of configuration and installation of energy equipment and operation and maintenance of the system, a two-stage configuration-operation model is established to solve the optimization objective function

\[
\min C_t = C_{IT} + 365 \sum_{m=1}^{M} p_t C_{IO} \tag{8}
\]

\( C_{IT}, C_{IO}, C_{IO} \) is the total, investment, operation cost of IES. \( p_t \) is the probability of a typical day. \( s \) is the amount of typical days. \( \tau \) is the coefficient of realizing value of equivalent annual investment. \( \tau = [(1+r)^y - 1]/r(1+r)^y \), \( r \) is the discount rate, \( \tau \) is the service life of IES.
4.1. The solution method of the two-stage planning optimization model

The two-planning optimization model is a mixed-integer nonlinear two-level programming problem. It is difficult and time-consuming to solve using non-numerical optimization algorithms. In order to improve the convergence and reduce the time-consuming solution, this article adopts the particle swarm optimization algorithm and CPLEX solver to avoid the population falling into the local optimum, which also own strong optimization ability and good convergence.

In the first stage, the PSO algorithm is used to solve the planning and configuration scheme of energy equipment in IES, which is sent to the second stage. The CPLEX solver calculates the cost under the operation constraints of the second stage, and the results are sent back to the first stage. The two stages iterate repeatedly to obtain the optimal solution until the algorithm converges or reaches the maximum algebra. The flow of algorithm solution is shown in Figure 2.

4.2. Objective function of two-stage planning optimization model

The objective function of the first stage can be described as:

\[ C_1 = \sum \sum I_{i,k} C_{i,k} + \sum \sum I_{i,q} C_{i,q} \]  \hspace{1cm} (9)

\( n, m \) is the \( i \)th energy conversion device and the \( q \)th energy storage device. \( I_{i,n}, I_{i,q} \) is the installation status, \( C_{i,n}, C_{i,q} \) is the investment cost.

The typical day operation cost of IES can be described as:

\[ C_{to} = C_{ele} + C_{gas} + C_{fo} + C_{pen} \]  \hspace{1cm} (10)

\( C_{ele} \) is the cost of electricity purchased minus electricity sold, \( C_{gas} \) is the cost of natural gas purchased, \( C_{fo} \) is the operation cost of energy device, \( C_{pen} \) is the penalty cost of energy shortage.

\[ C_{ele} = \sum \left( c_{buy,i} P_{buy,i} - c_{sell,i} P_{sell,i} \right) \Delta t \]  \hspace{1cm} (11)

\[ C_{fo} = \sum \sum \alpha_{n,i} P_{n,i} \Delta t \]  \hspace{1cm} (12)

\[ C_{gas} = \sum c_{gas,i} V_{gas,i} \Delta t + \sum \sum \alpha_{m,q} (P_{m,q} + P_{m,q}) \Delta t \]  \hspace{1cm} (13)

\[ C_{pen} = \sum m \]  \hspace{1cm} (14)

\( c_{buy,i}, c_{sell,i} \) is the price of electricity purchased and sold during the period \( i \), \( c_{gas,i} \) is the price of natural gas during the period \( i \), \( \alpha_{n,i}, \alpha_{m,q} \) is the operation cost. \( P_{n,i} \) is the energy conversion power during the period \( i \), \( P_{n,i} \in \{ P_{ele,i}, P_{ele,i} P_{ele,i}, P_{ele,i}, P_{ele,i} \} \), \( P_{m,q}^{ch}, P_{m,q}^{dis} \) is the power of charging and discharging during the period \( i \), \( C_{m} \) is the penalty cost of energy \( m \). \( E_{m}^{ens} \) is the shortage of energy \( m \).

4.3. Constraints of two-stage planning optimization model

The power interaction between IES and the local power grid can be described as:

\[ 0 \leq P_{buy,i} \leq \lambda_{buy} P_{buy,MAX} \]  \hspace{1cm} (15)

\[ 0 \leq P_{sell,i} \leq \lambda_{sell} P_{sell,MAX} \]  \hspace{1cm} (16)

\( P_{buy,MAX}, P_{sell,MAX} \) is the maximum power for purchasing and selling electricity. \( \lambda_{buy}, \lambda_{sell} \) is the status of power purchase and sale, \( \lambda_{buy}, \lambda_{sell} \in \{ 0, 1 \}, \lambda_{buy} + \lambda_{sell} \leq 1 \).

Similarly, the energy interaction between IES and the natural gas network can be described as:

\[ 0 \leq P_{gas,i} \leq P_{gas,MAX} \]  \hspace{1cm} (17)
is the maximum power for purchasing natural gas.

The output power of the energy conversion equipment can be described as:

\[ I_{\xi_{nk}} p_{nk,\min} \leq I_{\xi_{nk}} p_{nk} \leq I_{\xi_{nk}} p_{nk,\max} \] (18)

\( \xi_{nk} \) is the operation status, \( \xi_{nk} \in [0,1] \). \( p_{nk,\min} \) is the output power, \( p_{nk,\max} \) is the output limit power.

The energy storage device cannot charge and discharge energy at the same time, which can be described as:

\[ I_{\xi_{mq}} p_{mq,\min} \leq I_{\xi_{mq}} p_{mq} \leq I_{\xi_{mq}} p_{mq,\max} \] (19)

\[ I_{\xi_{mq}} p_{mq,\min} \leq I_{\xi_{mq}} p_{mq} \leq I_{\xi_{mq}} p_{mq,\max} \] (20)

\( p_{mq,\min} \) and \( p_{mq,\max} \) is the charging and discharging power and its limit during the period \( \tau \). \( \xi_{mq} \) is the operation status, \( \xi_{mq} \in [0,1] \). \( \xi_{mq}^{ch} + \xi_{mq}^{dis} \leq 1 \).

The SOC of energy storage devices can be described as:

\[ S_{min} \leq S_{mq} \leq S_{max} \] (21)

\( S_{mq} \) and \( S_{max} \), \( S_{min} \) is energy storage and its limit during the period \( \tau \).

The power backup of system energy conversion equipment and energy storage devices can be described as:

\[ R_{nk} \leq I_{\xi_{nk}} \left( p_{nk,\max} - p_{nk,\min} \right) \] (22)

\[ R_{mq} \leq I_{\xi_{mq}} \left[ p_{mq,\max} - \left( \xi_{mq}^{ch} p_{mq} \right) - \left( \xi_{mq}^{dis} p_{mq} \right) \right] \] (23)

\( R_{nk} \), \( R_{mq} \) is the backup power.

Reliability indicators can be added to constraints as followed:

\[ S_{EENS}^{n} \leq S_{EENS,\text{MAX}}^{n} \] (24)

\[ S_{EENS}^{n} \geq S_{EENS,\text{MIN}}^{n} \] (25)

\( S_{EENS,\text{MAX}}^{n} \), \( S_{EENS,\text{MIN}}^{n} \) is the limit of two indicators.

Figure 2. Flowchart of two-stage planning optimization model.
Figure 3. The curves of load and wind output of typical seasons and electricity price.

5. Simulation results and discussion
The typical seasonal load, wind power output and electricity price curve of a certain area in northern China are shown in Figure 3. In this paper, the time-of-use electricity price is adopted, and the electricity price for selling to upstream grids is 0.64 yuan/kW·h. In northern China, winter is longest, as a result, the typical daily occurrence probabilities in spring and autumn, winter and summer are 0.4, 0.4 and 0.2 respectively. The price of natural gas is 2.93 yuan/m³. The penalty costs of electricity, cooling and heat energy are 8.05, 3.04 and 3.59 yuan/kW·h respectively. The IES constructed in this paper has a service life of 20 years and a discount rate of 1%.

| Case | Scenario       | ES | HS | CS | Indicator 1 $S^1_{EENS}$ | Indicator 2 $S^2_{EENS}$ |
|------|----------------|----|----|----|--------------------------|--------------------------|
| 1    | Industrial     | √  | √  |    |                          |                          |
| 2    | Living-official| √  | √  |    |                          |                          |

By considering the energy storage devices, the scenarios with different applications of the IES are simulated. For industrial scenario, due to the large demand for electrical energy in factories, some processing factories also have a huge amount demand of heat energy, so electric energy and heat energy storage are considered to ensure that the energy provided by the system can meet the demand. However, there is little demand for electricity load for living-official scenario, so cooling and heat storage is considered to meet the demand, and electricity energy storage is not necessary.
energy storage is considered instead. At the same time, the boundary values of the two reliability indicators proposed in 4.2 are set to constrain the system. The scenario and case settings are presented in Table 1. In this paper, energy shortage rate’s limit is set to 10%, and energy supplement rate’s limit is set to 85%.

5.1. Simulation results
The configuration and optimization results of four cases are shown in Table 2 and Table 3.

| Table 2. Configuration numbers and capacities of energy device of four cases. |
|------------------|------------------|------------------|------------------|------------------|------------------|
| Case | CCHP | EB | AC | GB | WT | ES | CS | HS |
| 1 | 31.18 | 3.72 | 7.64 | 5.68 | 3.79 | 3540 | - | 3485 |
| 2 | 25.86 | 5.68 | 9.43 | 1.84 | 1.86 | 5794 | - | 5672 |
| 3 | 22.34 | 3.68 | 7.52 | 5.74 | 3.71 | - | 3794 | 1826 |
| 4 | 19.86 | 5.82 | 3.77 | 1.89 | 2.69 | - | 7574 | 5723 |

| Table 3. Optimization results of four cases. |
|------------------|------------------|------------------|------------------|------------------|------------------|
| Case | Investment cost (million yuan) | Operation cost/year (million yuan /KW) | E-EENS (kW·h) | C-EENS (kW·h) | H-EENS (kW·h) | Penalty cost (million yuan) | Total cost (million yuan) |
| 1 | 308.40 | 32.8712 | 21856 | 19576 | 43075 | 0.3901 | 908.6168 |
| 2 | 283.50 | 33.0925 | 2034 | 1788 | 3452 | 0.0342 | 881.2879 |
| 3 | 310.50 | 32.1843 | 25634 | 21782 | 45786 | 0.4369 | 899.1659 |
| 4 | 316.80 | 30.5738 | 3362 | 3621 | 7658 | 0.0579 | 869.5643 |

In the industrial scenario, compared with case 1, considering two reliability indexes, the capacity of EB, AC and energy storage devices installed in case 2 increases, while the capacity of CCHP, GB and WT decreases. Compared with the configuration scheme of case 1, the investment cost of case 2 is reduced by 24.9 million yuan, and the annual operation cost is slightly higher by 221,300 yuan than that of case 1, but the shortage of electricity, cold and heat energy is greatly reduced, which is about one tenth of that of case 1, which is reduced by 355,900 yuan. The penalty cost accounts for 91.23% of the one-year penalty cost of the scene. The optimization result shows that the configuration of case 2 reduces the total input cost of the system by 27.3289 million yuan compared with the operation scheme.

In the office life scenario, compared with case 3, considering two reliability indexes, the capacity of AC, GB and energy storage devices installed in case 4 increases, while the capacity of EB and WT decreases. Compared with the configuration scheme of case 3, the investment cost of scenario 4 increased by 6.3 million, but the annual operation cost decreased by 1.6105 million, effectively reducing the shortage of electricity, cold and heat energy, and reducing the penalty cost of 379,000 yuan, accounting for 86.74% of the penalty cost of case 3. The optimization result shows that the configuration of case 4 reduces the total cost of the system by 29.6016 million yuan compared with the operation scheme of case 3.

It can be seen that when the reliability index is added into the optimization model constraints, it can effectively reduce the missing energy of the system, make the system more stable and reliable, reduce the total input cost of the system, and ensure the stability and economy of the system.

5.2. Discussion
In case 2 and case 4, two reliability indexes are added to the second stage constraint of the model at the same time. In order to verify that the optimization results of the system are better under the
constraint of two indexes at the same time, the different results of adding single index and double index in the optimization constraint are compared as shown in Figure 4.

![Comparison of results with single and double indicators](image)

**Figure 4.** Optimal results with single or double indicators.

It can be seen from the results that the investment cost and annual operating cost of considering a single indicator and two indicators have little fluctuation in both industrial and office life scenarios, with the investment cost ranging from -3.36% to +6.34% and the annual operating cost ranging from -3.53% to +7.14%. However, considering two indicators, the annual penalty cost is greatly reduced and the total input cost is less than only the optimization results of industrial scenarios show that the annual operation cost considering two indicators is slightly larger than that considering a single indicator, but the investment cost is slightly smaller than that considering a single indicator.

To sum up, considering the double constraints of reliability indicators is not much different from considering the construction investment in the early stage and the operation cost in the later stage of a single indicator, but considering the constraints of two indicators at the same time can more effectively reduce the energy loss of the system, cut down the penalty cost of energy shortage, and thus reduce the total input cost.

On the basis of case 2 and case 4 in 5.2, the values of index 1 are changed to 8%, 10%, 12% and 14%, and the values of index 2 are changed to 82%, 85%, 88% and 91%, respectively, to verify the influence of different reliability index values on system energy shortage, as shown in Figure 5.

![Comparison of results with changing values of indicators](image)

**Figure 5.** Optimal results of changing value of indicators.

By changing the value of index 1 energy loss rate on the basis of case 2 and case 4, it can be seen that with the change of index 1 value by 8% ~ 14%, the expected value of electricity, cold and heat...
energy deficiency also increases, indicating that the lower the energy loss rate, the more stable the system provides energy, and the less the energy deficiency in case of failure.

By changing the value of energy supplement rate of index 2 on the basis of case 2 and case 4, it can be seen that with the change of 82% ~ 91% of the value of index 2, the expected value of energy deficiency decreases accordingly, which indicates that the higher the energy supplement rate, the more stable the system can supply energy in case of failure.

6. Conclusions
In this paper, a two-stage planning optimization model of IES is constructed. Considering the reliability of energy, two indexes are put forward and added to the second stage constraints of the optimization model to make the system run more stably. The following conclusions are obtained by the analysis of an example.

1) The two-stage planning optimization model constructed in this paper is suitable for various scenarios, which can reduce the influence of system energy uncertainty on system output, effectively improve the utilization of system energy, cut down the penalty cost of the system, reduce the total cost of the system and make the system more sustainable and economical at the same time.

2) With the constraints of two indicators, the penalty cost can be reduced at least 86.73%, and the total cost can save 27.32 million yuan. Compared with the single index constraint, under the dual constraints of two indicators, the penalty cost and total cost of the system can be greatly reduced. With the decrease of energy shortage rate, the system energy shortage decreases, while the energy supplement rate decreases and the system energy shortage increases.

Acknowledgements
This paper was funded by the Science and Technology Project of State Grid Liaoning Electric Power Company Ltd (2020YF-44), Research and Application of Panoramic Perception and Operation and Maintenance Management and Control Technology for Multi-scenario Integrated Energy System.

References
[1] Ahmad S, Kadir M Z A A, Shafie S 2011 J. Renewable and Sustainable Energy Reviews 15 897
[2] Koltatsakis NE, Dagoumas AS 2018 J Applied Energy 230 563
[3] Fang J, Zeng Q, Ai X, Chen Z, Wen J 2018 J. IEEE Transactions Sustainable Energy 9 188
[4] Salimi M, Ghasemi H, Adelpour M, Vaez-Zadeh S 2015 J. IET Generation, Transmission & Distribution 9 695
[5] Samsatli S, Samsatli NJ 2018 J. Applied Energy 220 893
[6] Huang Wujing, Zhang Ning, Yang Jingwei 2019 J. IEEE Transactions on Smart Grid 10 1452
[7] Shahmohammadi A, Moradi-Dalvand M, Ghasemi H, et al 2015 J. IEEE Transactions on Power Delivery 30 878
[8] Zhang X, Conejo AJ 2018 J. IEEE Transactions on Power Systems 33 1329
[9] Mavromatidis G, Orehoung K, Carmeliet J 2018 J. Applied Energy 222 932
[10] Barati F, Seifi H, Sepasian M S,et al 2015 J. IEEE Transactions on Power Systems 30 2527
[11] Li Yong, Zou Yao, Tan Yi,et al 2018 J. IEEE Transactions on Sustainable Energy 9 273
[12] Zhang X, Che L, Shahidehpour M,et al 2018 J. IEEE Transactions on Smart Grid 8 1658
[13] Nunes JB, Mahmoudi N, Saha TK, Chattopadhyay D 2018 J. Energy 153 539
[14] He C, Wu L, Liu T, et al 2018 J. IEEE Transactions on Power Systems 33 2140
[15] Juanwei C, Tao Y, Yue X, et al 2019 J. Applied Energy 242 260
[16] Zahedi Rad V, Torabi SA, Shakouri GH 2019 J. Energy 167 523
[17] Cheng Y, Zhang N, Lu Z, Kang C 2019 J. IEEE Transactions on Smart Grid 10 4859
[18] Li G, Huang Y, Bie Z 2018 J. IEEE Transactions on Sustainable Energy 9 1713
[19] Nunes JB, Mahmoudi N, Saha TK, Chattopadhyay D 2018 J. Energy 153 539
[20] Chaudry M, Jenkins N, Qadrdan M, Wu J 2014 J. Applied Energy 113 1171