A Comprehensive Evaluation Model for Microgrid with CCHP

Shuangchen Yuan1*, Zhijia Wu2 and Long Yan1

1 Binhai Power Supply Branch of State Grid Tianjin Electric Power Company, Tianjin, Binhai District, 300450, China
2 Chengxi Power Supply Branch of State Grid Tianjin Electric Power Company, Tianjin, Nankai District, 300190, China
*Corresponding author’s e-mail: yuanshuangchen@tju.edu.cn

Abstract. Microgrid with multi-energy complementarity is of significance to improve energy utilization efficiency and achieve sustainable development. The combined cooling, heating and power (CCHP) system can output electricity, heat energy and cold energy, and are widely used in microgrid. The popularity of CCHP in microgrid brings great challenges to the evaluation of microgrid. In this paper, a comprehensive evaluation model for microgrid with CCHP is proposed. The model can reflect the characteristics of microgrid with CCHP from five aspects, economy, environmental protection, reliability, energy efficiency and technicality. Then the combined ANP and entropy weight method is proposed to solve the evaluation model. In a numerical test, by comparison with different schemes of microgrid, the proposed evaluation model and method prove to be effective.

1. Introduction
Developing renewable energy technologies is an urgent issue for the shortage of energy resources. Microgrid has been viewed favorably because of its combination of variable energy. The combined cooling, heating and power (CCHP) can integrate various types of energy and improve energy efficiency, so it is widely used in microgrid. Study on how to evaluate microgrid with CCHP scientifically is crucial for the development of microgrid.

Evaluation of microgrid focuses on the evaluation model and method. In [1], some evaluation criteria systems are proposed such as economy, energy efficiency and environment protection. An integrated performance evaluation model of independent microgrid considering impacts of uncertain factors is proposed in [2]. The evaluation method includes subjective weighting evaluation method in [3], and objective weighting evaluation method in [4],[5]. The subjective evaluation method is easy to operate but may not reflect the characteristics of the evaluation system. The objective evaluation method is completely based on the characteristics of data, but cannot reflect the subjective will of evaluators. To overcome this, weighting method of combined subjective and objective are used in the evaluation process. In [6], the combined ANP and entropy weight method is utilized. In [7] the evaluation is implemented by the combined ANP and anti-entropy weight method. The improved AHP-TOPSIS is proposed to evaluate the distribution network in [8].

The multi-dimensional evaluation model for microgrid with CCHP from different aspects has not commonly seen in the above studies. To reflect the microgrid with CCHP comprehensively, this paper first proposes the evaluation model including indicators including economy, environmental protection,
reliability, energy efficiency and technicality considering the characteristics of microgrid with multi-energy complementarity. Then the combined ANP and entropy weight method is used to evaluate the proposed model. This method combines the experience of evaluator and the mathematical features of objective data together. In a numerical test containing 5 schemes, the effectiveness of the proposed model and method are tested.

2. Evaluation model
The structure of the microgrid with multi-energy complementarity includes the wind turbine (WT), photovoltaic (PV), electrical energy storage system (ESS), and combined cooling, heating and power (CCHP). This paper established the evaluation model of microgrid, in which 22 evaluation indicators are proposed from 5 aspects: economy, environmental protection, reliability, efficiency and technicality.

![Figure 1. Structure of microgrid with CCHP](image)

2.1. Economic indicators
Economic evaluation indicators are used to characterize the investment cost and operational benefits of microgrid projects, which reflect the construction value of microgrids, and provide guidance for future investment. In this part, 6 indicators are proposed.

**S11**: The operation benefit $B_{MG}$ is the benefit of supplying energy in a year, including supplying electricity benefit of renewable energy, supplying energy benefit of CCHP and peak load shifting benefit.

$$B_{MG} = c_a(W_{WT} + W_{PV} + W_{CCHP,e}) + c_{ESS}W_{ESS} + c_{heat}W_{CCHP,heat} + c_{cool}W_{CCHP,cool}$$

(1)

Where $c_a$, $c_{ESS}$, $c_{heat}$ and $c_{cool}$ are electricity selling price of microgrid, electricity price difference of peak load shifting benefit, heat energy selling price and cold energy selling price. $W_{WT}$, $W_{PV}$, $W_{CCHP,e}$ are electrical power generation of WT, PV and CCHP. $W_{ESS}$ is the electrical energy of peak load shifting. $W_{CCHP,heat}$ and $W_{CCHP,cool}$ are the heat energy and cold energy of CCHP.

**S12**: The construction cost $C_{cst}$ is the initial investment. The cost includes the investments of WT, PV, CCHP and ESS, which can be expressed as:

$$C_{cst} = C_{WT, cst} + C_{PV, cst} + C_{CCHP, cst} + C_{ESS, cst}.$$  

**S13**: The operation cost $C_{op}$ includes the operation and maintenance cost $C_{om}$ and purchasing energy cost $C_{pe}$ in a year, which can be expressed as:

$$C_{op} = C_{om} + C_{pe}.$$  

**S14**: The net present value ($NPV$) is the total net cash flow subtract construction cost among whole operating life. The bigger value means better economy. $NPV$ can be expressed as:

$$NPV = \sum_{t=1}^{T_{op}} \left( B_{MG}(t) - C_{op}(t) \right) (1+k_d)^{-t} - C_{cst}$$

(2)

Where $k_d$ is the discount rate, $T_{op}$ is the operating year of microgrid. $B_{IES}(t)$ and $C_{op}(t)$ are the operating benefit and cost in the $t_{th}$ year.

**S15**: The internal rate of return (IRR) is the discount rate when total inner benefits equal to the total present value of cost in the operating life and $NPV=0$. Bigger IRR means better economy.
Where $C_{ES}(t)$ is the cost in the $t_{th}$ year.

S16: The dynamic payback time $Pt$ is the period when the present value of accumulated net cash flow is positive. The smaller value means better economy.

$$Pt = T_{pt} - 1 + |NPV_{total}(t-1)|NPV^{-1}(t)$$

Where $NPV(t)$ is the net present value of microgrid in the $t_{th}$ year, and $NPV_{total}(t-1)$ is the present value of accumulated net cash flow in the $(t-1)_{th}$ year.

2.2. Environmental protection indicators

Environmental protection indicators can reflect the influence to the environment. The microgrid has significant advantages compared with the traditional energy supply system in environmental protection as part of the energy supply is provided by renewable energy. 6 indicators are proposed in this part.

S21: The proportion of renewable energy $\eta_{re}$ is the proportion of renewable energy in total load in microgrid, which can be expressed as: $\eta_{re} = (W_{WT} + W_{PV}) (W_e + W_h + W_c)^{-1}$, where $W_e$, $W_h$ and $W_c$ are the total electrical, heat and cold load of microgrid in a whole year.

S22: Pollutants emission $W_{p,em}$ comes from the operating gas-fired generator, internal combustion engines, and the coal fired power generation by the outside power system when microgrid purchases electricity. The pollutants include CO$_2$, SO$_2$, CO and NO$_x$. $W_{p,em} = W_{p,em,CO_2} + W_{p,em,SO_2} + W_{p,em,CO} + W_{p,em,NO_x}$.

S23: Pollutants emission reduction $W_{p,re}$ is reduced by WT and PV, which is equivalent to the emission of pollutants generated by coal-fired power generation in one year. It can be expressed as: $W_{p,re} = \sum_{i=1}^{N_p} \alpha_{cg,i} (W_{WT} + W_{PV})$, where $N_p$ is the type of pollutants, and $\alpha_{cg,i}$ is the emission of pollutants correspondingly generated by coal-fired generator.

S24: The environment benefit $B_{env}$ can be expressed as: $B_{env} = \sum_{i=1}^{N_p} (v_{e,i} + v_{p,i}) \alpha_{cg,i} (W_{WT} + W_{PV})$, where $v_e$ is the environmental value coefficient of pollutant, and $v_p$ is emission penalty coefficient of pollutant.

2.3. Energy efficiency indicators

The energy efficiency indicators for microgrid can reflect the utilization efficiency of various types of energy. It includes 4 indicators.

S31: Primary energy ratio $\eta_{per}$ describes the utilization ability of primary energy in microgrid. Energy produced by different forms need to be converted to energy produced by fired coal per unit. The $\eta_{per}$ can be calculated by $\eta_{per} = (W_{E,Load} + W_{H,Load} + W_{C,Load}) \left( p_{E}W_{E,E} + p_{G}W_{E,G} + p_{W}W_{E,WT} + p_{S}W_{E,PS} \right)^{-1}$, where $W_{E,Load}$, $W_{H,Load}$, $W_{C,Load}$ are the electrical, heat and cold load in one year. $p_{E}$, $p_{G}$, $p_{W}$, $p_{S}$ are conversion coefficients of electricity, natural gas, wind and solar energy. $W_{E,WT}$, $W_{E,PS}$ are the received wind and solar energy by WT and PV.

S32: Energy saving ratio $\eta_{esr}$ is the saved non-renewable energy proportion compared with the traditional energy supply method. $\eta_{esr} = (W_{WT} + W_{PV}) \left( W_{E,Load} + W_{H,Load}COP_{H}^{-1} + COP_{C}^{-1}W_{C,Load} \right)^{-1}$, where $COP_{H}$, $COP_{C}$ are the energy efficiency factors of electric heating and electric refrigeration device.

S33: Energy utilization ratio $\eta_{eur}$ describes the efficiency of energy utilization. Exergy is used to convert different energy to the same energy.
\[ \eta_{eu} = E_o E^{-1}_i = (E_E + E_H + E_C)(E_{Ext,E} + E_{Ext,G} + E_{PV} + E_{WT})^{-1}, \]

where \( E_i, E_o \) are the input exergy and consumed exergy of microgrid.

S34: Energy economic cost \( c_{p, multi} \) is
\[ c_{p, multi} = (c_e E_{Ext,E} + c_g E_{Ext,G} + c_{pv} E_{PV} + c_{wt} E_{WT} + c_z)(E_E + E_H + E_C)^{-1}, \]

where \( c_e, c_g, c_{pv}, c_{wt}, c_z \) are unit costs of input exergy.

2.4. Reliability indicators

The reliability indicator describes the stability of supplying energy. 4 indicators are proposed as follows.

S41: Energy shortage ratio \( \eta_{les} \) is the external energy supply proportion, which is expressed as:
\[ \eta_{les} = \left( p_e W_{E,E} + p_g W_{E,G}\right)(W_{E,Load} + W_{H,Load} + W_{C,Load})^{-1}, \]  
(5)

S42: Average of outage \( T_{fe} \) is the average recovered time after fault. The fault includes power failure, heat failure and cold failure. The indicator can be expressed as:
\[ T_{fe} = \left( \sum_{i=1}^{N_f} T_{f,i} \right) N_f^{-1}, \]  
where \( N_f \) is the average number of energy failure, and \( T_f \) is the time for energy failure.

S43: Outage ratio \( \eta_{le} \) is proportion of total energy failure time in operation time and \( \eta_{le} = \sum_{i=1}^{N_{tf}} T_{f,i} \).

S44: Energy supply reliability benefits ratio \( B_{esr} \) is calculate by
\[ B_{esr} = c_{AL} \sum_{i=1}^{N_{tf,c}} T_{fc,i} \],

are the average economic loss, number and time for energy failure of crucial load.

2.5. Technicality indicators

4 technicality indicators are proposed to describe the performance of microgrid construction.

S51: Equipment utilization ratio \( \eta_{eur} \) is calculated by
\[ \eta_{eur} = \frac{N_t^{-1}}{N_t} T_{eur,i}, \]  
where \( \eta_{eur,i} \) and \( T_{eur,i} \) are the utilization ratio and supply-energy time of equipment.

S52: The equipment operation efficiency \( \eta_{eoe} \) is calculated by
\[ \eta_{eoe} = N_t^{-1} \sum_{i=1}^{N_t} W_{i,i}, \]  
where \( \eta_{eoe,i} \) is the operation efficiency of the \( i \)th equipment, \( W_{i,i} \) and \( W_{o,i} \) are input and output energy of the \( i \)th equipment.

S53: Energy loss \( W_L \) includes transmission loss of electricity, natural gas, heat energy and cold energy \( (W_{E,L}, W_{G,L}, W_{H,L} \) and \( W_{C,L}) \), which can be expressed as:
\[ W_L = W_{E,L} + W_{G,L} + W_{H,L} + W_{C,L}. \]

S54: The energy supply quality is supplied energy quality of electricity, natural gas, heat energy and cold energy, which is addressed as a qualitative indicator in this paper.

3. Evaluation method

The microgrid evaluation model proposed in the last section includes qualitative indicators and quantitative indicators. The subjective evaluation method can give reasonable weights based on expert experience and operate easily, but mathematical characteristics of the evaluation subject may be ignored. The objective evaluation method can reflect the data characteristics of the evaluation subject, but evaluation data must be processed rationally. To ensure that the evaluation result is effective and can reflect the actual situation objectively, the combined ANP-entropy evaluation method for microgrid construction evaluation is proposed to take subjective and objective weights into consideration.
3.1. Normalization
Since the attribute values of the indicators have different dimensions, the data should be normalized first. Suppose the number of evaluation indicators is \( n \) and the number of evaluation subjects is \( m \), \( v_{ij} \) is the attribute value of the \( j \)th indicator for the \( i \)th subject. For the benefit-type indicator, the data normalization formula is
\[
e_{ij} = \frac{(v_{ij} - \min_{j \in [m]} v_{ij})(\max_{j \in [m]} v_{ij} - \min_{j \in [m]} v_{ij})}{\max_{j \in [m]} v_{ij} - \min_{j \in [m]} v_{ij}}.
\]
For the cost-type indicator, the data normalization formula is
\[
e_{ij} = \frac{(\max_{j \in [m]} v_{ij} - v_{ij})(\max_{j \in [m]} v_{ij} - \min_{j \in [m]} v_{ij})}{\max_{j \in [m]} v_{ij} - \min_{j \in [m]} v_{ij}}.
\]
\( v_{ij} \) and \( v_{ij} \) are the maximum and minimum value of index \( j \). The standardized decision matrix \( E = [e_{ij}]_{m \times n} \) is obtained after the standardization.

3.2. Subjective weighting method based on network layer analysis
The analytic network progress (ANP) is used as the subjective weighting method in this paper. The basic principle of the ANP evaluation method is to use the analytic hierarchy process in the control layer to determine the weight of the indicator, and then use Limiting Supermatrix in the network layer to get the weight of the attribute value. The calculate steps of the ANP evaluation method are:

1) Obtain the set form of attribute values and form the ANP structure. For the multi-attribute decision-making (MADA) problem, determine the independence of attribute values by judging the dependency and feedback relationship between them. Then determine the control layer, and analyse the relationship between attribute values and indicators.

2) Construct the ANP supermatrix. The ANP model is scaled by the nine-point method, and the ranking vector is obtained by the eigen-root method. If the consistency test is satisfied, the above-mentioned eigenvector will be the network element ranking vector (weight), and all the network element ranking vectors are combined and constructed as a matrix \( W_j \). By combining all the mutually influencing ranking vectors of the network layer, the supermatrix \( W \) of the control elements can be obtained. Assume \( a_{ij} \) as the weighting factor, then the weighted supermatrix \( W \) can be obtained.

3) Calculate Limiting Supermatrix. Calculate the limit relative ranking vector of each supermatrix:
\[
\lim_{k \to \infty} N^{-1} \sum_{k=1}^{N} \tilde{W}^k.
\]
The limit value is convergent and unique, which means that the row value of the element matrix is the stability weight of each evaluation indicator.

3.3. Objective weighting method based on entropy weight method
Entropy is a measure of the diversity or uniformity of microscopic states in thermodynamics, which describes the confusion degree of heated molecules. The larger entropy value of an indicator provides more information, and the weight is correspondingly larger in evaluation process. Assume there are \( n \) different states, and the probability of each state is \( P_j (j=1 \rightarrow n) \), then the entropy of the system can be expressed as
\[
E = -\sum_{j=1}^{n} P_j \ln P_j, \quad 0 \leq P_j \leq 1, \quad \sum_{j=1}^{n} P_j = 1.
\]
The entropy weight method modifies the weight value of the indicator by describing the degree of difference between the indicator values. The calculation steps are as follows:

1) Calculate the entropy value \( Y_j \) of indicator \( j \) by formula
\[
Y_j = -(\ln n)^{-1} \sum_{j=1}^{n} e_{ij} \ln e_{ij}, \quad \sum_{j=1}^{n} e_{ij} = 1.
\]

2) Calculate the information deviation degree \( D_j \) of the indicator \( j \) by formula
\[
D_j = 1 - Y_j.
\]

3) Calculate the evaluation weight of the indicator \( j \) by formula
\[
w_j = D_j \left( \frac{1}{\sum_{j=1}^{n} D_j} \right)^{-1}.
\]
3.4. Combined ANP-entropy weight calculation

For a certain indicator of the microgrid, assume that the subjective weight vector obtained based on the ANP method is 
\[ w' = \left( w'_1, w'_2, \ldots, w'_n \right) \]
and the objective weight vector obtained by the entropy weight method is 
\[ w^n = \left( w^n_1, w^n_2, \ldots, w^n_n \right) \], and \( \sum_{j=1}^{n} w_j = 1 \). Then, the weight calculation of this indicator can be: 
\[ w_j = \alpha w'_j + (1-\alpha)w^n_j, \quad 0 \leq \alpha \leq 1 \]. Evaluation result could be various with different value of \( \alpha \).

4. Case study

The basic information of a microgrid project is provided as: the electric load, heating load and cooling load are 3.70MW, 2.90MW and 2.40MW respectively, the annual electricity consumption of users-side is about 4,000 MWh, the self-sufficiency rate of renewable energy power supply is not less than 40%, and the operating year is 20 years. Assuming that the electricity purchased from the outside comes from coal-fired power plant, and the purchased electricity price is 0.64¥/(kW∙h). The network loss rate is about 5%. The CCHP units include internal combustion engines, gas turbines and absorption chiller units. The capacities of the three types of units are 600kW, 300kW and 400kW respectively. Five construction schemes of microgrid are as follows:

S1: 1.3 MW CCHP system with an additional 300kW internal combustion engines unit.
S2: Solar-gas complementary system, including 1.3 MW CCHP and 2.4MW PV.
S3: Wind-gas complementary system, including 1.3 MW CCHP and 2.4MW WT.
S4: Wind-solar-gas complementary system I, including 0.3MW WT, 2.0MW PV and 1.3 MW CCHP.
S5: Wind-solar-gas complementary system II, including 1.8MW WT, 0.6MW PV and 1.3 MW CCHP.

4.1. Calculation result of attribute values

Based on the evaluation model proposed in section 2, the attribute values of 22 indicators for five microgrid construction schemes S1-S5 can be calculated by the relevant formulas. Only attribute values of economy indicators are shown in Table 1 because of the limited length.

| economy indicators | S1     | S2     | S3     | S4     | S5     |
|--------------------|--------|--------|--------|--------|--------|
| operation benefit /10^4¥ | 665.2  | 779.8  | 866.4  | 827.2  | 861.4  |
| construction cost /10^4¥ | 1005.0 | 3149.8 | 1412.1 | 2832.3 | 1701.7 |
| operation cost /10^4¥ | 496.6  | 392.4  | 366.3  | 393.0  | 370.7  |
| net present value /10^4¥ | 783.3  | 149.2  | 3532.7 | 1044.6 | 3065.3 |
| IRR /%                | 19.48  | 8.58   | 39.21  | 12.38  | 29.56  |
| Dynamic payback time/year | 8.1    | 19.3   | 3.9    | 12.4   | 5.2    |
4.2. Evaluation result of entropy weight method
The evaluation result of the indicators based on the entropy weight method is shown in Figure 2. From the radar chart, the pros and cons of 5 microgrid construction schemes can be more intuitively obtained in dimensions of economy, environmental protection, energy efficiency, reliability, and technicality.

Only economy indicator is discussed because of the limited length. Evaluation results of five schemes obtained by entropy weight method are: $S_3 > S_5 > S_4 > S_1 > S_2$. WT has advantages in installation cost per unit capacity and annual fixed operation and maintenance costs compared with CCHP units and PV. Hence, the construction cost, operating cost and dynamic payback time of $S_3$ are the lowest, and the operating efficiency, net present value, and internal rate of return are all the highest. In other words, the economy indicator of $S_3$ is the best.

4.3. Evaluation result of ANP method
As shown in Figure 3, the evaluation results obtained by two methods are the same in economy, environmental protection, and reliability indicators, while energy efficiency and technology indicators are not completely consistent. ANP method pays more attention to the comprehensive utilization rate of energy and energy economic cost, which leads to a higher proportion of these two indicators in the evaluation process than the objective evaluation method based on data characteristics.

4.4. Analyzing of combined ANP - entropy weight method
When the combined weight is taken into consideration, the evaluation result may change with the different value of $\alpha$, especially in the evaluation process of energy efficiency and technical dimension. For technical indicators, the ANP evaluation method pays more attention to the energy supply quality and energy loss indicators as more actual operation experience are considered. Evaluation result of $S_2$ with a relatively high proportion of PV will be better than that of $S_3$ with a relatively high proportion of WT with the increase of $\alpha$.

5. Conclusion
Based on the characteristics of the microgrid, this paper proposes an evaluation model from five aspects: economy, environmental protection, reliability, energy efficiency and technology. Based on the expert experience and data characteristic, the combined ANP-entropy weight evaluation method is proposed to provide a more reasonable evaluation result for an operating microgrid. The proposed model can reflect the construction of microgrid comprehensively from multi-dimensional analysis and the result obtained from combined ANP-entropy evaluation method provides guidance for the planning and construction of microgrid project.

References
[1] Zhang, S., Lv, K. (2018) Evaluation method of park-level integrated energy system for microgrid. Power System Technology, 42: 2431-2439.
[2] Zeng, M., Li, N., Ma, M., et al. (2013) An integrated performance evaluation model of independent microgrid. Power System Technology, 37: 1-8.
[3] Wu, M., Zhao, M., Zhao, F., et al. (2018) Evaluation index system of microgrid operation effect and corresponding evaluation method. Power System Technology, 2018, 42: 690-697.
[4] Zong, X., Chang, C. (2016) Analysis and evaluation of operation state characteristics of power grid based on entropy weight method. Proceedings of the CSU-ESPA, 28: 1-5.
[5] Tang, Y., He, G., Liu, K., et al. (2017) Study on method of comprehensive energy efficiency evaluation for distributed energy system. In: IEEE Conference on Energy Internet and Energy System Integration, Beijing, pp. 1-5.
[6] Shi, Z., Guo, L., Su, X., et al. (2019) Evaluation of µPMU based intelligent distribution network by AHP and ANP-improved entropy weight methods. In: Renewable Power Generation Conference, Shanghai, pp. 1-7.
[7] Chen, B., Liao, Q., Liu, D., et al. (2018) Comprehensive evaluation indices and methods for regional integrated energy system. Automation of Electric Power Systems, 42: 174-182.

[8] Xu, B., Ma, J., Chen, Q., et al. (2019) Research on comprehensive evaluation index system and investment strategy of economic development zone distribution network based on improved AHP-TOPSIS method. Power System Protection and Control, 47: 35-44.