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Research on the generation mechanism and characteristics of an Energy Internet backbone network

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The Energy Internet adopts the mechanism of “regional coordination and hierarchical control” to realize the clean power compatibility and reliability in power operation. In the network topology, the traditional tree network is transformed to the hierarchical partition network. First, this paper analyzes the topological features of “hierarchical control, intra-layer partition, interregional interconnection, and regional autonomy” of the Energy Internet. On this basis, the hierarchical ring network autonomy (HRNA) topological generation and evolution mechanism of the Energy Internet is proposed, and the different levels of a Beijing power grid framework are taken as an example to expand and evolve to the Energy Internet. Based on the comparison and analysis of the network characteristics constructed in this paper with relevant literature studies, this mechanism generates a network that is close to the Internet in terms of average degree, network diameter, and aggregation coefficient. However, there is no centrality node with a higher degree of nodes in the Internet topology, which better reflects the equivalence concept of the Energy Internet.

KEYWORDS

energy internet, topological structure, evolutionary mechanism, network characteristics, backbone network

1 Introduction

The Energy Internet is regarded as the future development direction to solve the problems of clean energy compatibility, deep and efficient control, and safe and stable operation of a power system [1–3]. The structural characteristics of “regional autonomy and hierarchical regulation” of the Energy Internet have also been recognized by more and more experts and scholars [4, 5]. Considering the continuity and economy of power system construction, the construction of the Energy Internet does not completely remove the existing power grid but relies on further improvement and adjustment based on the existing power grid structure.

Scholars have studied and expounded the concept, architecture, key technologies, and management schemes of the Energy Internet and constructed its concept and architecture from several levels such as family energy LAN, urban Energy Internet, regional Energy Internet, and global Energy Internet. Home energy LAN is an energy management network

at the level of family buildings, including renewable energy power generation equipment, distributed controllable power generation equipment, energy storage system, and various intelligent loads [6]. The urban Energy Internet emphasizes future energy supply and consumption operation patterns and energy management models [7]. The regional Energy Internet focuses on the coupling of network systems such as power networks, electrical transport networks, natural gas networks, and information networks [8]. The global Energy Internet builds a ubiquitous and strong energy network with the UHV power grid as the backbone to promote clean substitution and electric energy substitution [9].

Since the concept of the Energy Internet was put forward, countries worldwide have successively conducted ELAN-level experimental projects. In 2008, Germany selected six pilot regions based on the smart grid for a 4-year “E-Energy” technology innovation promotion plan [10]. “Vision of future energy networks” (VoFEN), a research program executed by the Swiss Federal Institute of Technology, proposes a definition of “energy hub networking” [11, 12]. The National Science Foundation of the US proposed the construction of a future renewable electric energy delivery and management (FREEDM) network [13–15]. In 2011, “Digital Grid Alliance” in Japan advocated the “Digital Grid” and proposed to use “power routers” [16, 17] to coordinate and dispatch power in a certain area. The National Energy Administration and energy companies in China have paid great attention to the development process of the Energy Internet and have initialized multiple experimental projects at microgrid [18], ELAN [19], and urban Energy Internet [20] levels.

In summary, as the evolution direction of the power system in the future, the Energy Internet has been generally recognized. The research on the Energy Internet in various countries is developing from concept proposals and architecture design to plot the implementation stage. At present, the research on the Energy Internet is in the stage of “gradually clarifying the concept, generally agreeing on the framework, and conducting research on key technologies point by point.” The macro topology of “Hierarchical Regulation and Regional Autonomy” of the Energy Internet has been generally agreed. At present, the research results of the network networking mode and network characteristics are mainly “HUHM” and “Complex Hybrid Network.” However, there are some defects, such as the mismatch between the internal structure and energy distribution of the network and the deviation of evolution direction. Therefore, the typical research results in the current literature are compared, and the commonness of advanced grid structures at home and abroad is analyzed in order to provide a research basis for the construction of a macro topology model of the Energy Internet. It is urgent to study the evolution mechanism and network characteristics of the Energy Internet based on the current power system structure.

2 Literature review

2.1 Evolution mechanism and topology of a power network

How to topologicalize a real power system into a simulation network or generate a complex network similar to the characteristics

of a power network is the starting point of studying the structure and characteristics of a power system network. At present, relevant research is mainly carried out from the perspectives of the direct topology of a power network, evolution generation based on a complex network, and network reconfiguration considering physical characteristics.

① *Direct topology of the power system.* Taking the main equipment of the power system as the node and the physical adjacent or influence relationship between the equipment as the connection edge is a common way to solve the topology of a small power grid. Some studies directly topologicalize IEEE39, IEEE118, and IEEE300 standard networks and conduct simulation analysis based on the obtained networks [21, 22]. Some scholars directly topologicalize the real local power grid to improve the imitative effect of simulation research. For example, [23] directly topologicalized Iran’s 400-kV and 230-kV levels of the power grid structure when studying grid vulnerability. [24] analyzed the centrality of important nodes in the real power grid structure of Guangdong Province in China. ② *Evolutionary generation based on the complex network.* This method refers to the generation mechanism of complex networks to gradually evolve into a composite grid with similar characteristics to the real grid and studies the properties of a composite grid with different node sizes. The neighbor set information based on preferential attachment (*NSIPA*) in [25] evolves into the western power grid of the United States, the European power grid, and the Australian power grid. [26] simulated the German, Spanish, and French power grids that are consistent with the actual power grid parameters. [27] chose the network imitating method based on learning (*NIMBLE*) to generate the interconnected power grid in the western United States. ③ *Network reconstruction considering physical characteristics.* Some research studies are not satisfied with studying grid performance only from the network structure level and introduce physical characteristic parameters into nodes and edges to generate a weighted graph and directed graph, so that the network can represent the operation mechanism. Related typical studies mainly include the identification of vulnerable nodes by the weighted edge of electricity reactance [28], the study of network vulnerability by weighting power to nodes and edges [29], and the establishment of a weighted network based on power flow to study cascading failure [30].

2.2 Research on power grid characteristics based on the complex network

Power system topology analysis and complex network characteristics have always been the focus of grid vulnerability and cascading fault research. From the end of the 1990s, the study of the network structure of large complex systems [31–33] emerged, and it was soon applied in biology, sociology, transportation, and computer Internet industries, including electricity. Research on complex networks in the power system began in 1998 in the United States Cornell University marked by Watts and Strugatz, who found that the US power grid was a small-world (SW) network [34]. At present, the research on complex networks in the power system analyzes vulnerability and elasticity from small-world and scale-free properties, community structure, and centrality.

① Small-world and scale-free feature analysis. This kind of research studies the possibility and key path of cascading failure of a power grid by analyzing the small-world property and power-law characteristics of degree distribution of a real power grid. Many actual power grids have been confirmed to have small-world characteristics, for example, the Northern China Power Grid, the North China Power Grid, the Western United States Power Grid, and the Brazilian Power Grid [35–38]. Some scholars have pointed out that some power grid structures have certain scale-free characteristics [31, 39].

② Research on the community structure and centrality. Some studies identify key nodes and links by detecting community structures and centrality nodes in power networks. [40, 41] identified the key nodes of each IEEE standard network and several typical national grids from the aspects of network centrality and electrical centrality, and [24] proposed seven power network centrality metrics. For the grid community structure, [42] proposed the Newman algorithm to detect Italian grid community institutions and network partition, and [43] constructed an intergenerational genetic algorithm GGA + to detect European and North American grid community structures.

③ Network vulnerability and elasticity analysis. The research on the reliability of a power system from the network level is the focus of power network research, and the research hotspots are evolving from robustness and vulnerability to elasticity. Representative studies mainly include the overall robustness analysis of the network [43–45], the vulnerability identification of key nodes and links [46–52], and the dynamic reconfiguration of the elastic grid [53].

2.3 Research on the power network structure for Energy Internet

The Energy Internet, which has the characteristics of deep integration of power information, coordination in “source-grid-load-storage,” and stratified regional autonomy, is the main direction of future power network evolution. Future-oriented research on the power network structure is conducive to the orderly development of a power network. At present, the research of the Energy Internet topological network is mainly carried out from two aspects, interdependent binary network structure and macroscopic unified topology structure.

① Interdependent binary network structure. The research of the interdependent complex network mainly focuses on the characteristics of physical information fusion of the Energy Internet and studies the coupling mechanism and network performance based on the analysis of the power network and information network structure. The concept of an interdependent network and its vulnerability analysis framework are proposed by [54], which provides a theoretical basis for analyzing the interaction between coupling systems. In [55], the interdependence strategy of the power node and information node is elaborated, and the vulnerability point and network edge optimization strategy under different dependency strategies are analyzed. [56] studied the similarity of the topological structure between a power network and information network and proposed a structural stability enhancement strategy based on the vulnerability characteristics of low-degree nodes in a power information fusion system. Regarding

the node correspondence scheme of the power information interdependence network, there are many structures such as one-to-one [54], one-to-many [57], many-to-many [58], partial dependence [59], multiple dependence [60], and heterogeneous correspondence [61].

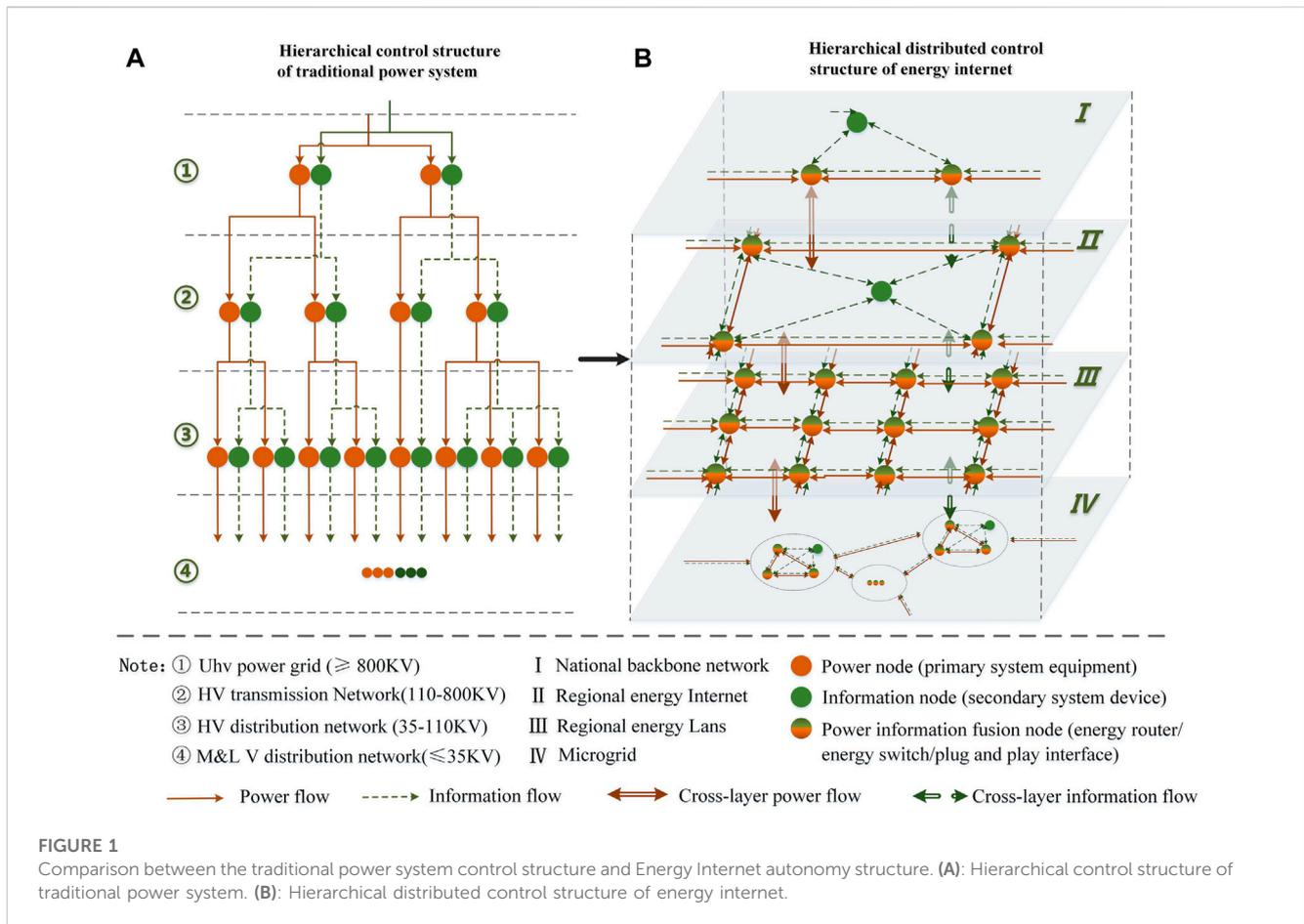
② Research on macroscopic unified topological features. In view of the characteristics of “hierarchical control and regional autonomy” of the Energy Internet, some scholars have made exploratory research from the direction of the macro topology of the Energy Internet. On the basis of establishing the backbone network, [62] layered an interconnection of micro-network nodes with different probabilities and constructed a macroscopic unified topology of the Energy Internet. [63] studied the evolution path of the Energy Internet topological nodes and proposed that the Energy Internet has chaotic typing characteristics in the structure. [64] introduced the system network analysis model based on the grid hierarchy and topology structure and put forward the idea of topology analysis of a large power grid under the trend of the Energy Internet based on graph theory. In the study of cascading faults of the power information physical fusion system in the literature [65], the generation mechanism of topological structure evolution of power CPS is constructed based on the seepage theory. [66] constructed an improved biogeography-based optimization (BBO) algorithm to evolve the IEEE-39 and IEEE-118 networks into a hierarchical and partitioned Energy Internet structure.

The above comprehensive analysis of the research on the complex network of the power system and the topology structure of the Energy Internet shows that ① the research studies on the evolution law and characteristics of power grid from the perspective of topological structure analysis and complex network generation have gained a general consensus among scholars and ② topology research of the complex power system under the trend of Energy Internet evolution is still in the exploratory stage. Therefore, starting from the current power grid architecture and considering the characteristics of the Energy Internet, this paper proposes the layered and zoned topology evolution mechanism of the Energy Internet backbone network based on the existing power grid structure and studies the characteristic parameters of the network by taking the Beijing power grid as an example.

3 Characteristics of the hierarchical partitioning structure of the Energy Internet

The realization of energy utilization efficiency optimization and power quality improvement of the Energy Internet relies on its hierarchical distributed control architecture and operation mechanism of “regional autonomy and global coordination” [67]. The hierarchical control of the traditional power system and the hierarchical distributed structure of the Energy Internet are shown in Figure 1.

The traditional power grid controls the power equipment from top to bottom. Hierarchical management is realized according to the voltage level in different geographical locations, and the power system control is realized through the dependence between the physical and information functions of the equipment. In the Energy Internet, the layering of the power grid is to meet



different functional requirements and is no longer limited by the geographical location. The power equipment has realized the information physical fusion, and the same functions are in the same level of management.

3.1 Characteristics of the regional autonomous structure of the Energy Internet

Compared with the top-down tree control structure of the traditional power system, the Energy Internet realizes decentralized and centralized control through a “regional autonomy” mechanism.

On one hand, the Energy Internet requires the two-way flow of information and energy within and between layers. It is difficult to respond to communication delays in a timely manner using the traditional centralized control model, and the use of the traditional centralized control model to process massive, real-time, and nonlinear data requires powerful computing power and high-speed information channels. The “regional autonomy” control mode of distributing the control center in the local area network at all levels is in line with the development direction of information technology such as distributed computing.

On the other hand, through demand-side management, the realization of a high penetration rate of renewable energy generation, optimal utilization of regional energy, and plug-and-play

of distributed equipment are the development direction of intelligent distribution grids. In this context, the demand side of the power system is more random in the operation state, and even the change of topology, regional intelligent regulation with short channels, and fast response provide an effective solution. In this regard, the realization of the interconnection of regional grids of the same level and the multi-channel response of control centers at different levels is the physical basis for the implementation of a hierarchical distributed control of the Energy Internet.

3.2 Characteristics of the hierarchical regulation structure of the Energy Internet

Compared with the regional distributed autonomous model, the hierarchical control architecture is widely studied and applied in the power system, different from the traditional hierarchical model of the power system based on geography and grid hierarchy. The Energy Internet also emphasizes the layering of functional requirements.

The traditional hierarchical mode based on geographical planning and voltage level is conducive to the isolation of local fault risk and the upgrading of the power grid. However, in the hierarchical distributed control mode, the inefficiency is caused by the delay of the communication channel. In view of the layering of the Energy Internet, scholars pay more attention to layering from the control function, including the energy router layer, the energy switch

TABLE 1 Comparative analysis of common characteristics of international advanced power grid structures.

Common characteristic	Primary coverage	Singapore power grid	Paris grid
“Dumbbell” structure	High degree of interconnection between high-voltage and low-voltage sides, good robustness, and relatively weak medium-voltage side grid structure	High-voltage side mesh interconnection, medium-voltage side “plum blossom” connection, and low-voltage side ring network connection	High-voltage ring network backbone network. Low-voltage “hand in hand” to ensure N-2, medium-voltage relatively weak radiation
Strong scalability	With the increase in regional load, it has good flexibility and scalability	Using a “petal” tangent and easy to expand the standardization of grid construction	When the load increases, a substation can be added between the two nodes of the circular partition structure to divide the partition into two
Full redundancy and high reliability	Structurally ensures the reliability of the high-voltage and low-voltage sides and provides certain backup and redundancy for weak links in the medium-voltage side	The “plum blossom” network structure can achieve no power outage in a single-line accident system but instantaneous power outage in a bus accident. Each petal-shaped network introduces a third power point with a capacity of less than 50% of the total capacity, ensuring the healthy operation level of the network	The “hand-in-hand” distribution network layout ensures hot standby for low-voltage faults, and for high-voltage or substation faults, this medium-voltage structure has the ability to provide N-2
Combined with urban characteristics	Combining the grid structure with local urban zoning and characteristics	Singapore has a balanced zoning, uniform load, and flat terrain	The Paris urban zoning is distributed in a circular radial pattern

layer, the energy interface layer, and other layering methods. Through hierarchical control, the energy efficiency, energy supply quality improvement, and energy balance optimization between each layer of the network are realized.

It can be seen from the above that relying on the physical architecture of the existing power system, on the basis of the existing hierarchical mode, according to the functional requirements of the Energy Internet, the connectivity and intelligent planning and transformation of the power network through energy routers, energy switches, and plug-and-play interfaces are the scientific models for the development of the physical architecture of the power system.

4 Energy Internet backbone network generation mechanism

In this section, according to the characteristics of the hierarchical and partitioned structure of the Energy Internet in the previous section, the layered ring network architecture of the Energy Internet is proposed, and an evolution model is constructed.

4.1 Energy Internet HRNA topological architecture model

Compared with the traditional tree-shaped power supply network, the backbone network under the Energy Internet has certain differences in function and architecture. In terms of function, the backbone network of the Energy Internet is mainly responsible for the access to the trans-regional UHV transmission network, regulation and coordination of local large-scale power generation bases and energy storage equipment, and interaction between different layers of the regional Energy Internet. In terms of architecture, in order to ensure the reliability of power supply and the interaction and coordination between energy routers, the backbone network will develop in the direction of a ring-like

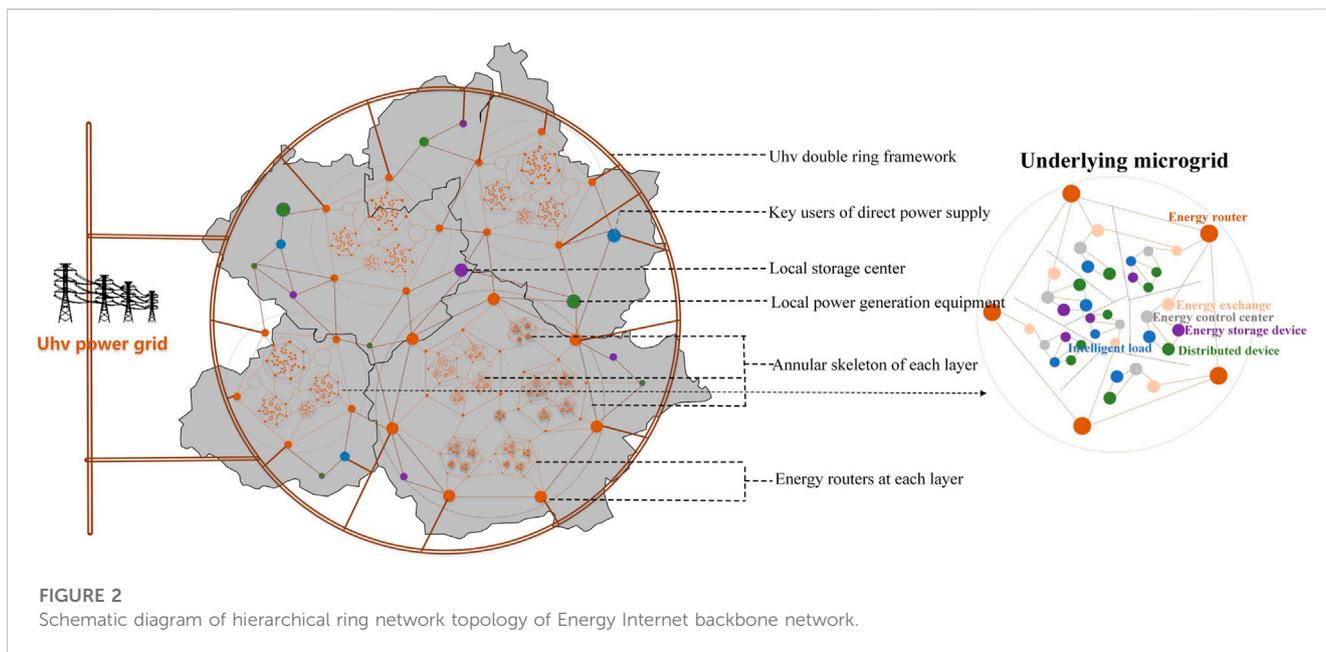
network structure with high connectivity and sufficient routing on the basis of a vertical tree.

Analyzing the internationally reliable power grid structures (Singapore and Paris) shows that they all have characteristics such as a “dumbbell” structure, good scalability, high reliability, and sufficient redundancy. Specific designs are made based on the administrative and load distribution characteristics of the region. The comparative analysis of the structural characteristics of international advanced power grid grids is shown in Table 1.

Improving power supply reliability while maximizing compatibility with renewable energy access is the main goal of Energy Internet construction. The internationally reliable power grid architecture provides a topology evolution approach for Energy Internet construction. At the same time, an example of topology evolution using the Beijing power grid was presented in Article 5.2 and compared with the Central China 500-kV power grid [57] Energy Internet generated by the HUHM model [64], Internet Network, and US Grid structures.

Considering the reality of the gridded management of the power system and the construction foundation of the Chinese power grid ring network, this paper proposes a layered ring-like network autonomous topology architecture model for the Energy Internet of “hierarchical autonomy, intra-layer partitioning, intra-regional ring formation, and inter-ring interconnection” (*Hierarchical Ring Network Autonomy, HRNA*), as shown in Figure 2.

Figure 2 considers the continuity and economy of Energy Internet architecture construction. Referring to the “dumbbell” structure of the foreign advanced power grid, this paper constructs the macro topology of the Energy Internet, and the national backbone node adopts the double-ring radial connection structure with good structural connectivity. The regional energy routing node adopts a hierarchical ring network structure of “intra-layer partitioning, intra-zone ringing, and inter-ring interconnection.” It ensures structural reliability and scalability flexibility while maximizing compatibility with existing network structures. The underlying micro-grid adopts the network interconnection with sufficient interconnection and ensures the



mutual support of the underlying autonomous units through the structure. Different autonomous units at the same level are connected through electronic devices such as soft switches, and it realizes power transmission or bidirectional power control between different ring networks.

The dual-loop network, backbone node of the country in the Energy Internet, is mainly responsible for the access and scheduling of the trans-regional UHV transmission network. The regional hierarchical ring network mainly coordinates energy routers at all levels, local large-scale power generation bases, and energy storage equipment. The fully interconnected underlying micro-grid ensures the full interaction and efficient coordination of autonomous units through a strong architecture.

4.2 Parameters of the Energy Internet HRNA topology generation mechanism

On the basis of the abovementioned hierarchical, partitioned, and gridded power grid, relevant parameters are set, and the backbone network structure of the Energy Internet is constructed.

The relevant parameters of each level and partition are set as follows:

The partition level of the research area in the grid division process has L_{total} levels;

The number of partitions of the layer i in the partitioning process is P_i ;

The number of nodes in the layer i is N_i ;

The number of nodes in partition j of layer i is PN_{ij} .

In the process of generating the backbone network structure of the Energy Internet, the connectivity and average degree of the network are directly related to the reliability requirements of the nodes, and backup requirements vary with the level of the power supply area. In this paper, considering the complexity of power supply in the Energy Internet environment, the current regional grid planning standards for different levels of power

distribution are appropriately improved, and energy storage centers are added at important nodes for regulation and backup.

4.3 Evolution mechanism of HRNA backbone network generation in the Energy Internet

On the basis of the above research, the Energy Internet backbone network is networked through the relevant knowledge of graph theory, and the specific steps are as follows.

STEP 1: Generating the UHV double-ring skeleton.

UHV transmission line landing nodes in the outer ring and the inner ring are planned, which radiate from the outer ring to the inner ring. The number of nodes in the outer link is N_{outer} , the number of nodes in the inner link is N_{inner} , and in principle, $N_{outer} \geq N_{inner}$. The number of inner nodes N_{inner} is set equal to the number of partitions in the lower level = 2, which is $P_2 = N_{inner}$. The undirected edge between nodes is $e(n_i, n_j) = 1$. The number of edges is greater than $3(N_{outer} + N_{inner})/2$.

All edges meet the following criteria.

① when $n_i, n_j \in N_{outer}$, $\sum e(n_i, n_j) = N_{outer}$ and $Count(n_i) = Count(n_j) = 2N_{outer}$;

② when $n_i, n_j \in N_{inner}$, $\sum e(n_i, n_j) = N_{inner}$ and $Count(n_i) = Count(n_j) = 2N_{inner}$;

③ $Count(n_i) \geq 3$ and $Count(n_j) \geq 3$.

STEP 2: Connecting each layer and each partition into a ring.

According to the principle of “intra-layer partitioning and intra-regional ringing,” the nodes of each layer and each district are connected into a ring. According to the top-down partitioning process, the number of l -layer partitions is equal to the total number of $l-1$ -layer nodes, which is $P_l = N_{l-1}$. Then, all node sets N_{lp} of the p partitions of the l layer are connected into p rings with PN_{lp} strip edges.

The following conditions need to be met:

$$\begin{cases} \sum e(n_{ij}, n_{mn}) = PN_{lp} \\ \text{Count}(n_{ij}) = \text{Count}(n_{mn}) = 2PN_{lp} \\ n_{ij} \in N_{lp}, n_{mn} \in N_{lp} \end{cases} \quad (1)$$

STEP 3: Interconnection of backbone nodes.

According to the power supply level of the node area, the networking mode is selected to connect the nodes in each ring with the upper backbone node or other nodes in the same layer.

For any node n_{ij} in the l -layer and p -partition in node set N_{lp} , which has a power supply level of a_{ij} in the region, it has

① If $a_{ij} = A^+$, the edges $e(n_{ij}, n_{l-1,p})$, $e(n_{ij}, n_{l-1,*})$, and $e(n_{ij}, n_{l,\#})$ are generated. Therefore,

$$\begin{aligned} n_{l-1,*} &= \text{random}\{N_{l-1}/n_{l-1,p} \notin N_{l-1}\}, \\ n_{l,\#} &= \text{random}\{N_l/n_{l,p} \notin N_l\}. \end{aligned}$$

② If $a_{ij} = A$, the edges $e(n_{ij}, n_{l-1,p})$, $e(n_{ij}, n_{**})$, and $e(n_{ij}, n_{\#\#})$ are generated. Therefore,

$$n_{**}, n_{\#\#} = \text{random}\{N_{l-1} \ N_l/n_{l-1,p} \ N_{l-1}, n_{l,p} \ N_l\}.$$

③ If $a_{ij} = B$, the edges $e(n_{ij}, n_{l-1,p})$ and $e(n_{ij}, n_{**})$ are generated. Therefore,

$$n_{**} = \text{random}\{N_{l-1} \ N_l/n_{l-1,p} \ N_{l-1}, n_{l,p} \ N_l\}.$$

④ If $a_{ij} = C$, the edge $e(n_{ij}, n_{l-1,p})$ is generated.

⑤ If $a_{ij} = D$, no new edge is generated.

STEP 4: Interconnecting with local power generation equipment.

The energy supply side of the Energy Internet adopts the combination of local power supply and UHV supply and makes full use of existing local power generation equipment and energy resources. The local energy supply rate in the study area is η , and the local power generation equipment node set $N_{LPGE/l}$ is generated according to the number of nodes in each layer of the backbone network. The number of local power generation equipment nodes in the i ($i > 1$) layer is $N_{LPGE/l=i}$.

$$N_{LPGE/l=i} = \eta N_i. \quad (2)$$

In order to ensure the reasonable layout of district energy equipment, the number of connection routes $r = 1/2/3/4$ between each district ring network and energy equipment is set. New edges are generated to connect the local power generation equipment and backbone node of each layer. Then, the number of edges connecting the local power generation equipment to the backbone nodes in l layer is rP_l .

Generating new edges meets the following criteria:

$$\begin{cases} \sum e(n_{LPGE/l}, n_{mn}) = rP_l \\ n_{LPGE/l} = \text{Random}\{N_{LPGE/l}\} \\ n_{mn} = \text{Random}\{N_{lp}\} \\ \text{Count}\{n_{mn}/n_{mn} \in N_{lp}\} = r \\ p = 1, 2, \dots, P_l \end{cases} \quad (3)$$

STEP 5: Interconnecting with local energy storage centers.

With the development of energy storage technology, it is necessary to plan energy storage nodes of different sizes to stabilize peak and valley loads and improve the level of system

backup. If the proportion of regional energy storage capacity to total electricity consumption is ε , the local energy storage center node set $N_{LESC/l}$ is generated according to the number of nodes in each layer of the backbone network, and the number of nodes in the i ($i > 1$) layer is $N_{LESC/l=i}$.

$$N_{LESC/l=i} = \varepsilon N_i. \quad (4)$$

The layout of local energy storage centers should not only consider the spatial distribution balance but also consider the reliability requirements of key power supply nodes. The number of ways t is set to $1/2/3/4/5/6$ of each energy storage center to connect the backbone nodes, and the process of generating new edge-connecting backbone nodes n_{ij} in the l -layer and the local energy storage centers according to the power supply level of the node is as follows.

For any node n_{ij} in the l -layer set N_l , which has a region power level of a_{ij} .

$$\sum e(n_{LESC}, n_{ij}) = t. \quad (5)$$

There are

① If $n_{ij}.a_{ij} = A^+$ and $t \leq \varepsilon P_l$, then $e(n_{LESC/l}, n_{ij}) = 1$, ② is entered; otherwise, the connection is complete.

② If $n_{ij}.a_{ij} = A$ and $t \leq \varepsilon P_l$, then $e(n_{LESC/l}, n_{ij}) = 1$, ③ is entered; otherwise, the connection is complete.

③ If $n_{ij}.a_{ij} = B$ and $t \leq \varepsilon P_l$, then $e(n_{LESC/l}, n_{ij}) = 1$, ④ is entered; otherwise, the connection is complete.

④ If $n_{ij}.a_{ij} = C$ and $t \leq \varepsilon P_l$, then $e(n_{LESC/l}, n_{ij}) = 1$, ⑤ is entered; otherwise, the connection is complete.

⑤ If $n_{ij}.a_{ij} = D$ and $t \leq \varepsilon P_l$, then $e(n_{LESC/l}, n_{ij}) = 1$; the connection is ended.

5 Topological characteristics of the Energy Internet backbone network taking the Beijing power grid as an example

The Beijing power grid is the power center of the north China power grid, and the conflict between environmental constraints and reliability requirements is particularly prominent. Adjusting the grid structure actively and constructing the Energy Internet are key paths to improve the reliability of power supply and reducing air pollution. Taking the Beijing power grid as an example, this paper analyzes the evolution mechanism of the backbone grid during the development of the power system to the Energy Internet.

According to the “Beijing Energy Development Plan for the 14th Five-Year Plan” and “The Medium and Long term Development Plan of Beijing Power Grid,” the Beijing power grid will build nine power supply big zones and implement gridded management of a distribution network. In this paper, the power grid architecture of Beijing is evolved in the direction of the Energy Internet by constructing a model, from the three levels of the Energy Internet top network, regional network, and local area network, and the topological characteristics of the generated network are studied. The number of nodes at each voltage level of the Beijing power grid and the number of Energy Internet nodes generated and evolved are shown in Table 2.

TABLE 2 Number and type of distribution of backbone nodes of the Energy Internet.

Network level	Corresponding voltage level	Expected number of power nodes	Energy generating nodes	Energy storage nodes
Energy Internet top network	1,000 kV/500 kV	2/18	7	4
Regional-level Energy Internet	220 kV	118	43	23
Local Energy Internet	110 kV	526	194	105

Note: ① Local energy supply rate: 37%; ② energy storage capacity ratio: 20%.

5.1 Evolution analysis of the Energy Internet backbone network in Beijing

Considering the sustainability of future power grid construction and the economics of Energy Internet construction, the evolution and construction process of the backbone structure of the Energy Internet in Beijing should fully rely on the existing power supply grid and further evolve on the basis of the existing 500-kV, 220-kV and 110-kV power supply grid structures.

According to the evolution model constructed in this paper, the 500-kV grid structure is evolved into an Energy Internet double-ring skeleton with a certain proportion of “source” and “storage” nodes as well as UHV access nodes. On the basis of the 220-kV grid structure, reasonable power nodes are added, “source” and “storage” nodes are designed according to a certain proportion, and an interconnected ring network is built to obtain a regional-level Energy Internet architecture. On the basis of the 110-kV grid structure, the “*Medium and Long term Development Plan of Beijing Power Grid*” is referred to add nodes, and the “source” and “storage” node requirements are considered for load balancing at this level, and a LAN-level Energy Internet network is built.

Figure 3 shows the topological structure of all levels of the power grid in Beijing and the Energy Internet evolved. Among them, the 500-kV power supply network refers to the “*14th Five-Year Plan for Beijing Energy Development*,” and the 220-kV and 110-kV power supply networks are up to 2020.

From the above-mentioned evolution of the backbone network of the Beijing power grid to the Energy Internet, the following conclusions can be drawn.

① From the perspective of an energy-using structure, Beijing’s energy-using structure mainly comes from UHV long-distance transmission, local natural gas generator units, and surrounding hydropower. Due to the large number of important and high-grade power users in Beijing, the power grid disaster-bearing capacity and power supply reliability requirements are extremely high, and the deployment of a certain proportion of power generation nodes and energy storage nodes at all levels of the Energy Internet is necessary for peak regulation, emergency response, and improvement in reliability.

② From the perspective of the grid structure, in the future, the construction of the Energy Internet of “partition operation, hierarchical regulation, and source-grid-load-storage coordination” on the basis of the current “double-ring skeleton and nine major partitions” plan of the Beijing power grid is feasible. The current planning and construction direction of the power grid is in line with the concept and structural characteristics of the Energy Internet.

③ From the perspective of the hierarchical structure, the 500-kV-level double-ring skeleton is basically formed, and it is necessary to further rationalize the layout of energy storage and power generation nodes. The 220-kV and 110-kV network structures are still being continuously improved, and the scale of nodes and edges is still far from the proposed Energy Internet structure.

5.2 Characteristic analysis of the backbone network of the Energy Internet in Beijing

The abovementioned Energy Internet topology networks of various voltage levels in Beijing are analyzed in complex network characteristic. Compared with the relevant network characteristics of Ref. [55] and Ref. [62], the characteristics of the Energy Internet backbone network constructed by the HRNA topology generation mechanism and the literature studies are compared and shown in Table 3.

The comparison leads to the following conclusions.

1) The macroscopic topology characteristics of the Energy Internet generated by the HUHM model in Ref. [62] are relatively close to the Internet network characteristics in terms of average degree, shortest path, and network diameter. However, this paper finds that the topological characteristics of the Beijing Energy Internet backbone network are different from those of both the traditional power grid and the Internet.

① The average degree of the Energy Internet backbone network generated by this mechanism (4.3, 4.6, 5.4) is much greater than that of the traditional power grid (2.7), but there is also a certain gap compared to the Internet (6.8).

② The average shortest path of the network obtained by the HRNA mechanism (2.5, 3.8, 5.2) in this paper is also between the traditional power grid (18.9) and the Internet (3.81) without considering the special needs of the top-level Energy Internet network (2.5), but it is especially close to the Internet.

③ The network diameter (5, 7, 9) constructed in this paper is much smaller than the traditional grid (46), and it is also smaller than the Internet diameter (11).

④ In terms of the maximum degree, the generated network in this paper (8, 11, 12) is closer to the traditional power grid (38), but it is quite different from the Internet (4042) and the results of the construction network (530, 1090, 2480) in Ref. [62].

Based on the above analysis, the characteristics of the Energy Internet network generated in this paper mainly have two points. First, compared with the traditional power grid, although the proportion of nodes and edges is not much different, the node

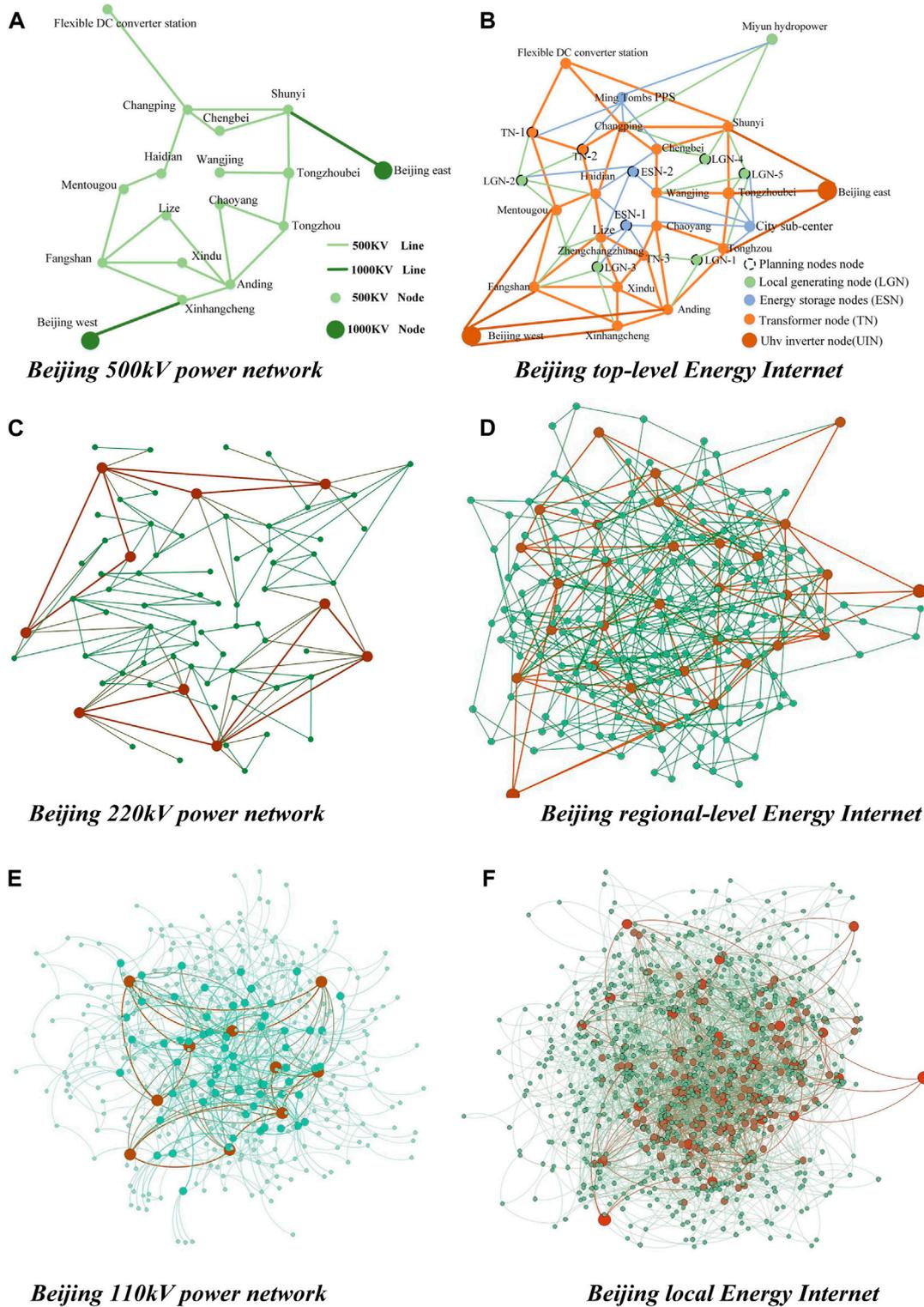


FIGURE 3
Topology of the power grid and Energy Internet at all levels in Beijing. (A): Beijing 500 kV power network. (B): Beijing top-level Energy Internet. (C): Beijing 220 kV power network. (D): Beijing regional-level Energy Internet. (E): Beijing 110 kV power network. (F): Beijing local Energy Internet.

degree is larger, the network diameter is smaller, and the average shortest path is smaller than those of the traditional tree structure with more leaf nodes to a more closely interacted network structure.

Second, the gap between the Energy Internet and the Internet structure is large in terms of the maximum degree; it is shown that in the Energy Internet, there is no central node with star-shaped

TABLE 3 Comparison of parameter characteristics of the Beijing Energy Internet backbone network with relevant literature.

Network		Number of nodes	Number of edges	Average degree	Average shortest path	Aggregation coefficient	Network diameter	Maximum degree
Beijing grid	Beijing 500-kV power grid	17	21	2.471	3.007	0.213	6	5
	Beijing 220-kV power grid	74	136	3.649	4.274	0.37	9	10
	Beijing 110-kV power grid	401	656	3.272	5.04	0.03	10	14
HRNA grid	Beijing top-level Energy Internet	31	84	5.419	2.512	0.467	5	8
	Beijing regional-level Energy Internet	215	499	4.624	3.857	0.088	7	11
	Beijing local Energy Internet	1,040	2,259	4.344	5.265	0.021	9	12
Typical grid	Central China 500-kV power grid ^[57]	210	253	2.41	10.10	0.063	---	--
	Energy Internet generated by the HUHMM model ^[64]	5,000	16,940	6.56	3.9	--	19	530
		10,000	34,140	6.91	3.88	--	18	1,080
		20,000	67,490	6.74	3.85	--	18	2,480
	Internet network	45,067	153,356	6.8	3.81	--	11	4,042
US grid	4,941	13,188	2.669	18.989	--	46	38	

topological characteristics and more of a ring-like and network-like topology.

2) Longitudinal comparison is made between different levels of networks generated by the HRNA mechanism in this paper. The characteristics of the Energy Internet at different levels are different from those of the current power grid.

It can be seen from the table that ① the characteristics of the 500-kV grid of the Central China power grid and the 500-kV grid of the Beijing power grid in 2020 are similar. After evolving into the top-level Energy Internet with a “double-ring skeleton” structure, the average degree (5.4) and aggregation coefficient (0.47) are larger, the network aggregation is higher, nodes support each other better, and power supply reliability is higher. ② Compared with the characteristics of the 220-kV network in Beijing, the average degree increase in the regional Energy Internet is not particularly large (3.6→4.6), and the average shortest path (4.2→3.8) and the maximum degree (10→11) are also small. It shows that the 220-kV structural connectivity of the Beijing power grid is good, and the development rhythm is good and takes into account the reliability requirements. ③ The 110-kV power grid and the local Energy Internet are very similar in their characteristic structures (average degree: 3.272→4.344; average shortest path: 5.04→5.265; aggregation coefficient: 0.03→0.021; network diameter: 10→9; and maximum degree: 14→12), and the foundation for the construction of the Energy Internet is very good through improvement and adjustment. ④ It is not difficult to see from the comparison of the characteristics of the top-level Energy Internet to the regional and local level networks that with

the reduction in the level and the increase in nodes, the average degree and aggregation coefficient of the network continue to decrease and the tightness of the network tends to be stable.

5.3 Analysis of network characteristics and differentiation reasons

The reasons for the differences in topological characteristics between the energy interconnection network generated in this paper and related literature studies (literature [62], US power grid and internet) are analyzed as follows:

① The average degree of the energy interconnection network generated in this paper is between the power grid and the Internet. This shows that compared with the traditional power grid, the connectivity of the Energy Internet is better, and the grid structure is stronger, but it does not reach the level of Internet connectivity.

② The diameter and average path of the energy interconnection network generated in this paper are close to the Internet. This shows that the Energy Internet is close to the Internet in the degree of aggregation and has the characteristics of short connection path and rapid diffusion;

③ The maximum degree of nodes in the network generated in this paper is different from that in the internet, and it does not exist as the central node connecting most nodes in the Internet. However, it is similar to the traditional power grid. On one hand, it can well reflect the characteristics of distribution, shared peer-to-peer and regional autonomy. On the other hand, it shows that the high connectivity level of the network depends on the regular and orderly interconnection, rather than the relay and aggregation of the central node.

6 Conclusion

In this paper, the evolution path and network characteristics of the traditional tree-shaped power grid under the trend of “hierarchical control and zoning coordination” architecture of the Energy Internet are studied. The network characteristics are analyzed by taking the 500-kV, 220-kV, and 110-kV grid structures of the Beijing power grid as an example, and the conclusions are as follows.

① Considering the continuity and economy of power grid construction, it is valuable and feasible to evolve the traditional tree-shaped power grid structure into a multi-layer network structure of the Energy Internet with hierarchical partitions.

② Using the Energy Internet HRNA evolution mechanism proposed in this paper, the structure of different levels of the grid structure in the Beijing power grid evolves in the direction of the Energy Internet, and it is found that the current direction of power grid planning and construction is in line with the direction of the Energy Internet structure.

③ The network generated by the mechanism proposed is close to the Internet in terms of average degree, network diameter, and aggregation coefficient, but there is no central node with a very high maximum degree in the Internet topology, which, to a certain extent, reflects the concept of Energy Internet equivalence.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material; further inquiries can be directed to the corresponding author.

Author contributions

XL: writing–original draft and writing–review and editing. ZZ: writing–original draft and writing–review and editing. YZ:

writing–original draft and writing–review and editing. PL: writing–review and editing. LJ: writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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