Regional Energy Community Planning Considering Wind Power Uncertainty

Long Zhao¹, Yueming Pan¹, Peng Qiu¹, Lv Xuan²*

¹State Grid Liaoning Electric Power Co., Ltd. Jinzhou Power Supply Company, Jinzhou 121000, Liaoning Province, China;
²State Grid Liaoning Electric Power Co., Ltd. Yingkou Power Supply Company, Yingkou 115000, Liaoning Province, China
* Corresponding author’s e-mail: ncon@ahlctl.com

Abstract. Large-scale uncertain wind power grid connection will put forward higher requirements for system planning, and also bring challenges to power quality, power reliability, safe and economic operation of power system. In view of the problem of considering the uncertainty of wind power scenarios in system planning, in this paper, the k-means clustering method is used to cluster and reduce the historical data of wind farms to obtain typical days of wind power output. The regional energy community planning model that considers the uncertainty of wind power and uses the minimum planning cost as the objective function is established. The obtained typical wind power scenarios replace the wind power scenarios of the regional energy community in the planning period for simulation analysis. The results based on the simulation software show that the scenario method can improve the feasibility and effectiveness of planning for wind power factors in the regional energy community, promote the scale development of wind power, reduce the wind abandonment rate and planning costs to maximize the benefits of planning.

1. Introduction

In recent years, the energy structure dominated by traditional fossil energy such as coal and oil has brought significant challenges to the world, such as fossil energy depletion and environmental pollution. In addition, there is a lack collaboration among different energy sectors, which often limits the effects of energy transition within an individual energy sector and can introduce unexpected challenges to other sectors. Coordinated planning and operation of an integrated energy system with multiple energy sources and various energy carriers can realize optimal allocation of resources and improve the efficiency of energy utilization[1]. Regional energy community (REC) is an embodiment of the integrated energy concept at a regional level (urban block, industry, park, etc.). Within the REC, complementary effects among flexibility of multiple stakeholders and energy systems are assured and utilized to achieve optimal energy operation and to effectively address problems of system expansion[2].

At the same time, wind power as one of the most potential clean energy solutions has been developed on a very large scale over the years. However, the volatility and randomness of wind energy increase the uncertainty of system operation, even threaten the safe and stable operation of the power system. In view of consolidating the existing energy system models and studies for the REC, it is necessary to carry out more detailed research and analysis on the planning of the REC while taking into account wind power uncertainty. Existing research mainly adopts stochastic programming method...
or robust optimization method to deal with wind power uncertainty [3], [4] pointed out that stochastic programming based on scenario-based method is the most widely used method at present.

Typical scenario analysis method applied to wind power uncertainty characterization usually assumes that the prediction error of wind power output follows a known distribution characteristics[5-8]. According to the distribution characteristics, Monte Carlo sampling, Latin Hypercube sampling or other methods are used to generate multiple possible error scenarios[9]. And then scenario reduction technology is used to reduce the generated error scenarios in order to achieve a balance between computational efficiency and completeness.

In this paper, we develop the REC planning solution that consider both multi-energy and the uncertainty of wind power. Facing the uncertainty of wind power, k-means algorithm is applied to cluster the uncertain output scenarios of wind power based on historical annual wind data. Based on this, an energy system model-based planning solution is developed in order to achieve the maximum economic and environmental benefits for the REC. The effectiveness of the scenario method and planning model are verified by simulation. The results also indicate how scenario-based uncertain characterization and integrated energy system planning involving electricity and heat contribute can lead to cost-effective energy system green transition.

2. Regional Energy Community Planning of wind power

2.1 Scenario analysis based on K-means

K-means clustering can obtain several kinds of reduced scenario sets with similar characteristics by clustering a large number of initial wind power data. The basic steps of k-means algorithm are described as follows:

1) Randomly take k data from the initial set as the initial clustering centers of k clusters.
2) Calculate the similarity of other sample data to k cluster centers, and divide these data into the clusters with the highest similarity.
3) According to the clustering results, the arithmetic mean of each dimension of all objects in the cluster is taken to update the centers of the selected k clusters.
4) After the data is collected, all the data are re-clustered according to the new clustering center.
5) If stop criteria is reached, go to step 6; otherwise, go to step 3.
6) Output clustering results.

2.2 The regional energy community planning model considering wind power

Wind power scenarios derived by k-means clustering will fit into a relatively generic REC planning model. The objective of the planning is given in (1), which is to minimize the annualized energy system cost under Ns number of wind power scenarios.

\[
\min Z = \sum_{s=1}^{Ns} \sum_{t=1}^{T} \lambda_t [(1 - \gamma \frac{\lambda_t}{\bar{\lambda}_t})C_{inv}(t) + C_{op}(t) + C_{a}(t)]
\]  

(1)

The annualized energy system cost is the sum of annualized capital expense, operation expense and cost of abandoned wind power. The expression for each cost item is given in (2)-(4) respectively, and (5) calculates the present value coefficient \( \lambda_t \) of year t.

\[
C_{inv}(t) = \sum_{g=1}^{Ng} C_g P_g^{max} z_g + \sum_{l=1}^{Nl} C_l P_l^{max} z_l + \sum_{f=1}^{Nf} C_f H_f^{max} z_f + \sum_{c=1}^{Nc} C_c P_c^{max} z_c
\]  

(2)

\[
C_{op}(t) = \sum_{d=1}^{Nd} \sum_{h=1}^{Nh} \left( \sum_{g=1}^{Ng} P_g O_g + \sum_{f=1}^{Nf} H_f O_f + \sum_{c=1}^{Nc} P_c O_c + \sum_{gs}^{Ns} S_{gs} O_{gs} \right)
\]  

(3)
Other variables and parameters given in (1)-(5) include: \( \pi \) is the probability of the s wind power scenario; \( T \) is the total planning period; \( d \) is the number of days per scenario; \( h \) represents the number of time periods in a day; \( N_p, N_N, N_f, N_e, N_g \) represent the number of conventional power units, transmission lines, gas-fired boilers, CHP units and natural gas power units respectively; \( C_p, C_e, C_f, C_e \) respectively represent the per unit capital expense for the above mentioned energy units. The capacity and commitment status each energy unit are modeled as \( P_g^\text{max}, P_f^\text{max}, P_e^\text{max} \) and \( z_g, z_f, z_e \). \( O_p, O_e, O_f, O_g \) represent the unit operating cost. \( C_w \) is the unit wind abandonment cost; \( \Delta P_w \) is the wind abandonment volume; \( \tau \) is the capital discount rate and \( \gamma \) is the capital recovery rate.

The objective are subject to operation constraints (6)-(14), where in (6)-(8) model the commitment status of different units, and \( T_e \) is the maximum number of years for the equipment in operation. (9)-(11) model electricity power flow and the network constraints of the power system, with \( P, Q, V \) denote node active power, reactive power and voltage. (12)-(14) model the energy balance and network constraints of the heat system.

Accordingly, \( W_{LI} \) is the rated heat load and \( Q_e \) is the heat load provided by the heat exchanger. \( G_{ij}^\text{max}, G_{ij}^\text{min} \) are the upper and lower limits of the working fluid flow for pipelines; \( T_i^\text{min}, T_i^\text{max} \) are the upper and lower limits of the heat network node temperature.

3. Case study
The planning algorithm described in section 2 is applied to a case study of the REC, which potentially could have a system setup as given in Figure 1. The region has electricity demand 55TWh/year and heat demand 254.47TWh/year and already has boilers and heat pumps etc., for energy supply. Typical loads curves of the region are given in Figure 2 and Figure 3 respectively.
3.1 Cluster analysis of wind power
A one year hourly-based historical wind power data of a wind farm in a region of northern China is firstly applied to generate scenarios. The results are given in Figure 4, with eight clusters were identified.

The eight types of deterministic scenarios can represent the year-round wind power uncertainty with probability characteristics. The corresponding details of each scenario are given in Table 1 and Figure 5.
Table 1 Scenario characteristics

| Scenario characteristics | Center Of Clustering | Classified Number | Typical Date    | Probability Of Occurrence |
|--------------------------|----------------------|-------------------|-----------------|---------------------------|
| Scenario1                | 0.6372               | 31                | 20160913        | 0.0847                    |
| Scenario2                | 0.145                | 55                | 20161209        | 0.1503                    |
| Scenario3                | 0.8953               | 38                | 20160428        | 0.1038                    |
| Scenario4                | 0.4939               | 55                | 20160215        | 0.1503                    |
| Scenario5                | 0.0491               | 41                | 20160727        | 0.1120                    |
| Scenario6                | 0.3672               | 61                | 20160930        | 0.1667                    |
| Scenario7                | 0.2442               | 44                | 20160126        | 0.1202                    |
| Scenario8                | 0.7474               | 41                | 20160502        | 0.1120                    |

3.2 Comparative planning cases

In order to validate the developed solution, three planning cases are set up as following:

- case1: Without consideration of the wind power uncertainty of wind power. Instead, the historical annual data for hourly wind power output is used. Meanwhile, the heat loads are met by heat pumps and electric boilers only.
- case2: Extend case 1 by using scenario-based wind power. The rest of the REC remains unchanged.
- case3: Extend case 2 with increased CHP and heat storage capacity to the REC planning.

3.3 Simulation results

The simulation results are summarized in Figure6, Figure7 and Figure8, which illustrate comparisons among the three planning cases with respect to cost, CO2 emission, as well as wind power abandon rate.
From the cost perspective, there is a clear trend showing cost reduction when the case number increases, although the difference between case 1 and case 2 is rather small. Although the investment for case 3 is larger than the other two cases, the induced reduction on total planning cost is much larger. This makes case 3 as the best. Similar trend can be observed for the reduction of the primary energy and the corresponding reduction of CO2 emission. When comparing the effectiveness of wind abandonment reduction, except for September and November, the results of case 2 is better than case 1, proving the valuing of using scenario-based uncertainty characterization. Due to the addition of CHP and heat storage which can enhance the flexibility and capacity of power to heat pathway, case 3 resulted in the lowest wind abandon rate among the three cases.

4. Conclusion
This study takes into account the uncertainty of wind power and performs a model-based analysis for characterizing the potential benefits of introducing integrated energy aspects into regional energy community planning exercises. The results of the study show that the scenario method is a theoretical and methodological guidance that can enable uncertain characterization for wind power integration analysis. The integrated energy planning approach for regional energy communities can effectively reduce planning costs for the system and facilitate the development of regional-scale renewable energy. Future research effort will be on using live energy system data or data simulated by commercial simulation tools for model calibration and improvement and for further validation of the proposed solution.

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