Classification of Energy Supply Modes for Regional Integrated Energy Supply Systems

Yan Yang 1, Jiaxin Zhao 1, Yuqing Wang 1, Ming Zeng 1, Shengyu Wu 2 and Shiju Wang 3

1North China Electricity Power University, School of economics and management, Beijing, China
2State Grid Energy Research Institute Co. Ltd, Beijing, China
3State Grid Tianjin Electric Power Company Economic and Technological Research Institute, Tianjin, China

*Corresponding author e-mail: 1173416446@qq.com

Abstract. This paper focuses on how to classify the energy supply modes in regional integrated energy system scientifically and reasonably. On the basis of considering the difference of energy supply in different regions, this paper designs and puts forward the classification index system of energy supply mode of regional integrated energy system considering different aspects such as regional climate characteristics and resource endowment characteristics, establishes the classification model of energy supply mode of regional integrated energy system, and carries out an example analysis of the index system and classification model, and finally summarizes and draws a conclusion. Fourteen provinces to be classified belong to seven typical regional energy supply models.

1. Introduction

Energy is the foundation of human survival and development, and all countries in the world regard it as a national core strategic resource. However, with the sustained development of the economy and society, energy production and demand continue to grow, and the excessive exploitation and utilization of traditional fossil energy has led to environmental pollution, depletion of fossil energy, etc., which poses great challenges to sustainable development and energy efficiency [1]. At present, China has less analysis on the overall regional energy supply, and there is blindness in energy supply planning. In addition, with the increasing proportion of new energy supply in the overall energy system, the rapid application and promotion of related technologies such as distributed energy and energy storage equipment, the optimization of energy supply structure through regional integrated energy supply system planning, in the protection of demand Under the premise, while ensuring the safety and economy of the integrated supply system and diversifying the regional energy supply, it is also conducive to solving the contradiction between energy use and environmental gas emission reduction in the region [2]. In this context, how to absorb diversified energy technologies, strengthen coordination and optimization between energy supply systems, achieve multi-energy supplements and improve the comprehensive utilization efficiency of regional integrated energy supply side is particularly important [3].
This paper focuses on the research of energy supply mode in regional integrated energy supply system, takes the energy Internet model as the guide, studies the typical energy supply mode of regional energy supply system guided by energy Internet mode, establishes the classification index system and the regional classification model of energy supply mode of regional integrated energy supply system, and selects fourteen provinces for example analysis. Our research can be applied to the formulation and evaluation of energy and electric power development planning, and play a leading role in the planning theory and method of integrated energy supply system in the important transition period of energy development [4].

2. Classification of energy supply modes for regional integrated energy supply systems

2.1. Regional integrated energy system energy supply model classification index system

This paper selects relevant indicators from eight dimensions: resource endowment, climatic conditions, economic conditions, local energy supply, and energy import, and builds a classification index system for energy supply modes of regional integrated energy supply systems, as shown in Table 1 [5, 6].

Table 1. Classification index system of regional integrated energy supply system energy supply mode.

| Classification Index System of Energy Supply Patterns for Regional Integrated Energy Supply System | First level index | Two level index | First level index | Two level index |
|---|---|---|---|---|
| Resource endowment | u1 | u11: Coal reserves | u1 | u6: Energy import conditions |
| | | u12: Petroleum reserves/oil and gas reserves | | u61: Import electricity |
| | | u13: Natural gas reserves | | u62: Quantity of imported coal |
| | | u14: Average illumination | | u63: Import oil quantity |
| | | u15: Potential reserves of hydropower resources | | u64: Import gas volume |
| | u2: Climatic conditions | u21: Average temperature | | u51: Trans-regional transmission network capacity |
| | | u22: Precipitation | | u52: Capacity of Cross-regional Oil Pipeline Network |
| | | u23: Mean humidity | | u53: Capacity of Cross-regional Gas Pipeline Network |
| | u3: Economic condition | u31: Total GDP | | u54: External power consumption |
| | | u32: Industrial structure | | u55: Quantity of coal transported outside |
| | | u33: Total population | | u56: Oil delivery quantity |
| | u4: Local Resource Supply Conditions | u41: Wind power installed capacity | | u57: Outgoing air volume |
| | | u42: Installed capacity of coal-fired power generation | | u58: Outgoing transmission network capacity |
| | | u43: Installed capacity of gas power plant | | u61: Capacity of delivery pipeline network |
| | | u44: Installed capacity of hydropower generation | | u62: Capacity of Outgoing Gas Pipeline Network |
| | | u45: Installed capacity of biomass power generation | | u63: Electric load |
| | | u46: Energy storage capacity | | u64: thermal load |
| | | u47: Wind power generation capacity | | u65: Cooling load |
| | | u48: Heat power generation capacity of coal-fired units | | u66: Terminal coal consumption |
| | | u49: Generation capacity of gas turbine | | u67: Terminal oil consumption |
| | | u50: Photovoltaic power generation | | u68: Terminal Natural Gas Consumption |
| | | u51: Hydropower generation capacity | | u69: Replacement Elasticity in Gas-Coal Production |
| | | u52: Biomass power generation | | u70: Gas-oil production substitution elasticity |
| | | u53: Nuclear power generation | | u71: Renewable Energy-Replacement Elasticity of Coal Production |
| | | u54: Coal production | | u72: Replacement Elasticity of Renewable Energy-Gas Production |
| | | u55: Oil and gas production | | / |
| | | u56: Heating capacity | | / |
| | | u57: Cooling capacity | | / |
| | | u58: Capacity of Local Transmission and Distribution Network | | / |
| | | u59: Capacity of Natural Gas Pipeline Network | | / |
| | | u60: Heating Network Capacity | | / |
2.2. Classification Model of Energy Supply Patterns for Regional Integrated Energy Systems

In this paper, when classifying the energy supply modes of regional integrated energy system, the idea is to first analyze the original data of energy supply classification indicators of each region by principal component analysis and extract the principal components and their contribution rates; secondly, cluster analysis is carried out on each region based on the principal components of the extracted index system, and the clustering results are obtained; finally, according to each region, the principal components of the energy supply classification indicators are extracted. The comprehensive scores of the principal components extracted from the region and their principal components are obtained, and are used as input data for subsequent cloud model calculation. Then the cloud model is used to draw cloud distribution maps to display the typical energy supply patterns. Finally, the cloud model is used to judge the standard model of the new region. The general idea of the classification model is shown in Figure 1 [7].

Figure 1. General idea of energy supply pattern classification model for regional integrated energy system.

(1) Fuzzy Cluster Analysis

Fuzzy clustering analysis uses membership function to represent the difference between samples. Hard clustering algorithm can also be expressed as membership function $\mu_{jk} \in \{0,1\}$, and it satisfies that each object belongs to only one class. If the membership degree of this class is 1, the membership degree of other classes is 0. Therefore, the fuzzy clustering algorithm can be seen as an extension of the hard clustering algorithm, which extends $\mu_{jk} \in \{0,1\}$ to $\mu_{jk} \in [0,1]$. The membership function is extended from a certain value to an interval, which can mine more details and reflect the real world more objectively.

Suppose the cluster sample set with n samples is $X={x_1, x_2, \ldots, x_n}$, and each sample $x_k$ has d feature indexes. The sample set was divided into $c(2 \leq c \leq n)$ categories. Let the sum of membership degrees of each cluster be 1, that is $\sum_{j=1}^{n} \mu_{jk} = 1$, $k = 1, 2, \ldots, n$.

Define the fuzzy partition matrix $U$ as shown in Formula (1):

$$U = \begin{bmatrix}
\mu_{11} & \mu_{12} & \cdots & \mu_{1n} \\
\mu_{21} & \mu_{22} & \cdots & \mu_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
\mu_{c1} & \mu_{c2} & \cdots & \mu_{cn}
\end{bmatrix}$$

(1)
Among them, the membership function of j clustering subsets of matrix U's j behavior, while the k of matrix U is listed as the membership value of sample \( x_k \) to c subsets, that is, \( \mu_{jk} \) \( (1 \leq j \leq c, 1 \leq k \leq n) \) represents the membership degree of sample to j subsets.

(2) Hierarchical Clustering Algorithms

Among many clustering algorithms, hierarchical clustering algorithm is the most common. Hierarchical clustering algorithm decomposes the given data hierarchically until a certain condition is satisfied. There are two schemes in detail, one is condensation and the other is splitting. Aggregated hierarchical clustering is a bottom-up strategy. Firstly, each object is treated as a cluster and then merged into larger and larger clusters until all objects are in one cluster or terminate under certain conditions. Instead of clustered hierarchical clustering, split hierarchical clustering uses a top-down strategy, which first places all objects in one cluster and then one by one. Gradually subdivide into smaller and smaller clusters until each object has its own cluster, or to some termination condition.

In this paper, a hierarchical clustering algorithm based on agglomeration is used. For a given data set \( D = (d_1, d_2, \ldots, d_n) \), its algorithm idea is as follows:

1) Each data in D is treated as a clustering center \( c_i = (d_i) \) to form a clustering set \( C = (c_1, c_2, \ldots, c_n) \) of D.

2) Compute the similarity between each cluster pair \( (c_i, c_j) \) in C, \( \text{sim}(c_i, c_j) \),
   \[
   \text{sim}(c_i, c_j) = \frac{\left| c_i \right| \cdot \left| c_j \right|}{\sqrt{\left| c_i \right| \cdot \left| c_j \right|}} \cdot c_j = \sum_{k=1}^{n} c_{ik} c_{jk}, \quad \left| c_i \right| = \sum_{k=1}^{n} c_{ik} c_{ik}, \quad \left| c_j \right| = \sum_{k=1}^{n} c_{jk} c_{jk}
   \]

3) Select two clustering \( (c_i, c_j) \) with the greatest similarity, merge \( \text{max} \text{sim}(c_i, c_j) \) into a new clustering \( c_k = c_i \cup c_j \), and merge the feature vectors of \( c_i \) and \( c_j \) to form a new clustering set \( C = (c_1, c_2, \ldots, c_{n-1}) \) of D.

4) Repeat the above and get the final clustering result according to the number of clusters to be generated.

The above steps are the basic steps of hierarchical clustering algorithm. When classifying the energy supply modes of regional integrated energy system, the similarity between the two regions is calculated on the basis of determining the final standard mode classification number m, and the regions with the highest similarity are merged into m regions until they are merged into m regions, which is the typical energy supply mode of M type.

(3) Cloud Model Computing

Cloud model is a kind of model involving qualitative and quantitative transformation. The application of cloud model in this paper can not only clearly and intuitively show the clustering results of energy supply modes, but also get the cloud distribution map of typical energy supply modes by calculating the cloud characteristics of typical energy supply modes. The specific algorithms of the expected values Ex, En and Hyper-Entropy He of cloud model are as follows:

\[
\text{Ex} = X = \frac{1}{n} \left( x_1 + x_2 + \cdots + x_n \right)
\]

\[
\text{En} = S^2 = \frac{1}{n-1} \sum_{i=2}^{n} (x_i - X)^2
\]

\[
\text{He} = \sqrt{S^2 - \text{En}^2}
\]
3. Example analysis

3.1. Raw data
This paper selects 14 provinces including Gansu, Ningxia, Shaanxi, Shanxi, Hubei, Henan, Beijing, Tianjin, Hebei, Shandong, Jiangsu, Anhui, Zhejiang, and Shanghai as the areas to be classified. According to the 2016 provincial statistical yearbooks, the provinces are collected. The cross-section data corresponding to the classification index can be used as the original data for the analysis of the example.

3.2. Principal Component Analysis
Firstly, the primary data corresponding to the six secondary indicators under the first-level indicator-resource endowment are standardized; secondly, the primary component factors are extracted for the six secondary indicators under the resource endowment, and Table 2 is the primary-level indicator-resource The contribution rate of the three principal components of F1, F2, and F3 extracted from the endowment and each principal component.

From the principal component analysis process, the analytical expressions of F1, F2, and F3 are:

\[ F_1 = 0.127 \times u_{11} + 0.358 \times u_{12} + 0.324 \times u_{13} + 0.123 \times u_{14} + 0.342 \times u_{15} - 0.250 \times u_{16} \]
\[ F_2 = -0.484 \times u_{11} + 0.109 \times u_{12} - 0.108 \times u_{13} + 0.629 \times u_{14} + 0.203 \times u_{15} - 0.262 \times u_{16} \]
\[ F_3 = 0.522 \times u_{11} - 0.364 \times u_{12} + 0.391 \times u_{13} - 0.115 \times u_{14} - 0.239 \times u_{15} + 0.493 \times u_{16} \]

It can be seen from the above analytical expression that the indicators u_{12}, u_{13}, and u_{15} have higher loads on the first principal component, which collectively reflect the oil reserves, natural gas reserves, and average illumination; the index u_{14} has a higher load on the second principal component, reflecting the average wind speed; indicators u_{11} and u_{16} have higher loads on the third principal component, mainly reflecting the coal reserves and the potential reserves of hydropower resources.

| principal component | F_1       | F_2       | F_3       |
|---------------------|-----------|-----------|-----------|
| Contribution rate   | 37.50%    | 21.83%    | 19.11%    |

The explanatory degree of the three principal components of F1, F2 and F3 to the six secondary indicators under the resource endowment of the first-level indicators (i.e. the sum of the contribution rates of each principal component) reached 78.44%. Therefore, it shows that the three principal components extracted can well represent the secondary indicators of resource endowment. Similarly, the remaining eight first-level indicators are treated similarly according to the above steps, and the corresponding principal component results are obtained.

3.3. Cluster Analysis
Based on the obtained principal components, cluster analysis was carried out on 14 provinces. The clustering results are shown in Figure 2. It can be seen from the graph that when the tree diagram of Ward connection is selected and the distance is adjusted to about 4, the energy supply modes can be classified into seven categories.
3.4. **Cloud Model Computing**

Firstly, the principal component analysis is continued, and then the comprehensive scores of the principal components of each province are obtained, which are used as input data for cloud model calculation. Secondly, the expected values $E_x$, $E_n$ and $H_e$ of typical energy supply modes are calculated, and the cloud distribution maps of typical energy supply modes are drawn, as shown in Figure 3.

![Figure 3. Cloud distribution of energy supply patterns for regional integrated energy systems](image)

3.5. **Example conclusion analysis**

Based on the above research, this paper divides the energy supply modes of integrated energy supply system in 14 provinces into seven categories, and summarizes the different types of energy supply modes.

1. **Category 1: Gansu, Ningxia—Renewable Energy Base and Large-scale Electric Power Delivery Model**

   Renewable energy accounts for a high proportion in the energy supply structure of Gansu and Ningxia, while coal and petroleum are the main sources of fossil energy supply. Because of the relatively low level of regional economic development, there is a large amount of energy available for external transfer or export, which is the main power transmission area. In terms of energy production substitution, Gansu's gas-coal, gas-oil, renewable-gas and Ningxia's renewable-coal, renewable-oil production substitution elasticity are all negative, and the absolute value is greater than 1, indicating that the region has great potential for clean substitution and electric energy substitution.

2. **Category 2: Shaanxi—Primary Energy Base and Large-scale Energy Delivery Model**

   The coal and other resources in Shaanxi are highly enriched, and the amount of fossil energy exploitation is huge. Shaanxi's power supply structure is mainly thermal power, supplemented by renewable energy for energy supply. Due to the restriction of its economic development level, a large number of primary energies, mainly fossil energy, can be sent out, which is the main energy delivery area. In terms of energy production substitution, the substitution elasticity of gas-coal and renewable-
coal in Shaanxi is between 0 and 1, which indicates that clean substitution and energy substitution effect are strong in Shaanxi, but the substitution elasticity is weak compared with one kind of region.

(3) Category 3: Shandong, Jiangsu - Energy Supply Mode Combining Local Supply with Import

Shandong and Jiangsu rely on imports for fossil energy, which is a typical region where local supply and imported energy are combined. Shandong has a large demand for fossil energy. In 2016, the net primary energy input was 248.653 million tons of standard coal, ranking first in the country, while Jiangsu power grid is the largest provincial receiving power grid in China. In energy production substitution, the production substitution elasticity of renewable-coal and renewable-oil in Shandong Province is negative, and the absolute value is greater than 1, which indicates that the substitution effect of electric energy is very strong; the substitution elasticity of gas-coal, gas-oil and renewable-coal in Jiangsu Province is between 0 and 1, which reflects that their clean substitution effect and energy substitution effect are the same as Shaanxi Province in the second region.

(4) Category 4: Energy supply modes coexisting with local energy production, import and export in Henan, Hebei, Shanxi and Anhui provinces

Due to the diversification of energy consumption structure, the energy supply structure of Henan, Hebei, Shanxi and Anhui is a mode of energy supply in which local energy production coexists with import and export. Shanxi is a coal-rich area, ranking in the forefront of the country. But its petroleum and natural gas resources are barren, and basically need to be imported; Henan is a major province of electricity consumption, with imported electricity ranking the first in the country in 2016; Hebei is rich in petroleum resources, with annual output accounting for 5% of the country; coal and petroleum and other fossil energy are used for both local consumption and outward transmission; Anhui's annual power transmission accounts for 15.49% of the country; coal has both local consumption and outward transmission, while oil and natural gas are the main ones. Depend on imports. In terms of energy production substitution, the absolute values of renewable-coal and gas in Shanxi Province, gas-coal, renewable-coal, gas and oil in Henan Province, gas-coal, oil, coal, gas, oil in Hebei Province and renewable-coal, gas, oil in Anhui Province are all between 0 and 1, indicating that clean substitution and energy substitution effect are stronger in this region.

(5) Category 5: Energy supply mode combining Zhejiang-local power production with energy import

Zhejiang Province is short of fossil energy resources. Its main power source structure is thermal power, supplemented by renewable energy resources such as wind power. The energy supply characteristic of this kind of area is that most primary energy is imported. In 2016, coal, crude oil and natural gas as the main primary energy sources accounted for 10% of the country's total. The trans-regional transmission network has a capacity of 53 million kilowatt, of which 16 million kilowatts is transferred to 67.553 billion kilowatt-hours, which is the national energy receiving area.

(6) Category 6: Hubei-Hydropower Base and Large-scale Electric Power Delivery Model

Hubei Province is the only province in the 14 selected provinces with hydropower as the main energy source. Its energy supply mode is mainly hydropower, followed by thermal power. Because of the limited energy consumption in this kind of region, there is still a lot of room for external transfer or export while satisfying its own energy consumption. In addition, the construction of energy transmission channels and other supporting facilities in Hubei Province is relatively perfect. As of the end of 2016, the capacity and quantity of cross-regional transmission network rank the first in the country, and it is the national power transmission terminal area. In energy production substitution, the absolute value of substitution elasticity of renewable coal and renewable oil production is greater than 1, which reflects the strong substitution effect of electric energy.

(7) Category 7: Beijing, Tianjin, Shanghai - Energy Supply Model with Import as the Main Part

Beijing, Tianjin, Shanghai and other areas are the areas with the greatest development intensity, but also the areas with significantly enhanced resource and environmental constraints. Its energy supply structure shows that almost all kinds of energy needed are in a gap state, and most of them are transferred from outside the region, which is the national energy receiving area. In terms of energy production substitution, the absolute values of energy production substitution elasticity of Beijing's gas-coal, renewable-coal, gas and Shanghai's gas-oil, renewable-gas and oil are between 0 and 1, reflecting their
strong clean substitution and energy substitution, which are at the same level as those of the second and fourth types of regions.

4. Conclusion
Considering the difference of energy supply side in different regional integrated energy systems, this paper classifies the typical modes of energy supply and analyses the characteristics of regional energy supply under different modes. Firstly, this paper designs and puts forward a classification index system of energy supply modes of regional integrated energy system considering eight aspects such as regional climate and resource endowment characteristics, establishes a classification model of energy supply modes of regional integrated energy system, and makes an example analysis of the index system and classification model. Finally, seven typical energy supply modes are summarized. The research results of this paper are helpful to build an economical and efficient integrated energy supply system and promote the large-scale utilization of renewable energy. In the future research, we will continue to study the energy use mode of regional energy system, and integrate the energy supply and energy use mode to study the regional integrated energy supply system.

Acknowledgments
This paper is supported by Science and Technology Project of State Grid Corporation of China (Research on regional comprehensive energy supply system model and planning technology).

References
[1] Wei XU. Research on Integrated Energy Access to Grid Control Technology System[A]. Science and Engineering Research Center. Proceedings of 2018 International Conference on Communication, Network and Artificial Intelligence (CNAI 2018)[C]. Science and Engineering Research Center: Science and Engineering Research Center, 2018:4.
[2] Crown. Benefit analysis and Optimization Study of power generation side and power consumption side participating in power substitution[D]. North China Electric Power University (Beijing), 2017.
[3] Cheng Haozhong, Hu Wu, Wang Li, Liu Yuquan, Yu Qi. Review of Regional Integrated Energy System Planning[J]. Power System Automation, 2019, 43 (07): 2-13.
[4] He-li CHU. Application and Research of Interactive Display System for Regional Integrated Energy System[A]. Science and Engineering Research Center. Proceedings of 2018 International Conference on Computer, Electronic Information and Communications (CEIC 2018) [C]. Science and Engineering Research Center: Science and Engineering Research Center, 2018:6.
[5] Chen Baisen, Liao Qingfen, Liu Didun, Wang Wenyi, Wang Zhiyi, Chen Siyuan. Comprehensive evaluation index and method of regional integrated energy system[J]. Power system automation, 2018, 42 (04): 174-182.
[6] Dong Fugui, Zhang Ye, Shangmeimei. Study on multi-index comprehensive evaluation of distributed energy system[J]. Journal of Electrical Engineering of China, 2016, 36 (12): 3214-3223.
[7] Wen Zhengying, Li Yundi. A large data mining algorithm based on fuzzy hierarchical clustering analysis[J]. Journal of Henan University of Engineering (Natural Science Edition), 2018, 30 (03): 70-74+80.