An AHP-Bayesian Model for Operational Risk Evaluation of Integrated Energy Systems

Yongqi Yang¹, Wanlei Xue¹, Chaoyuan Li², Xin Zhao¹ and Nan Xu¹

¹Economic and Technology Research Institute, State Grid Shandong Electric Power Company, Jinan, China
²School of Finance, Shanghai University of Finance and Economics, Shanghai, China
Email: yangyongqincepu@163.com

Abstract. The rapid development of Integrated Energy Systems (IES) is of great significance in solving the increasingly serious environmental problems by promoting China’s energy evolution. Under the huge policy support, China’s IES technology has taken a great- leap-forward development. Meanwhile, a large number of IES projects will be carried out extensively. Therefore, operational risk evaluation for IES projects is of great urgency. In the first place, we will summarize the basic structure of IES and build operational risk evaluation index system for IES projects based on characteristics of China’s IES systems. Secondly, the improved Bayesian operational risk evaluation model will be established. In this improved model, AHP method will be used to calculate the weight of every index. Last but not least, a case study is implemented to prove the practicality of the model and provide references for the IES projects decision and optimization.

1. Introduction

As a key support of economic and social development, China’s energy supply-utilization system, which relies on fossil fuel, has led to several serious environmental problems. China is now experiencing an important restructuring period, an energy revolution is of great urgency to change the present traditional extensive energy development mode to a more intensified mode[1]. IES, which is able to integrate multiple energy (including oil, coal, natural gas and power), is considered to be the key method to build the new energy system relies on clean energy[2,3]. The core idea of IES is multiple energy complementation and optimal coordination between “source-grid-load-energy storage”, IES is able to enhance the energy efficiency and promote clean energy consumption.

IES was developed based “Internet plus initiative” and “Energy Internet”. Since publication of the Guidance for the Promotion and Development of Smart Energy based on Internet Plus Initiative from National Development and Reform Commission, the related technologies of IES has developed rapidly[4,5]. [5] investigates multi-period optimal energy flow and energy pricing in carbon-emission embedded integrated energy systems, including electricity, natural gas, and district heating networks. A bilevel optimal coordinated control strategy for park-level integrated energy system is proposed in[6]. [7] has built a day-ahead scheduling optimization model, and the rigid coupling between heating network and power grid is improved by adjusting CHP output. [8] has proposed a typical integrated energy system which includes typical energy conversion technologies, after building energy demands and energy conversion processes in TIES are abstracted and simplified by a typical energy flow map, a dimensionless equation for calculating TIES energy and exergy efficiency is developed.

Now many industrial parks have established IES to fulfill users’ energy demand, however, many studies focus on multiple energy conversion and system operation optimization. There are few
researches in operational risk evaluation. Therefore, this paper will propose the basic structure of IES and establish operational risk evaluation index system at first. Second, AHP method will be introduced and build improved Bayesian Model. Last but not least, a case study will be carried out based on an IES project in North China, the operational risk of three different schemes of this project will be calculated to provide reference to the optimization and decision of project schemes.

2. Basic Structure of IES
Nowadays, several industrial parks are seeking to fulfill users’ energy demand through IES. Basic structure of these IES is shown in Figure 1.

![Figure 1. Basic structure of IES](image)

The basic structure of IES can be divided into three parts:

For supply side, power supply mainly relies on distributed generation including distributed wind generation, distributed photovoltaic generation, etc. Cooling, heating and natural gas supply depend on CCHP and heat pump[9]. Along with the large-scale long distance energy transmission network, flexible coal-fired generation can be connected to IES to provide ancillary services for distributed generation. In addition, oil and gas can be transmitted through this long distance network.

For transmission side, micro energy grid is the main grid of IES. The structure of micro energy grid is established based on micro grid. Micro energy grid connects distributed energy generation and large-scale long distance energy transmission network, and it’s able to set up multiple energy integrated devices on micro energy grid. Hence micro energy grid is able to realize the coordination between hydro energy, electric power, heat and gas. As for long distance energy transmission network, micro energy grid can be treated as a relatively independent energy supply-demand module. Multiple Energy Coordination Optimization System (MECOS), cloud data integration and multiple clients transaction platform should be built on transmission side to realize the optimized allocation of resources.

For demand side, MECOS is able to integrate demand side resources, in addition, MECOS can upgrade demand side management and demand side response to comprehensive energy utilization management and energy utilization response[10]. Therefore, demand side of IES is able to form controllable energy demand curve along with the organized charge-discharge energy storage operation mode, which can trace the energy supply curve to realize the supply-demand side coordination.
3. Evaluation Index System
According to the characteristics of IES projects in China, this paper has built the index system in three categories (supply, transmission and demand sides) as shown in Table 1.

Table 1. Investment risk evaluation index system for IES projects

| Categories | Code of Indexes | Indexes                        |
|------------|----------------|-------------------------------|
| Supply     | $R_1$          | Wind curtailment              |
|            | $R_{11}$       | Solar energy curtailment      |
|            | $R_{12}$       | SOx pollution rate            |
|            | $R_{13}$       | NOx pollution rate            |
|            | $R_{14}$       | COx pollution rate            |
|            | $R_{15}$       | Dust pollution rate           |
|            | $R_{16}$       | Primary energy utilization    |
| Transmission | $R_2$       | Energy conversion efficiency  |
|            | $R_{21}$       | Rate of energy loss during transmission |
|            | $R_{22}$       | Payback period                |
|            | $R_{23}$       | Internal rate of return       |
| Demand     | $R_3$          | Energy demand forecast accuracy|
|            | $R_{31}$       | Energy consumption per unit of GDP |
|            | $R_{32}$       | Regional GDP growth rate      |

For one thing, energy conversion efficiency is included to demonstrate the conversion efficiency between multiple kinds of energy, renewable energy utilization rate, etc. For another, IES project should be able to achieve economic benefits as well as social benefits including pollution reduction, GDP growth rate, etc. Therefore, the index system is built in Table 1 according to the requirements above.

4. Improved Bayesian Model

4.1. AHP Method
AHP weighting approach is introduced and performed according to the following steps:
1) $R$ represents the comprehensive benefit, which includes economic benefit $R_1$, energy efficiency $R_2$ and social benefit $R_3$. The set of comprehensive benefit is $R = \{R_1, R_2, R_3\}$, and their weight is $W = \{W_1, W_2, W_3\}$. As for the second level indexes, $R_1$ can be divided into wind curtailment $R_{11}$, solar energy curtailment $R_{12}$, etc. Their weight is $w_1 = \{w_{11}, w_{12}, ..., w_{17}\}$, $i$ represents decision indexes and its number is $n$, $j$ represents different schemes and its number is $m$. The rest indexes can be done in the same manner[11].
2) The importance can be determined through pairwise comparison, scale meaning is used to demonstrate the importance of each index[12]. Scale meaning of AHP is shown in Table 2.

Table 2. Scale meaning of AHP

| Values | Definition                                                |
|--------|----------------------------------------------------------|
| 1      | Equally important                                        |
| 2      | Experience and judgment slightly favor one index over another |
| 3      | Experience and judgment strongly favor one index over another |
| 4      | An index is favored very strongly over another            |
| 5      | The evidence favoring one index over another is of the highest possible order of affirmation. |

3) The judgement matrix can be built through pairwise comparison. Here we take the first level index as an example, $R = \{R_1, R_2, R_3\}$, and its judgement matrix is:
Where $q_{ij}$ is the comparison result between supply and transmission, if supply is more important than transmission, the value of $q_{ij}$ is higher than 1, otherwise it’s less than 1. Obviously $q_{11}=q_{22}=q_{33}=1$.

4) Solve the following formula to get the weight of each index:

$$QW = \lambda_{\text{max}} W$$

Where $\lambda_{\text{max}}$ is largest eigenvalue of matrix $Q$, $W$ is the feature vector of $\lambda_{\text{max}}$, hence $W_1, W_2, W_3$ is the weight of $R_1, R_2, R_3$.

5) Consistency check should be performed, the consistency index is calculated as:

$$CI = \frac{\lambda_{\text{max}} - n}{n - 1}$$

$$CR = \frac{CI}{RI}$$

(3)

(4)

Where the value of $RI$ varies with the order of judgement matrix $Q$, as it’s shown in Table 3:

| $n$ | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 |
|-----|----|----|----|----|----|----|----|----|----|----|
| $RI$ | 0  | 0  | 0.58 | 0.9 | 1.12 | 1.24 | 1.32 | 1.41 | 1.46 | 1.49 |

When $CR=0$, the consistency of judgement matrix is fully stochastic.

When $CR>0.1$, the consistency of judgement matrix do not meet the consistency requirements, the judgement matrix should be further modified.

When $CR<0.1$, the consistency requirements are fulfilled. Hence $W=(W_1, W_2, W_3)$ (after normalization) is the weight of $R_1, R_2, R_3$.

4.2. Bayesian Risk Investment Evaluation Model

The calculation process of Bayesian operational risk evaluation model is as follows:

In decision-making space $S=\{s_1, s_2, ..., s_n\}$, $s_n$ represents decision scheme, $S$ is the state space. Among those, $\delta_1$, $\delta_2$ and $\delta_3$ separately reflect that the situation of the market is high risk, average risk and low risk. Therefore, $P(\delta_1)$, $P(\delta_2)$ and $P(\delta_3)$ demonstrates the probability of $\delta_1$, $\delta_2$ and $\delta_3$. According to the authoritative analysis report, this paper sets $P(\delta_1)=0.2$, $P(\delta_2)=0.4$, $P(\delta_3)=0.4$. Obviously, there is a risk in this prediction, so the risk factors should be added into the prediction of market situation[13]. In this model, $\mu_1$, $\mu_2$ and $\mu_3$ means the prediction accuracy is low, average, high.

According to 3.1, the weight vector is $w_1=(w_{11}, w_{12}, ..., w_{17})$, $w_2=(w_{21}, w_{22}, ..., w_{24})$, $w_3=(w_{31}, w_{32}, w_{33})$. Therefore, the benefit function can be obtained, as shown in Equation (5).

$$B = w_{11}R_{11} + w_{12}R_{12} + ... + w_{17}R_{17} + w_{21}R_{21} + w_{22}R_{22} + ... + w_{24}R_{24} + w_{31}R_{31} + w_{32}R_{32} + w_{33}R_{33}$$

(5)

The risk decision table is shown in Table 4.

Table 4. Risk decision table

| Scheme     | $\delta_1$ | $\delta_2$ | $\delta_3$ |
|------------|-------------|-------------|-------------|
| Scheme 1   | $a_{11}$    | $a_{12}$    | $a_{13}$    |
| Scheme 2   | $a_{21}$    | $a_{22}$    | $a_{23}$    |
| Scheme 3   | $a_{31}$    | $a_{32}$    | $a_{33}$    |
Risk of every scheme is shown in Equation (6).

\[
E(B_i) = P(\delta_1)\alpha_i + P(\delta_2)\alpha_{i2} + P(\delta_3)\alpha_{i3}
\]  (6)

The purpose of decision-making process is to calculate and get the operational risk of every scheme under every market situation. Therefore the basis of selection is demonstrated in Equation (7).

\[
E(B_i)_{\text{max}} = \max_i E(B_i) \quad (i \in [1, n])
\]  (7)

Besides, the risk factor of prediction will be introduced into the modeling, the table of relevance between the prediction of market situation and the prediction accuracy are shown in Table 5[14].

**Table 5** Relevance between the prediction of market situation and the prediction accuracy

| Prediction Accuracy | \(\delta_1\) | \(\delta_2\) | \(\delta_3\) |
|--------------------|------------|------------|------------|
| \(\mu_1\)          | \(\beta_{11}\) | \(\beta_{12}\) | \(\beta_{13}\) |
| \(\mu_2\)          | \(\beta_{21}\) | \(\beta_{22}\) | \(\beta_{23}\) |
| \(\mu_3\)          | \(\beta_{31}\) | \(\beta_{32}\) | \(\beta_{33}\) |

The Bayesian formula is shown in Equation (8). And use (8) we can calculate operational risk of each scheme.

\[
P(\delta|\mu_j) = \frac{P(\delta,\mu_j)}{P(\mu_j)} = \frac{P(\delta)P(\mu_j|\delta)}{\sum_{\delta'} P(\delta')P(\mu_j|\delta')}
\]  (8)

5. Case Study

Case study of this paper was performed by an IES project in North China. After the calculation process of AHP, the weight of indexes is shown in Table 6.

**Table 6.** Weight of indexes

| Main index | First level indexes | Weight | Second level indexes | Weight | CR |
|------------|---------------------|--------|----------------------|--------|----|
| Supply     | Wind curtailment    | 0.220  | Solar energy curtailment | 0.220  |    |
|            | SOx pollution rate  | 0.106  | NOx pollution rate    | 0.106  | 0.032<0.1 |
|            | COx pollution rate  | 0.106  | Dust pollution rate   | 0.106  |    |
|            | Primary energy utilization | 0.136 |                   |        |    |

| Operational risk | Energy conversion efficiency | 0.351 | Rate of energy loss during transmission | 0.126 | 0.012<0.1 |
|                 | Payback period              | 0.224 | Internal rate of return                 | 0.299 |    |

| Demand | Energy demand forecast accuracy | 0.322 | Energy consumption per unit of GDP | 0.426 | 0.051<0.1 |
|        | Regional GDP growth rate       | 0.252 |                               |       |    |

Weight vector of indexes is able to be calculated through the AHP method. The result is \(W = (0.103, 0.103, 0.050, 0.050, 0.050, 0.064, 0.115, 0.041, 0.074, 0.098, 0.065, 0.086, 0.051)\).

Based on the model established in Section 4, the benefit of all schemes is shown in Table 7.
Table 7. The results of benefit calculations

| Scheme    | $\delta_1$ | $\delta_2$ | $\delta_3$ | Expectations |
|-----------|------------|------------|------------|--------------|
| Scheme A  | 0.313      | 0.327      | 0.313      | 0.319        |
| Scheme B  | 0.451      | 0.429      | 0.438      | 0.437        |
| Scheme C  | 0.412      | 0.427      | 0.420      | 0.421        |

Table 8. Relationship between prediction accuracy and market situation

| Market Schemes | $\delta_1$ | $\delta_2$ | $\delta_3$ |
|----------------|------------|------------|------------|
| $\mu_1$        | 0.64       | 0.20       | 0.17       |
| $\mu_2$        | 0.21       | 0.68       | 0.13       |
| $\mu_3$        | 0.15       | 0.12       | 0.70       |

Table 9. The results of operational risk calculations

| Scheme    | $\delta_1$ | $\delta_2$ | $\delta_3$ | Expectations |
|-----------|------------|------------|------------|--------------|
| Scheme A  | 0.561      | 0.183      | 0.149      | 0.245        |
| Scheme B  | 0.265      | 0.818      | 0.160      | 0.444        |
| Scheme C  | 0.173      | 0.144      | 0.824      | 0.422        |

According to the results, the expectations of scheme B is 0.444, which means scheme B has the highest comprehensive benefit and lower risk, hence this project should be performed by scheme B. This result is in accordance with the practical implementation result of the projects.

6. Conclusion

IES, which is able to realize multiple energy complementary optimization and coordination between “source-grid-load-energy storage”, will be a key method to carry out China’s energy revolution. Nowadays many industrial parks are planning to provide energy supply through IES. However, related researches still focus on IES planning and dispatching technologies, there are few researches about operational risk evaluation of IES projects.

According to present research status, we have proposed the basic structure of IES including energy supply, transmission and demand. Evaluation index system of IES operational risk has been established based on IES characteristics. The improved Bayesian model with AHP as its weighting method has been designed and proved by the case study. As shown in the case study, the improved Bayesian model is able to evaluate the operational risk of IES projects accurately. In conclusion, the model and theory in this paper have great importance in realizing the optimization of IES system operation as well as resource allocation. The result of Bayesian analysis can provide valuable data and reference to the decision making process of IES operation scheme selection.
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