Abstract: Electricity is one of the most widely used forms of energy. However, environmental pollution from electricity generation and the mismatch between electricity supply and demand have long been bothering economies across the world. Under this background, cross-border electricity trade provides a new direction for sustainable development. Based on the complex network approach, this paper aims to explore the structural characteristics and evolution of cross-border electricity trade networks and to figure out the factors influencing the formation of the network by using the more advanced network analysis method—ERGM. The results show that: (1) The scale of the electricity trade network is expanding, but there are still many economies not involved. (2) The centrality of the network shifts from west to east. The level of internal electricity interconnection is high in Europe, and Asian countries’ coordination role in cross-border electricity trade networks is enhanced. (3) Cross-border electricity trade helps to reduce CO\textsubscript{2} emissions, achieve renewable energy transformation, and reduce power supply and demand mismatch. Large gaps in GDP, electricity prices, industrial structure, geographical distance and institutional distance between economies are not conducive to form the cross-border trade network, while the common language is on the contrary.

Keywords: cross-border electricity trade; complex network analysis; renewable energy

1. Introduction

Electric power plays a significant role in our human society. It is the core of modern energy security and economic development. The development of industrialization has once again intensified the demand for electric energy in various economies, and the global demand for electric power will continue to grow fast. Whether economies can provide high-quality electric power to meet the social need is of great significance. However, the global electricity industry is facing the problems of slow growth, the mismatch between supply and demand, and environmental concerns:

First, the growth rate of global electricity generation is slow, unable to meet the rapid growth of GDP. According to data from the Statistical Review of World Energy 2020 [1], global electricity generation in 2019 only increased by 1.3%, and most economies experienced weak or even negative growth. In 2019, the global economic growth rate fell to 2.3%. It is the lowest level in a decade, but still higher than the growth rate of electricity generation [2]. Nowadays, 770 million people, mainly in sub-Saharan Africa, have no access to electricity, and hundreds of millions of people have very limited access to electricity [3]. At the same time, the impact of the COVID-19 has magnified the scarcity of electricity and energy. The lack of electricity makes the backward areas unable to meet the medical needs in time, accelerating the spread of the epidemic.

Second, there is a serious mismatch of global electricity supply and demand. The European electricity market is densely networked, and the integration of the electricity market [4] is enough to support the development of the European region. In sharp contrast,
there is a shortage of electricity in Asia and Africa. Facing the opportunities of world industrial transfer and global value chain reconstruction, scarcity of electricity in some areas (e.g., Southeast Asia) may result in slow industrialization and high unemployment rate.

Finally, renewable energy accounts for a relatively small proportion of electricity generation sources, and carbon dioxide emissions are relatively high, causing serious environmental concerns. The electricity generation sector generates the most carbon dioxide [5]. Renewable energy is the main development direction of the electricity generation industry [6,7] and is conducive to driving economic growth [8,9]. These problems have made it valuable to explore the possibility of cross-border electricity trade.

With the development of economic globalization, trade integration and production decentralization, trade between economies is getting more and more complex. As a kind of commodity, energy is gradually networked. Compared with the traditional energy trade, the cross-border electricity trade is more inclined to be regional, due to the limitation of technology and geographical location. As a result, it has not yet formed a complete network. In addition, electricity has unique properties. For example, once generated, electricity can hardly be stored, so continuous supply and demand matching is necessary [10], which also provides exploratory significance for the study of cross-border electricity trade. Technology and economic development promote the continuous growth of cross-border electricity trade. Cross-border electricity trade may solve the three problems mentioned above effectively. Economies can give full play to their comparative advantages, optimize resource allocation and speed up electricity power production by trading with each other [11]. Through the cross-border electricity trade, economies can increase the use of renewable energy, and reduce carbon dioxide emissions, which is conducive to promoting the world’s low-carbon energy transformation and socially sustainable development [12,13]. Moreover, energy has a fundamental role to play in efforts to eradicate poverty [14,15]. However, cross-border electricity trade accounts for a small proportion of global electricity supply and demand. The scale of European electricity trade is large, but the proportion of electricity exports in electricity production and the proportion of electricity imports in electricity consumption are only about 10% respectively. While Asia’s electricity trade is smaller, with electricity exports accounting for less than 1% of total electricity production. The detailed information is provided in Appendix B. So, this paper explores the structural characteristics and influencing factors of cross-border electricity trade network in order to expand the scale of global electricity trade.

The existing literature on cross-border electricity trade mainly focuses on the analysis of the ecological environment, the potential of cooperation between economies and trading markets. First, researchers have analyzed the impact of cross-border electricity trade on the environment. Through the calculation of carbon dioxide emissions in electricity trade, they find that electricity trade has a significant impact on emission factors and implied carbon, and electricity trade will reduce carbon dioxide emissions from electricity consumption in various areas [16–18]. Renewable energy plays an increasingly important role in the power sector [19], and the large use of fossil energy will increase environmental pollution [20]. Increasing the proportion of renewable energy in electricity generation can effectively reduce CO₂ emissions [21,22], so through cross-border electricity trade, electricity can be transferred from high renewable energy electricity generation countries to low renewable energy electricity generation countries. Economies can effectively alleviate environmental problems by strengthening the construction of cross-border electricity trade infrastructure and improving renewable energy policies [23]. Second, many scholars assess the cooperation potential and potential benefits of regional cross-border electricity trade [24,25]. Strengthening cross-border electricity trade cooperation in South Asia can bring scale economy of investment, more cost-effective expansion of renewable electricity, and environmental benefits. Therefore, governments should take measures to support the development of cross-border electricity trade [12,26]. By building cross-border electricity trade in Asia and Europe, the total social welfare can be increased by 140 M€ and 5370 thousand metric tons of carbon dioxide emission can be reduced every year [27].
Third, scholars have studied the electricity dispatching problem in the trading market. The relationship between the development of renewable electricity cross-border trade and the current electricity trading market is complex [28]. On the one hand, the development of renewable electricity trade may bring bad motivation of insufficient investment, resulting in upward pressure on prices and price differences in different regions [29]. For price and investment issues, scholars believe that different technology groups should have different investment levels [30], and can control RES investment based on auction or pay a market premium based on market demand [31]. On the other hand, renewable electricity trade may cause power grid congestion, that is, renewable energy generation does not have appropriate network expansion to meet the growing demand of transmission capacity from production to consumption [32]. Cross-border electricity trade will increase the burden of interconnection lines, leading to network congestion, which limits the power market transactions [33]. Compared with export regions, the larger the renewable energy supply in import regions, the lower the probability of congestion [34]. Congestion further leads to the problem of market power. In peak hours, the large-scale competition of renewable energy weakens the market power abuse, while in off-peak hours, congestion leads to market fragmentation and the market power abuse can be enhanced [28]. In the long run, the traditional system can be modified to meet the new needs, but in the short run, the network congestion must be alleviated by anti-transaction or redispatch [35].

Complex network analysis methods are widely used in economic and trade research as an interdisciplinary subject. It is based on relational data, putting individuals in the network [36]. It not only can analyze the characteristics of each individual but also can intuitively display its status and role in the network, which is an extension of traditional measurement methods [37,38]. Researchers use the complex network analysis method to analyze the structural characteristics of a network from three levels: individual structure, overall structure and community structure [39–41]. The complex network analysis method is also widely used to study the influencing factors of relational data. Quadratic Assignment Procedure (QAP) is a nonparametric method, which does not need to assume that independent variables are independent of each other, so it is more robust than parametric method, and it is widely used in the empirical analysis of economic network [42,43]. Exponential Random Graph Models (ERGM) is a general model based on the comprehensive consideration of various network production processes. It can infer whether a certain structural feature in the real network is obviously different from that in the random network. It is considered to be one of the most effective tools for empirical analysis of social network science-related theories [44,45].

To date, a few studies on energy trade using the complex network method mainly focus on the traditional energy trade [46–48], but the analysis of electricity trade is lacking. For example, the trade networks of coal [49], oil [50], natural gas [51,52], crude oil [53] and virtual water [54] have been studied in detail. The existing articles on electricity trade mainly focus on the analysis of electricity trading market mechanism and environment, rarely focus on the evolution of cross-border electricity trade network, the status of economies in the global electricity trade and the driving force of the formation of electricity trade network from a macro perspective. Although the complex network analysis method has been applied to electricity trade [55], it only simply analyzes the network structure characteristics and does not further find the influencing factors. Therefore, the main purpose of this paper is to analyze the evolution and structural characteristics of the global electricity trade network from a global perspective. We can’t only see the growth process of the whole network, but also the status change of each country in it. In addition, since cross-border electricity trade is one of the effective ways to meet sustainable development, it is necessary to further analyze the influencing factors of promoting the formation of cross-border electricity trade.

The main contributions of this paper are as follows: (1) Analyze the structural characteristics of the cross-border electricity trade network from the macro, individual, and micro perspectives and show the evolution of the electricity trade network comprehensively.
(2) Use the ERGM model to explore the factors of the cross-border electricity trade network, analyze the influencing factors internally and externally, and avoid endogenous problems. 
(3) Propose recommendations for the further development of cross-border electricity trade based on our results.

The structure of this paper is as follows, Section 2 introduces the construction of the network, data sources and methods. Section 3 describes the characteristic facts of relevant economies, mainly including carbon dioxide emissions and the proportion of renewable energy in electricity generation energy. Section 4 analyzes the cross-border electricity trade network structure from overall, individual and microstructure. Section 5 uses the ERGM model to explore the factors that influence the formation of the cross-border electricity trade network. Section 6 gives conclusions and recommendations.

2. Materials and Methods
2.1. Cross-Border Electricity Trade Network Construction

We construct the cross-border electricity trade network using the data collected from UNcomtrade database [56] in 2000–2018. The cross-border electricity trade network consists of N nodes representing economies and L edges composed of trade relations, denoted as G = (V, E). The electricity trade matrix is \( V = [v_{ij}] \) (i ∈ N, j ∈ N, i ≠ j), with the vector \( V_i \) as exporters and \( V_j \) as imports. E = [e_{ij}] (i ∈ N, j ∈ N, i ≠ j) represent the trade flow relationship between economies, and each e_{ij} corresponds to a pair of nodes (V_i, V_j) in V. According to the nature of the electricity trade network, this paper constructs a directed weighted network. We select the data with an electricity trade volume of more than USD 1000 and eliminate the data where electricity trade in the two regions is impossible due to geographic restrictions. Differences in statistical caliber and human factors lead to inconsistent import and export data between two economies. Some scholars believe that the companies may deliberately underreport and conceal in order to avoid tariffs [57], so data with higher values are more realistic. Other scholars believe that import data should be used, because import supervision is relatively stricter, and the accuracy of import data is higher than export data [17]. This paper draws on the method of using the higher numerical data for calculation.

2.2. Network Feature Measurements

This paper analyzes the structural characteristics of the electricity trade network from the overall, individual and microstructure levels. The overall structure is composed of clustering coefficient and reciprocity coefficient, showing the evolution of the global electricity trade network from a macro perspective. The individual structure focuses on showing the status of an economy in the cross-border electricity trade network.

2.2.1. Overall Structural Features

(1) Average clustering coefficient

The average clustering coefficient represents the average value of the clustering coefficients of all economies in the cross-border electricity trade network. With the gradual development of connections between nodes in the direction of regionalization and grouping, the average clustering coefficient is a good measure of the clustering effect in the network:

\[
\bar{C} = \frac{1}{n} \sum_{i=1}^{N} C_i
\]

\[
C_i = \frac{|\{e_{ij}\}|}{k_i(k_i - 1)}
\]

\( C_i \) is the clustering coefficient of economy i, representing the ratio of the number of connections between adjacent nodes to the number of possible connections in economy i. The \( e_{ij} \) indicates the trade relationships of economy i and economy j in the network. The \( k_i \)
denotes the number of neighboring nodes of economy i. The larger the average clustering coefficient is, the stronger the aggregation effect is in the network [58].

(2) Reciprocity coefficient

Reciprocity represents the interoperability of trade between economies [59]. The higher the reciprocity is, the closer the trade interaction between economies is, which is the basic direction of network development. It is defined as follows:

\[ \Phi = \frac{m_d}{m} \] (3)

The m denotes the total number of edges in the network, m_d represents the number of edges with bidirectional relationships. Economies prefer bilateral reciprocal trade rather than unilateral trade, which is more conducive to the stability of relationships between economies.

2.2.2. Individual Structural Features

(1) Degree centrality

The degree centrality shows the number of economies that have electricity trade with an economy [60]. The higher the degree centrality is, the higher the status of the economy is in the electricity trade network, and the degree centrality can be further divided into in-degree centrality and out-degree centrality. The in-degree indicates that the economy i imports electricity from other economies, and the out-degree denotes that the economy i exports electricity to other economies. In order to eliminate the influence of network scale change, we standardize it by dividing the degree by the largest number of connections between economy i and other economies. It is defined as follows:

\[ ID_i = \sum_{i=1(i \neq j)}^n \frac{d_{ij}}{(n - 1)} \] (4)

\[ OD_i = \sum_{i=1(i \neq j)}^n \frac{d_{ij}}{(n - 1)} \] (5)

\[ D_i = \frac{(ID_i + OD_i)}{(2n - 2)} \] (6)

The \(d_{ij}\) represents economy i exports electricity to economy j. If there is electricity trade between economy i and economy j, \(d = 1\), otherwise \(d = 0\). ID represents in-degree, OD represents out-degree. The \(D\) is composed of ID and OD.

(2) Betweenness centrality

Betweenness centrality reflects an economy’s role as a “bridge” in the electricity trade network [61]. The higher the betweenness centrality is, the more important the economy’s coordination and control role are in the international electricity trade network. It is defined as follow:

\[ BC_i = \sum_j \sum_k \frac{b_{jk}(i)}{b_{jk}(i \neq k \neq j)} \] (7)

The \(b_{jk}\) represents the number of shortest paths for electricity trade between economy j and economy k. The \(b_{jk}(i)\) represents the number of shortest paths through economy i when economy j and economy k establish an electricity trade relationship.

2.2.3. Microstructure Features

The motif refers to the connection mode of the interaction of nodes in the network, which can be widely understood as the local connection mode that often appears in the network. The motif is not limited to 3 nodes, and the sub-network structure composed of multiple nodes can also be regarded as the motif. According to different characteristics of
nodes and different weights of edges, motifs can be arranged into multiple subgraphs. The Z-score can be used to evaluate the importance of the motifs in the network [62].

\[ Z_i = \frac{N_{\text{real},i} - N_{\text{rand},i}}{\sigma_{\text{rand},i}} \] (8)

The \( N_{\text{real},i} \) denotes the number of times the motif appears in the real network. The \( N_{\text{rand},i} \) denotes the number of times the motif appears in the random network. The \( \sigma_{\text{rand},i} \) represents the standard deviation of the motif in the random network. A large Z-score means this type of motif shows up frequently in the network, so the motif can be of high importance.

2.3. ERGM Conceptualization

ERGM (Exponential Random Graph) is mainly used to study the influencing factors in relational data that affect the formation of the network. After estimation, diagnosis, simulation, comparison and improvement, the network structure characteristics obtained by simulation are close to the real network [63–65]. At present, scholars use the Markov chain Monte Carlo maximum likelihood estimation method to estimate and test the model. The general form of the ERGM model is:

\[ \Pr(Y = y|\theta) = \left(\frac{1}{\kappa}\right) \exp\left\{ \sum_H \theta^T_H g_H(y) \right\} \] (9)

The \( Y_{ij} \) represents the trade relationship between economy \( i \) and economy \( j \). \( Y_{ij} = 1 \) means that economy \( i \) exports electricity to economy \( j \), and \( Y_{ij} = 0 \) otherwise. The \( y_{ij} \) is the observation value of \( Y_{ij} \). \( \Pr(Y = y|\theta) \) represents the probability of \( y \) in \( Y \) under the condition of \( \theta \). The \( \kappa \) is a standardized constant to ensure that it conforms to the probability distribution. The \( H \) indicates all the factors that may contribute to forming a cross-border electricity trade network. If the influencing factors are further expanded, the model turns as follows:

\[ \Pr(Y = y|\theta) = \left(\frac{1}{\kappa}\right) \exp\{\theta^T_\alpha g_\alpha(y) + \theta^T_\beta g_\beta(y, x) + \theta^T_\gamma g_\gamma(y, g)\} \] (10)

Influencing factor \( H \) is composed of network endogenous structural factor \( \alpha \), behavior attribute \( \beta \), and other external network influence factors \( \gamma \) that affect the network (\( \alpha, \beta, \gamma \in H \)). Equation (10) includes three statistics that affect network generation. The \( g_\alpha(y) \) represents endogenous network structure, which only comes from the internal processes of the network relationship system. The processes usually appear based on the effect of degrees, which is called “preference attached”. If some economies or regions are at the center of the network and have more electricity trading partners, more people will trade with them. The \( g_\beta(y, x) \) includes the characteristics of economy attributes \( x \). Due to differences in resources, climate, geography, political culture and other factors between economies, economic attributes are also called “actor attributes”. Other exogenous situational factors \( g_\gamma(y, g) \) will also affect the formation of the electricity trade network, usually using binary relational covariates to measure the influence of the exogenous network on the electricity network.

3. The Characteristic Fact Analysis

3.1. Electricity Market

As a special commodity, electric power transactions have become complex and diverse, developing from physical to financial ones, including a variety of derivatives. According to the trading volume, the electricity trading market can be divided into the retail market and wholesale market. Retail electricity transactions are carried out at the level of distribution lines, mainly between dealers and end consumers; wholesale electricity trading refers
to transactions at the transmission line level, which mainly occur between electricity generators and electricity sales companies or large enterprises [66]. Cross-border electricity trade is mainly composed of wholesale transactions. In the wholesale market, electricity trading is further divided into power exchange and over-the-counter trading (OTC trading). Power exchange refers to transactions conducted in an organized place, and OTC trading occurs in a non-public place. The former already has a standardized model and a high degree of automation, while the latter has a relatively low degree of standardization.

The electricity markets transaction mechanism is mainly composed of financial transactions and spot transactions. The Day-Ahead Markets (DAM) and the Intra-Day Markets (IM) are important components of electricity trading, and they are great complements [67]. The Day-Ahead Market is a discrete transaction and a one-time bidding market, where trading happens on the day before. While the Intra-Day Market is a continuous transaction market, and its main purpose is to continue to adjust the electricity trading when the Day-Ahead Market is closed.

In cross-border electricity trading, the European electricity trading market is relatively mature. Europe leads electricity trading market reform worldwide, and the Nord Pool is the first cross-border electricity trading market. Most of the cross-border electricity transactions in Europe belong to OTC trading, with a high degree of integration [68]. In addition, the global electricity futures market is developing rapidly. As an advanced form of the electricity market, the global electricity futures market helps to avoid risks. Electric power has become the third-largest energy derivative after oil and natural gas [69]. Currently, multiple countries, including the United States, Australia, Europe, etc., have electricity futures trading.

3.2. Electricity Production and Electricity Consumption, CO$_2$ and Renewable Energy

The cross-border electricity trade network is obviously regional. This paper divides the world into seven regions based on BP World Energy Development [1] regional classification index: Asia-Pacific, Europe, North America, Africa, CIS countries, Middle East, and Central and South America. This section describes the electricity production, electricity consumption, carbon dioxide emissions and the proportion of renewable energy in the electricity generation of each region, looking for the relationship between cross-border electricity trade and the environment of each economy.

Figure 1 shows the evolution of fossil energy’s CO$_2$ emissions from 2000 to 2018 based on the Enerdata database [70]. It is clear that carbon dioxide emissions in the Asia-Pacific region are showing a straight upward trend, and the growth rate is obvious. Since 2000, carbon dioxide emissions in the Asia-Pacific region have increased by 1.24 times, which is closely related to the transfer of world industries to the Asia-Pacific region. The Asia-Pacific region is mostly engaged in related industries at the low end of the value chain, which not only increases the demand for electricity but also gradually increases carbon dioxide emissions. The CIS countries, Latin America, Africa and the Middle East have seen a slight increase in carbon dioxide, which has also increased carbon dioxide emissions while developing the economy. In sharp contrast, the carbon dioxide emissions of fossil energy in Europe and North America have a downward trend, which is inseparable from the relatively advanced electricity trade and the use of renewable energy. The development of electricity markets and the reduction of carbon dioxide emissions in North America and Europe have provided a model for the development of the cross-border electricity trade, breaking the traditional mindset of simultaneous growth of the economy and carbon dioxide emissions. According to statistics from the IEA database [71], North America is the region with the highest per capita carbon dioxide emissions. From 2000 to 2018, North America’s per capita carbon dioxide fell from 15.9 t to 12.1 t. Europe’s per capita carbon dioxide emissions fell by 17.14%, and the emissions in the rest of the world increased. Among them, the largest increase is in the Asia-Pacific region. Although its per capita carbon dioxide emissions are less than 4t, the increase rate reached 85.7%. Regardless of
whether it is per capita carbon dioxide emissions or total carbon dioxide emissions, the trend remains the same.

Figure 1. Fossil fuel carbon dioxide emissions (Mt).

Figure 2 shows the production and consumption of electricity in different regions, and all of them keep the same upward trend. In terms of absolute value, the growth rate of electricity production is greater than that of electricity consumption. The Asia-Pacific region has the largest growth rate, with electricity production increasing by 9114 TWH and electricity consumption increasing by 7133 TWH. At the beginning of the 21st century, the Asia-Pacific has become the largest electricity production and consumption region in the world, surpassing North America. At the same time, carbon dioxide emissions in this region are also the largest. In terms of relative value, the growth rate of global electricity production is 72.03%, and the growth rate of global electricity demand is 74.03%. The low-speed growth of electricity production cannot meet the high-speed growth of power demand, resulting in a global electricity imbalance. The change in production and consumption of electricity is relatively consistent with the changing trend of carbon dioxide emissions, which proves that carbon dioxide emissions are closely related to electricity, and the growth of electricity demand and electricity generation also brings higher carbon emissions. However, North America and Europe are two exceptions. Their electricity supply and demand are also rising, but their carbon dioxide emissions, as we mentioned, are falling.
Figure 3 shows the proportion of renewable energy electricity generation in various regions. The proportion of renewable energy in global electricity production is on the rise. The highest proportion of renewable energy is in Latin America, exceeding 50%. A renewable energy development report released by the Inter-American Development Bank shows that four of the countries with the best renewable energy development index in the world are from Latin America, namely Brazil, Chile, Mexico and Uruguay. Latin America has abundant tidal energy, and its use far exceeds that of fossil fuels. However, with the economic development and industrial structure transformation in Latin America, the proportion of fossil energy electricity generation has increased. Asia–Pacific has the second-largest share of renewable energy in electricity generation. In 2018, the proportion can reach 49.26%. The Pacific region makes a greater contribution, which is rich in hydropower and wind energy, while the Asian region accounts for less than half. The third place is occupied by Europe, where the proportion of renewable energy electricity generation can reach 36.41%, and the proportion continues to rise. Europe aims to increase the use of renewable energy, and through an advanced electricity trading market, increase the export of electricity from countries with more renewable energy. The growth rate of renewable energy in electricity generation in Africa and other regions is relatively low, and the proportion of fossil fuels is growing faster than that of renewable energy. Europe and North America have high growth rates, increasing by 81.23% and 51% respectively, which mutually confirms the reduction in carbon dioxide emissions and sufficient electricity in Europe and North America above.

Figure 3. Renewable energy in electricity generation (%).

4. Structural Characteristics of Cross-Border Electricity Trade Network
4.1. Overall Network Structure

This section describes the three aspects of network scale, clustering coefficient and reciprocity coefficient, showing the evolution of the overall structure of the cross-border electricity trade network.

From Figure 4, we can see that electricity trade is not as densely networked as ordinary commodities, but rather regional. The network density of European economies is large, showing a complex and interwoven shape, and the electricity trade is relatively mature. Russia, as the link between Eurasia and Europe, radiates to Asia and Europe, while China is more inclined to trade electricity with economies in South Asia and Southeast Asia. North America, South America and southern Africa also have their own internal electricity trade network, among which the trade volume between the United States and Canada is very large.
Figure 4. Global electricity trade network in 2018. The thickness of the line indicates the volume of trade, the thicker the lines, the greater the electricity trade between the two economies.

Figure 5a displays the number of nodes and edges of the cross-border electricity trade network from 2000 to 2018. The overall scale of the network continues to expand. During the 19 years, the number of economies participating in the cross-border electricity trade network has changed from 103 in 2000 to 121 in 2018, and the number of global electricity trade relations increased from 265 in 2000 to 434 in 2018, an increase of 63.77%. After 2005, the scale of trade began to continue to rise sharply, indicating that with the deepening of globalization, electricity trade connections between economies have become closer. The increase in the number of electricity trade relationships between nodes is greater than the increase in the number of economies participating in the cross-border electricity trade network, indicating that the growth of the global electricity trade network is more about vertical expansion on the existing network, while the horizontal expansion process of adding new economies is slow.

Figure 5. Overall network structure of cross-border electricity trade network: (a) 2000–2018 cross-border electricity trade network scale; (b) 2000–2018 cross-border electricity trade clustering coefficient and reciprocity coefficient.
In the overall structure of the trade network, the close connections between nodes are gradually developing towards regionalization and grouping. We measure the clustering coefficient in the cross-border electricity trade network to show the agglomeration effect in the network. Reciprocity represents the interoperability of trade between economies. The following conclusions can be drawn from Figure 5b: (1) The reciprocity of the global electricity trade network is high. Its lowest value is 0.572 in 2003, while the highest is 0.724 in 2010. (2) Since 2001 and 2012, the reciprocity of the cross-border electricity trade network declined sharply, and they reached the bottom in 2003 and 2014 respectively. At the beginning of the 21st century, the global economic recession is accompanied by the rise of oil prices, which reduce electricity trade. In the post-crisis era, the global economy still faces many uncertainties, leading to uncertainty in trade. (3) The clustering coefficient of cross-border electricity trade varies between 0.36 and 0.45. It has a good upward trend from 2000 to 2009, reaching its peak in 2009, but there has been a downward trend since then. This is due to the addition of new economies, as well as geographical constraints, which leads to a decline in the degree of agglomeration.

4.2. Analysis of Individual Network Structure

At the individual level of the cross-border electricity trade network, this paper describes the degree centrality and betweenness centrality, and further decomposes the degree centrality into in-degree centrality and out-degree centrality to measure each economy’s status in the network. Our purpose is to show the changing status of each economy in the global power trade network. Although the European electricity market is highly integrated with a lot of small countries, we do not regard it as a whole because comparison with other countries can better show the development of each country in the global electricity trade network. Table 1 shows the statistical results.

The degree centrality reflects the number of electricity trade relations between an economy and other economies in the electricity trade network. It can be seen from Table 1 that whether it is in-degree centrality, out-degree centrality or total degree centrality, the top nine in the world over the years are almost European countries. The reason is that the electricity trade in Europe started early and has relatively mature technology and institutional systems, which has established its status in the global electricity trade network. The European Union proposes that in 2020, the interconnection capacity of each member country will account for at least 10% of the national installed capacity, and it will reach 15% in 2030. Meanwhile, Europe’s total electricity installed capacity ranks third, followed by the Asia–Pacific region and North America. However, the proportion of renewable energy installed capacity in Europe far exceeds that in North America and the Asia–Pacific region, and the growth rate is relatively fast, increasing from 23.48% in 2000 to 45.92% in 2018. Europe has relatively high electricity installed capacity and the proportion of renewable energy installed capacity, which has promoted the development of cross-border electricity trade in European countries. See Appendix C for details. Germany has been among the top six in degree centrality for 19 years. However, Germany’s trading partners are stable between 25 and 30 economies, and the increase is not as large as that of economies such as the Czech Republic and Bulgaria. The main reason is that Germany is located in central Europe, and its electricity trading partners are almost limited to Europe, while economies such as the Czech Republic and Bulgaria are located in central and eastern Europe and can trade electricity with Asian economies to expand trading partners. With the construction of the Eurasian electricity sub-network in recent years, Uzbekistan’s centrality of out-degree has risen to the top in 2018. Uzbekistan is located at the junction of the European and Asian sub-networks, giving full play to its geographical advantages to trade electricity with other economies. The last few economies with degree centrality are mostly developing economies in Africa, South America, South Asia and Southeast Asia. These economies have backward electricity trade development and underdeveloped infrastructure, and they can only trade electricity with neighboring economies. However, it also reflects from the
side that with the expansion of global electricity trade, more and more new economies have joined it for mutual benefit.

Table 1. Individual structure characteristics of cross-border electricity trade network.

| Year | Rank | In-Degree Centrality | Out-Degree Centrality | Degree Centrality | Betweenness Centrality |
|------|------|-----------------------|-----------------------|-------------------|-----------------------|
|      |      | Economy ID | Economy OD | Economy D | Economy BC |
| 2000 | 1    | DEU 12    | DEU 13    | DEU 25    | CHE 0.114 |
|      | 2    | CHE 10    | RUS 13    | CHE 20    | RUS 0.107 |
|      | 3    | FRA 9     | CHE 10    | RUS 20    | SVK 0.106 |
|      | 4    | SVK 8     | BEL 10    | FRA 28    | SCG 0.101 |
|      | 5    | HRV 8     | FRA 9     | BEL 16    | DEU 0.097 |
|      | 6    | SWE 8     | GBR 8     | SVK 15    | POL 0.082 |
|      | 7    | NLD 7     | SVK 7     | GBR 15    | BGR 0.059 |
|      | 8    | GBR 7     | HRV 7     | HRV 15    | FIN 0.047 |
|      | 9    | SCG 7     | AUT 7     | SVN 14    | NLD 0.038 |
| 2005 | 1    | DEU 15    | DEU 14    | DEU 29    | SRB 0.096 |
|      | 2    | SVN 12    | POL 10    | SVN 22    | RUS 0.081 |
|      | 3    | CHE 12    | SVN 10    | CHE 21    | DEU 0.081 |
|      | 4    | HRV 10    | HRV 10    | HRV 20    | BIH 0.074 |
|      | 5    | CZE 10    | CZE 10    | CZE 20    | FIN 0.068 |
|      | 6    | GBR 9     | CHE 9     | ESP 18    | DNK 0.067 |
|      | 7    | ESP 9     | ESP 9     | POL 16    | NOR 0.067 |
|      | 8    | AUT 8     | ROU 9     | GBR 15    | SVN 0.051 |
|      | 9    | HUN 7     | UKR 8     | ROU 14    | HUN 0.046 |
| 2010 | 1    | SVN 20    | CZE 18    | SVN 36    | RUS 0.155 |
|      | 2    | CZE 17    | SVN 16    | CZE 35    | UKR 0.125 |
|      | 3    | GRC 16    | CHE 14    | DEU 27    | HRV 0.105 |
|      | 4    | DEU 14    | DEU 13    | CHE 26    | ROU 0.087 |
|      | 5    | CHE 12    | HUN 13    | GRC 24    | DEU 0.086 |
|      | 6    | SRB 12    | HRV 11    | SRB 23    | SVK 0.081 |
|      | 7    | HRV 11    | ESP 11    | HRV 22    | CHN 0.074 |
|      | 8    | AUT 10    | SRB 11    | HUN 21    | GRC 0.069 |
|      | 9    | ROU 8     | RUS 11    | ESP 19    | CZE 0.066 |
| 2015 | 1    | NLD 26    | CZE 19    | CZE 39    | RUS 0.153 |
|      | 2    | CZE 20    | SVN 17    | SVN 35    | SVN 0.150 |
|      | 3    | SVN 18    | BGR 17    | NLD 31    | NLD 0.114 |
|      | 4    | GRC 14    | ITA 14    | DEU 27    | IRL 0.107 |
|      | 5    | SRB 14    | DEU 13    | CHE 26    | ITA 0.099 |
|      | 6    | DEU 14    | CHE 13    | ESP 25    | CHN 0.088 |
|      | 7    | CHE 13    | ESP 13    | SRB 25    | BIH 0.088 |
|      | 8    | ESP 12    | RUS 12    | BGR 24    | EST 0.075 |
|      | 9    | ITA 10    | SRB 11    | ITA 24    | ROU 0.067 |
| 2018 | 1    | CZE 23    | UZB 23    | CZE 44    | RUS 0.191 |
|      | 2    | BGR 18    | CZE 21    | BGR 34    | GRC 0.115 |
|      | 3    | SVN 17    | BGR 16    | SVN 32    | GEO 0.111 |
|      | 4    | GRC 15    | SVN 15    | GRC 28    | CZE 0.111 |
|      | 5    | DEU 14    | DEU 14    | DEU 28    | UZB 0.101 |
|      | 6    | SRB 12    | GRC 13    | UZB 25    | KGZ 0.099 |
|      | 7    | CHE 12    | ITA 12    | ITA 23    | KAZ 0.098 |
|      | 8    | ITA 11    | SRB 11    | SRB 23    | TUR 0.091 |
|      | 9    | HUN 11    | HUN 11    | CHE 22    | CHN 0.079 |

When analyzing the network, we should not only look at the number of trading partners of an economy but also whether this economy plays an important role in the network. The economies with high betweenness centrality in 2000 were all European economies, and most of them were economies in Central and Western Europe because...
there was relatively little electricity trade between economies in other continents. In 2010, economies with high betweenness centrality gradually moved from west to east within Europe. Eastern European economies such as Russia, Ukraine and Romania were connected to Asia, connecting Europe and the Asian continent, forming the Eurasian sub-network. With the pass of time and the expansion of the electricity trade network, the economies with high betweenness centrality in the cross-border electricity trade network in 2018 were not limited to Europe but expanded to Asia. It is precisely because these economies are located in important hubs that the networks of various regions can be connected. Whether it is degree centrality or betweenness centrality, there is a trend of eastward migration, while the trend of betweenness centrality shifting eastward is obvious.

4.3. Analysis of Network Motif

In order to further explore the microstructure of cross-border electricity trade, this paper uses Mavisto software [72] to get statistics on the partial structure that appears repeatedly in the network. We conducted 1000 random simulations to compare the frequency of the corresponding structure in the real network and the random network to decide whether this motif exists significantly in the cross-border electricity trade network. If \( p = 0 \), it is significant, and vice versa. The higher the Z-score is, the more important the motif is in the cross-border electricity trade network. The content of this section is closely related to the analysis of influencing factors below. From the above analysis, we can know that the scale of global electricity trade in 2015 and 2018 are quite similar. Therefore, due to the availability of data, this article takes 2015 as an example for analysis.

Table 2 reports the relevant situation of the motif in the cross-border electricity trade network in 2015. The motifs F7F, F8R, and GCR are not significant in the cross-border electricity trade network, which means the frequency of these three modes in the real network is lower than that in the random network. It may be because these three motifs neither include reciprocal edges, and there is no connection between the two economies. With the continuous and deep evolution of economic globalization, reciprocal trade has become an important pattern in international trade. The K4F model has the highest Z-score which means that the mode of reciprocal trade between the two economies is more important in the electricity trade network, but its frequency is less, so it is necessary to further expand the reciprocal trade in the cross-border electricity trade network. The Z-scores of GQX and GDF models ranked second and third respectively, and both included two reciprocal sides, which once again confirmed the importance of reciprocal trade in the real network. F8R, F8X, and GCX are the most frequently used motifs, which reflect the imbalance in cross-border electricity trade. These three motifs share the pattern that two economies have no trade relationship, and there is a one-way export situation, indicating that in the cross-border electricity trade, there is more one-way transmission trade, and the electricity demand and supply of economies are imbalanced. The last column shows that the top three economies of various motifs in the cross-border electricity trade network are all located in Europe, and most of the top three economies are dominated by the Czech Republic, Slovenia and Germany. The European electricity trade network covers a wide range. From the centrality analysis in the previous section, it can also be seen that the Czech Republic, Slovenia and Germany take part in cross-border electricity trade frequently and play an important role in the formation of the network.
Table 2. Individual structure characteristics of cross-border electricity trade network in 2015.

| Code | Motif | Frequency | p-Value | Z-Score | Top Three |
|------|-------|-----------|---------|---------|-----------|
| F7F  | 1     | 1555      | 1       | 0       | CZE (332); SVN (301); DEU (213) |
| F8R  | 2     | 2859      | 1       | 0       | SVN (600); DEU (426) |
| F8X  | 3     | 2297      | 0       | 22.415  | CZE (555); SVN (532); DEU (361) |
| FHX  | 4     | 1182      | 0       | 33.073  | SVN (348); CZE (310); DEU (219) |
| FMF  | 5     | 484       | 0       | 47.008  | CZE (129); DEU (95) |
| GCR  | 6     | 1620      | 1       | 0       | NLD (355); CZE (354); SVN (320) |
| GCX  | 7     | 2228      | 0       | 20.369  | CZE (563); SVN (533); DEU (377) |
| GDF  | 8     | 881       | 0       | 50.037  | SVN (234); CHE (159) |
| GOX  | 9     | 346       | 0       | 21.173  | SVN (107); CZE (90); DEU (71) |
| GQX  | 10    | 731       | 0       | 73.844  | SVN (259); CZE (204); DEU (170) |
| IMF  | 11    | 873       | 0       | 43.343  | SVN (290); CZE (236); DEU (191) |
| JQF  | 12    | 451       | 0       | 41.072  | SVN (147); CZE (126); DEU (98) |
| K4F  | 13    | 102       | 0       | 98.609  | SVN (38); CZE (29); DEU (25) |

5. Analysis of Influencing Factors of Cross-Border Electricity Trade Network

Analyzing the cross-border electricity trade model from the overall and individual structure can help us to better understand the evolution of the global electricity trade network. We are also curious about the internal reasons behind the structure. This paper uses the ERGM model to further explore which factors have affected the formation of the cross-border electricity trade network. The biggest feature of ERGM is that it has both endogenous structure and exogenous structure, which can solve the endogenous problems in network analysis and simplify the analysis method. Table 3 shows the meaning of ERGM structural statistic variables.
5.1. Variables

5.1.1. Pure Structural Effect

In some cases, the internal structure of the network will promote the formation of the network which is called pure structural effect. The endogenous structure variables of the network mainly include the edges, reciprocity, out-3 stars, in-3 stars and more. However, due to strong convergence, adding triangular structure variables to the ERGM model may cause the model to attenuate or even not converge [73]. Therefore, in order to better show the role of various factors in promoting the formation of the cross-border electricity trade network, this paper selects the edges and reciprocity.

5.1.2. Actor Attribute Effect

Actor attribute variables are the nature of the node, and they can be used to test the influence of different attributes between economies on the formation of the electricity trade network. This paper specifically analyzes the four aspects of homophily, heterophily, receiving effect and sender effect: (1) Homophily applies to binary attribute variables.

| Effect Classification | Variable Symbol | Variable Name | Schematic Diagram | Meaning |
|-----------------------|-----------------|---------------|-------------------|---------|
| Pure structural effect | Edges           | Edges         | ![Diagram](image)  | The influence of network density on the formation of network relations, which is similar to a constant. |
|                       | Mutual          | Reciprocity   | ![Diagram](image)  | Whether the network economies prefer reciprocal trade. |
|                       | Ostar-K         | Out-K Star    | ![Diagram](image)  | The impact of scalability on the formation of network relationships. |
|                       | Istar-K         | Istar-K       | ![Diagram](image)  | The influence of convergence on the formation of network relationships. |
| Homophily             | Homophily effect| ![Diagram](image)  | Whether economies with the same node attributes are more inclined to form network relationships. |
| Heterophily           | Heterophily effect| ![Diagram](image)  | The influence of economies with different node attributes on the formation of network relationships. |
| Receiver              | Receiver effect | ![Diagram](image)  | The influence of node attributes on network inbound relationships. |
| Sender                | Sender effect   | ![Diagram](image)  | The influence of node attributes on network outgoing relationships. |
| Network embedding effect | NCov            | Network covariates | ![Diagram](image)  | The influence of other network relationships on the cross-border electricity trade network relationships. |
To test whether economies with the same level of per capita carbon dioxide emissions are more inclined to trade in electricity, we divide per capita carbon dioxide emissions into three levels: high, medium, and low. The top 25% belongs to the low carbon group, the bottom 25% being high, and the rest are medium grades. The result is analyzed separately based on the medium grade. (2) Heterophily applies to continuous variables to test the influence of the differences in attributes between economies on the formation of the electricity trade network. This paper selects the economic development level of economies, industrial structure, electricity price and electricity installed capacity to measure the impact of attribute differences. (3) The receiving effect is used to analyze whether an economy with a certain attribute in the network is more inclined to import electricity, and the sending effect corresponds to the inclination to export electricity. In this part, we select the proportion of renewable energy electricity generation, electricity production, electricity demand and electricity loss.

5.1.3. Network Embedding Effect

Network covariates examine the important factors in the formation of the electricity trade network from the exogenous context. We analyze the common language network, the distance network and the institutional difference network from the perspective of the “embedding” of the exogenous network. Common language selects whether the two economies have the same official language. Having a common language between the two economies will reduce the cost of trade and thus facilitate the occurrence of trade between economies [74]. Distance has a greater impact on trade [75]. With the development of technology and the diversification of transportation methods, the impact of distance on general trade has been greatly reduced. However, since electricity trade has high requirements for geographical restrictions, trade may be more likely to occur in economies that are close to each other. In order to better illustrate the positive influence of distance, we select the reciprocal of distance for analysis. The institutional difference index is calculated according to Equation (11). The political system and governance model between economies will affect the formation of global trade to a large extent [76]. The institutional difference index comprehensively measures the governance indicators of various economies from the six governance dimensions of voice and accountability, political stability and no violence, government effectiveness, regulatory quality, rule of law and control of corruption [77,78]. In Equation (11), WGI is the institutional distance between economy i and economy j, and respectively represent the scores of i and j in institutional dimension k, and represent the maximum and minimum of institutional dimension k respectively.

\[
WGI_{ij} = \frac{1}{6} \sum_{k=1}^{6} \frac{|I_{ik} - I_{jk}|}{\max I_k - \min I_k}
\] (11)

5.2. ERGM Results

Table 4 shows the ERGM results. See the Appendix A for the meaning of variables. First, analyze the benchmark model (1) that only includes endogenous structural variables. The edges are negative and the edges are mainly used as the intercept term in ERGM, so there is no need to explain its economic meaning. Mutual is significantly positive at the 1% level, indicating that economies in the cross-border electricity trade network are more inclined to have electricity trade with each other, and compared with random networks, the probability of reciprocal trade between economies in the real network is higher. The existing trade can no longer be fully explained by comparative advantages and factor endowments and is more inclined to intra-industry trade, which is consistent with the results of the motif analysis.
Table 4. ERGM analysis of cross-border electricity trade in 2015.

| Variables | Benchmark Model | Attribute Model | Network Covariate Model | Compound Model |
|-----------|----------------|----------------|-------------------------|----------------|
|           | (1)            | (2)            | (3)                     | (4)            | (5)            | (6)            |
| Pure structural variables |               |                |                         |                |                |                |
| Edges     | -4.540 ***     | -4.087 ***     | -3.329 ***              | -4.115 ***     | -4.799 ***     | -4.250 ***     |
|           | (0.095)        | (0.046)        | (0.045)                 | (0.043)        | (0.040)        | (0.039)        |
| Mutual    | 5.491 ***      | 5.314 ***      | 5.138 ***               | 5.263 ***      | 4.683 ***      | 4.596 ***      |
|           | (0.205)        | (0.019)        | (0.019)                 | (0.018)        | (0.019)        | (0.018)        |
| Homophily (pc2) | 0.373 ***  | 0.231 ***      | 0.354 ***               | 0.224 ***      | 0.141 ***      | 0.141 ***      |
|           | (0.086)        | (0.070)        | (0.066)                 | (0.062)        | (0.065)        | (0.065)        |
| Receiver (pc2low) | -0.113 *** | -0.090 **     | -0.177 ***              | -0.022 ***     | -0.088 ***     | -0.088 ***     |
|           | (0.040)        | (0.042)        | (0.039)                 | (0.036)        | (0.033)        | (0.033)        |
| Sender (pc2low) | -0.840 *** | -0.826 ***    | -0.913 ***              | -0.762 ***     | -0.815 ***     | -0.815 ***     |
|           | (0.037)        | (0.040)        | (0.037)                 | (0.036)        | (0.034)        | (0.034)        |
| Receiver (pc2high) | 0.546 *** | 0.560 ***     | 0.513 ***               | 0.470 ***      | 0.448 ***      | 0.448 ***      |
|           | (0.053)        | (0.053)        | (0.054)                 | (0.055)        | (0.054)        | (0.054)        |
| Sender (pc2high) | -0.307 *** | -0.263 ***    | -0.349 ***              | -0.317 ***     | -0.341 ***     | -0.341 ***     |
|           | (0.050)        | (0.050)        | (0.051)                 | (0.049)        | (0.048)        | (0.048)        |
| Heterophily (GDP) | -0.0002 **   | -0.0002 **    | -0.0002 **              | -0.0002 **     | -0.0002 **     | -0.0002 **     |
|           | (0.0001)       | (0.0001)       | (0.0001)                | (0.0001)       | (0.0001)       | (0.0001)       |
| Receiver (GDP) | 0.0001 **   | 0.0001 **     | 0.0001 *               | 0.0001 **      | 0.0001 **      | 0.0001 **      |
|           | (0.0001)       | (0.0001)       | (0.001)                 | (0.001)        | (0.001)        | (0.001)        |
| Sender (GDP) | 0.0004 ***    | 0.0004 ***    | 0.0004 ***              | 0.0002 **      | 0.0002 **      | 0.0002 **      |
|           | (0.0001)       | (0.0001)       | (0.0001)                | (0.0001)       | (0.0001)       | (0.0001)       |
| Heterophily (industry) | -33.682 *** | -29.308 ***   | -31.232 ***             | -17.055 ***    | -14.236 ***    | -14.236 ***    |
|           | (0.143)        | (0.138)        | (0.141)                 | (0.135)        | (0.135)        | (0.135)        |
| Heterophily (price) | -0.042 ***  | -0.040 ***    | -0.042 ***              | -0.027 ***     | -0.029 ***     | -0.029 ***     |
|           | (0.009)        | (0.009)        | (0.009)                 | (0.010)        | (0.010)        | (0.010)        |
| Heterophily (capacity) | 0.001         | 0.0003 (0.001) | 0.001                   | 0.004         | 0.003         | 0.003         |
|           | (0.001)        | (0.001)        | (0.001)                 | (0.001)        | (0.001)        | (0.001)        |
| Receiver (renewable) | 0.169 *** | 0.191 ***     | 0.193 ***               | 0.309 ***      | 0.290 ***      | 0.290 ***      |
|           | (0.035)        | (0.022)        | (0.023)                 | (0.014)        | (0.014)        | (0.014)        |
| Sender (consumption) | -0.013 *** | -0.015 ***    | -0.013 ***              | -0.013 ***     | -0.013 ***     | -0.013 ***     |
|           | (0.003)        | (0.003)        | (0.003)                 | (0.004)        | (0.004)        | (0.004)        |
| Sender (generation) | 0.012 *** | 0.013 ***     | 0.011 ***               | 0.012 ***      | 0.012 ***      | 0.012 ***      |
|           | (0.003)        | (0.003)        | (0.003)                 | (0.003)        | (0.003)        | (0.003)        |
| Sender (loss) | -0.0003        | 0.00001 (0.003) | -0.002 (0.003)          | 0.006 ** (0.003) | 0.005 * (0.003) | 0.005 * (0.003) |
|           | (0.003)        | (0.003)        | (0.003)                 | (0.003)        | (0.003)        | (0.003)        |
| Network covariates |               |                |                         |                |                |                |
| Edgewise (WGI) | -3.204 ***     | 0.719 ***      | 0.401 ***               | -1.820 ***     | -1.820 ***     | -1.820 ***     |
|           | (0.011)        | (0.020)        | (0.011)                 | (1.546)        | (1.546)        | (1.546)        |
| Edgewise (language) | 974.138 *** | 863.523 ***   | 863.523 ***             | 9188.713       | 1958.653       | 1958.653       |
| Edgewise (distance) | 2567.345 ,345 | 2414.505      | 2311.548                | 2378.616       | 1988.713       | 1958.653       |
| BIC       | 2581.942       | 2558.577      | 2442.918                | 2509.986       | 2120.083       | 2104.620       |

Note: * significant at 10%, ** significant at 5%, *** significant at 1%.

Model (2) adds actor attribute variables to the benchmark model. Firstly, we analyze the impact of the environment on cross-border electricity trade. Homophily (pc2) is significantly positive, indicating that the current global electricity trade occurs between economies with the same level of carbon dioxide emissions per capita. The reasons are as follows: on the one hand, the electricity trade network is under development, and most of the trade happens within regions. Therefore, from a global perspective, cross-border electricity trade is still carried out among economies with the same per capita carbon dioxide emission level. On the other hand, in the ERGM matching test, the classification data is used to divide the per capita carbon dioxide into three levels, which can only show the trade situation between the levels, but not the trade situation within each level. Furthermore, we test whether economies with more per capita CO2 emissions or economies with less per capita CO2 emissions tend to import and export electricity from sender effect and receiver effect. Receiver (pc2low) and Sender (pc2low) are significantly negative at the 1% level, which means that economies with low per capita carbon dioxide emissions
are not inclined to electricity trade. The main reason is that economies with low per capita carbon dioxide emissions are concentrated in Asia, Africa and some areas in Latin America. These economies are economically backward, technologically underdeveloped and geographic restrictions can stop them from trading electricity on a global scale. Receiver (pco2high) and Sender (pco2high) are significantly positive and significantly negative at the 1% level respectively. That means, economies with higher per capita carbon dioxide emissions are more inclined to import electricity rather than export it, which is conducive to the improvement of the global environment.

Secondly, we analyze the impact of economic development level on cross-border electricity trade. Heterophily (GDP) is significantly negative at the 5% level, indicating that economies with large GDP gaps are not inclined to develop electricity trade. Electricity trade and economies with similar economic development levels are also very similar in industrial structure and are more prone to trade. Receiver (GDP) and Sender (GDP) are significantly positive, showing that economies with high GDP levels are more inclined to develop electricity trade. Economies with higher economic levels also have high demand for and supply of electricity, so they are more inclined to have trade relations with other economies.

Thirdly, we explore the influence of industrial structure and electricity structure on the formation of the electricity trade network. Heterophily (industry) is significantly negative, showing that economies with large differences in industrial structure are not inclined to electricity trade. The reason may be that economies with different industrial structures have inconsistent electricity supply and demand, which makes it impossible to conduct electricity trade. Heterophily (price) is significantly negative at the 5% level. The difference in electricity prices between neighboring countries is small, and the geographical distance hinders the long-distance cross-border electricity trade. Therefore, cross-border electricity trade is more likely to occur between economies with small differences in electricity prices. Sender (renewable) is significantly positive at the level of 1%, showing that economies with a relatively high proportion of renewable energy electricity generation are more inclined to export electricity. The electricity generation in economies with high renewable energy resources can benefit the protection of the ecological environment by strengthening their electricity export, which proves once again that cross-border electricity trade is beneficial to the environment. Sender (consumption) and Sender (generation) are significantly negative and positive respectively at the 1% level, which means that electricity-producing economies tend to export electricity while electricity-consuming economies are more inclined to import electricity, confirming that cross-border electricity trade is helpful to solve the problem of electricity supply and demand mismatch, thereby accelerating the speed of global electricity production. In addition, the installed capacity and electricity losses have no significant effect on the formation of the global electricity trade.

Next, we study the impact of institutional cost, cultural cost, and transportation cost on the formation of cross-border electricity trade. Based on the attribute model (2), we successively add the institutional difference network Edgecov (WGI), the common language network Edgecov (language) and the distance network Edgecov (distance). Model (3) examines the influence of institutional differences on the formation of the cross-border electricity trade network. It is significantly negatively correlated at the level of 1%, indicating that economies with greater institutional differences are less likely to develop electricity trade, considering the increased trade costs and uncertainty risks. If an economy’s institution is more relaxed than another economy’s institution, thereby reducing the production costs of products, we say the economy has institutional comparative advantages [79]. Model (4) adds the common language network variable, and the coefficient is significantly positive, showing that trade is more likely to occur when two economies have a common language and cultural foundation. Barrier-free communication will promote the formation of trade and reduce misunderstandings about cooperation agreements, which can reduce cultural costs and trade risks. Model (5) adds the distance network variable, the coefficient is significantly positive. The result makes sense since we use the reciprocal of
the actual geographic distance. It means long distances can lead to higher transportation costs between economies, which is not conducive to generating electricity trade.

In addition, the compound model (6) puts all variables together for ERGM regression, and the results of variables are approximately the same. The AIC and BIC values in the compound model are relatively lower than the previous results, indicating that the goodness of fit of the model has been further improved. The influence of distance is greater which means that geographical factors play important roles in developing global electricity trade, and distance is more restrictive for cross-border electricity trade.

To test the robustness of the conclusions, we further use ERGM to analyze the factors affecting electricity trade in 2005 and 2010. Table 5 shows the dynamic comparison of the factors affecting the cross-border electricity trade network in 2005, 2010, and 2015. Since we only obtain electricity price data in 2015, we don’t include electricity price in the dynamic analysis. It can be seen from Table 5 that the ERGM results in 2005 and 2010 are roughly the same as the results in 2015. Except for individual variables that have changed, other variables remain relatively stable. For example, heterophily (GDP) is not significant in 2010, but the sign remains negative. Among them, Sender (pco2high) changes the most, from negative significant to negative significant, which indicates that economies with large per capita carbon dioxide emissions are gradually reducing electricity export.

Table 5. Dynamic evolution of influencing factors in cross-border electricity trade.

| Variables                      | 2005                      | 2010                      | 2015                      |
|--------------------------------|---------------------------|---------------------------|---------------------------|
|                                | Attribute Model           | Compound Model            | Attribute Model           | Compound Model            | Attribute Model           | Compound Model            | Attribute Model           | Compound Model            |
| Pure Structural variables      |                           |                           |                           |                           |                           |                           |                           |                           |
| Edges                          | -3.821*** (0.050)         | -4.032*** (0.070)         | -4.621*** (0.039)         | -4.839*** (0.044)         | -4.303*** (0.035)         | -4.391*** (0.031)         |                           |                           |
| Mutual                         | 4.327*** (0.016)          | 3.555*** (0.018)          | 5.609*** (0.015)          | 4.985*** (0.016)          | 5.342*** (0.013)          | 4.614*** (0.012)          |                           |                           |
| Homophily (pco2)               | 0.347*** (0.088)          | -0.018 (0.110)            | 0.299*** (0.071)          | 0.046 (0.090)             | 0.365*** (0.066)          | 0.121* (0.065)            |                           |                           |
| Receiver (pco2low)             | -0.492*** (0.045)         | -0.366*** (0.054)         | -0.873*** (0.032)         | -0.791*** (0.035)         | -0.158*** (0.040)         | -0.123*** (0.004)         |                           |                           |
| Sender (pco2high)              | -0.691*** (0.048)         | -0.455*** (0.058)         | -0.388*** (0.039)         | -0.445*** (0.045)         | -0.885*** (0.037)         | -0.846*** (0.005)         |                           |                           |
| Receiver (pco2high)            | 0.231*** (0.068)          | 0.064 (0.078)             | 0.324*** (0.055)          | 0.245*** (0.064)          | 0.555*** (0.053)          | 0.441*** (0.051)          |                           |                           |
| Sender (pco2high)              | -0.015 (0.069)            | -0.118 (0.081)            | 0.149*** (0.054)          | 0.121* (0.063)            | -0.326*** (0.050)         | -0.359*** (0.044)         |                           |                           |
| Heterophily (GDP)              | -0.0003*** (0.0001)       | -0.0003*** (0.0001)       | -0.0002 (0.0001)          | -0.0001 (0.0001)          | -0.0002** (0.0001)        | -0.0002** (0.0001)        |                           |                           |
| Receiver (GDP)                 | 0.004*** (0.0001)         | 0.004*** (0.0001)         | 0.0001 (0.0001)           | 0.0001* (0.0001)          | 0.0002*** (0.0001)        | 0.0002*** (0.0001)        |                           |                           |
| Sender (GDP)                   | 0.0005*** (0.0001)        | 0.001*** (0.0001)         | 0.0004*** (0.0001)        | 0.0003** (0.0001)         | 0.0003*** (0.0001)        | 0.0003*** (0.0001)        |                           |                           |
| Heterophily (industry)         | -46.373*** (0.092)        | -30.567*** (0.093)        | -32.978*** (0.112)        | -17.278*** (0.104)        | -36.069*** (0.137)        | -15.817*** (0.135)        |                           |                           |
| Heterophily (capacity)         | -0.002 (0.001)            | -0.001 (0.001)            | -0.0003 (0.001)           | -0.0002 (0.001)           | 0.0005 (0.001)            | 0.0002 (0.001)            |                           |                           |
| Heterophily (renewable)        | 0.119*** (0.045)          | 0.205*** (0.052)          | 0.541*** (0.037)          | 0.894*** (0.043)          | 0.134*** (0.031)          | 0.270*** (0.012)          |                           |                           |
| Heterophily (consumption)      | -0.029*** (0.006)         | -0.028*** (0.006)         | -0.026*** (0.005)         | -0.026*** (0.006)         | -0.011*** (0.003)         | -0.012*** (0.004)         |                           |                           |
| Heterophily (loss)             | 0.027*** (0.005)          | 0.025*** (0.006)          | 0.024*** (0.004)          | 0.023*** (0.005)          | 0.010*** (0.003)          | 0.011*** (0.003)          |                           |                           |
| Heterophily (loss)             | 0.007 (0.007)             | 0.025*** (0.008)          | 0.007 (0.005)             | 0.019*** (0.005)          | -0.001 (0.003)            | 0.004 (0.003)             |                           |                           |
Table 5. Cont.

| Variables          | Attribute  | Compound | Attribute  | Compound | Attribute  | Compound |
|--------------------|------------|----------|------------|----------|------------|----------|
|                    | Model      | Model    | Model      | Model    | Model      | Model    |
| Edgecov (WGI)      |            |          | −1.440 *** | (0.028)  | −1.673 *** | (0.014)  |
| Edgecov (language) | 0.738 ***  | (0.163)  | 0.499 ***  | (0.017)  | 0.371 ***  | (0.009)  |
| Edgecov (distance) | 801.902 ***| (1.189)  | 754.871 ***| (1.539)  | 875.894 ***| (1.537)  |
| AIC                | 1638.516   | 1368.874 | 2025.382   | 1654.681 | 2434.686   | 1963.468 |
| BIC                | 1747.725   | 1498.560 | 2140.263   | 2175.103 | 2551.459   | 2102.137 |

Note: * significant at 10%, ** significant at 5%, *** significant at 1%.

6. Conclusions

Based on the complex network analysis method, this paper analyzes the characteristics of the cross-border electricity trade network structure from three levels: the overall, individual and microstructure level. Furthermore, ERGM is used to reveal the factors affecting the formation of the cross-border electricity trade network. The conclusions of this paper are as follows:

(1) From the perspective of overall structural characteristics, the cross-border electricity trade network continues to expand. However, due to the limitations of technology and geographical location, many economies are still outside of the global electricity trade. At present, the electricity trade network mainly expands in depth, and the growth of trade relations is faster than that of the number of economies participating in electricity trade. In addition, the degree of reciprocity among economies has been increasing, indicating that economies tend to trade with each other.

(2) From the perspective of individual structural characteristics, the level of cross-border electricity trade in Europe is high and plays an important role in the global electricity trade network. With the improving status of Asian economies in the betweenness centrality, the global electricity trade network is moving eastward.

(3) From the perspective of influencing factors analysis, the cross-border electricity trade network presents more reciprocity, and the influence factors on global electricity trade are relatively stable. In terms of the environment, economies with a higher proportion of renewable energy tend to export electricity, and economies with higher per capita carbon dioxide emissions also tend to import electricity rather than export electricity, which helps to reduce air pollution. In terms of heterophily, large gaps in GDP, electricity prices and industrial structure between economies are not conducive to the formation of a cross-border electricity trade network. With the development of the global value chain and the prevalence of intermediate product trade, the economies with similar industrial structures and similar economic development levels are more prone to intra-industry trade. Moreover, in terms of electricity structure, electricity producing economies tend to export electricity in the network, while electricity demand economies tend to import electricity, which is conducive to reducing the mismatch of electricity supply and demand. Economies with a high proportion of renewable energy generation also tend to export electricity, which promotes the development of renewable energy. The installed electricity capacity and electricity loss have no significant impact on cross-border electricity trade. Among network covariates, geographic distance has the strongest negative influence on the formation of the electricity trade network. Having a common language makes it easier to carry out electricity trade, and large institutional gaps are barriers to the formation of a cross-border electricity trade network.

Based on the conclusions of this paper, in order to promote the expansion of the cross-border electricity trade network and achieve sustainable development, we make the following suggestions to both market participants and the governments:

Participants in the electricity market should form a benign competitive relationship to avoid the problem of line congestion. They should also abide by market rules and
take social responsibility. Electricity generation enterprises and sales companies could actively strengthen cooperation with foreign electricity industries under the coordination of national policies.

Governments should give full play to their leading roles and actively guide cross-border electricity trade. Firstly, the governments should formulate energy conservation and emission reduction policies. They could also provide technical and financial support to electricity producers, to increase the proportion of renewable energy electricity generation and reduce CO\textsubscript{2} emissions. Secondly, governments of all economies should actively seek transnational power cooperation to promote global grid interconnection. Strengthen electricity trade cooperation to achieve steady growth of global electricity production and reduce the mismatch between supply and demand. Europe and North America should accelerate the transfer of technology to other backward regions, forming a new development pattern of mutual assistance and mutual benefit. Thirdly, with the eastward transfer of cross-border electricity trade network, Asian economies should strengthen the construction of power grid infrastructure, accelerate the use of renewable energy for electricity generation, and cover the power grid to backward areas. The Eurasian continent should strengthen the power interconnection and realize the power flow from low CO\textsubscript{2} emissions economies to high CO\textsubscript{2} emissions economies. Finally, economies should lower the threshold of cross-border electricity trade and promote the free trade of electricity. For example, reducing the institutional cost, cultural cost and transportation cost between economies will contribute to the development of cross-border electricity trade networks.

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### Appendix A. Data Source and Data Description

**Table A1.** The definition and source of influencing factors in ERGM analysis.

| Variable | Definition | Source |
|----------|------------|--------|
| **Pure structural effect** | | |
| Edges | The influence of network density on the formation of network relations, which is similar to a constant | ERGM https://cran.r-project.org/web/packages/ergm/index.html (accessed on 17 February 2021) |
| Mutual | Reciprocity | ERGM https://cran.r-project.org/web/packages/ergm/index.html (accessed on 17 February 2021) |
| **Actor attribute effect** | | |
| pco2 | Carbon dioxide emissions per capita (It is divided into three levels according to the emissions) | World Development Indicators Database (WDI) https://databank.worldbank.org/source/world-development-indicators (accessed on 17 February 2021) |
| GDP | Gross domestic product (current prices, millions of US dollars) | UNdata database https://data.un.org/ (accessed on 17 February 2021) |
Table A1. Cont.

| Variable          | Definition                                      | Source                                                                 |
|-------------------|-------------------------------------------------|------------------------------------------------------------------------|
| **Actor attribute effect**                                                                                                          |
| industry          | Proportion of secondary industry in GDP         | World Development Indicators Database (WDI)                            |
|                   |                                                 | [https://databank.worldbank.org/source/world-development-indicators](https://databank.worldbank.org/source/world-development-indicators) | accessed on 17 February 2021 |
| renewable         | Proportion of renewable energy in electricity production | International Renewable Energy Agency (IRENA)                         |
|                   |                                                 | [https://www.irena.org/](https://www.irena.org/)                      | accessed on 17 February 2021 |
| capacity          | Electricity installed capacity (MW)             | International Renewable Energy Agency (IRENA)                         |
|                   |                                                 | [https://www.irena.org/](https://www.irena.org/)                      | accessed on 17 February 2021 |
| consumption       | Electricity domestic consumption (TWh)          | UNdata database                                                        |
|                   |                                                 | [https://data.un.org/](https://data.un.org/)                           | accessed on 17 February 2021 |
| generation        | Electricity production (TWh)                    | UNdata database                                                        |
|                   |                                                 | [https://data.un.org/](https://data.un.org/)                           | accessed on 17 February 2021 |
| loss              | Electricity losses (kilowatt-hours, million)   | UNdata database                                                        |
|                   |                                                 | [https://data.un.org/](https://data.un.org/)                           | accessed on 17 February 2021 |
| price             | Electricity price (price of electricity, US cents per kWh) | Doing Business                                                       |
|                   |                                                 | [https://databank.worldbank.org/source/doing-business](https://databank.worldbank.org/source/doing-business) | accessed on 17 February 2021 |

**Network embedding effect**

| Variable | Definition                             | Source                                                                 |
|----------|----------------------------------------|------------------------------------------------------------------------|
| WGI      | Matrix of institutional distance       | World Development Indicators Database (WDI)                            |
|          |                                        | [https://databank.worldbank.org/source/world-development-indicators](https://databank.worldbank.org/source/world-development-indicators) | accessed on 17 February 2021 |
| language | Matrix of common language (official language) | CEPII Database                                                       |
|          |                                        | [http://www.cepii.fr/cepii/en/bdd_modele/bdd.asp](http://www.cepii.fr/cepii/en/bdd_modele/bdd.asp) | accessed on 17 February 2021 |
| distance | Matrix of geographical distance        | CEPII Database                                                        |
|          |                                        | [http://www.cepii.fr/cepii/en/bdd_modele/bdd.asp](http://www.cepii.fr/cepii/en/bdd_modele/bdd.asp) | accessed on 17 February 2021 |

Appendix B. Electricity Trade, Electricity Supply and Demand

Figure A1. Feature facts: (a) Share of electricity exports in electricity production (%); (b) Share of electricity imports in electricity consumption (%).
Appendix C. Electricity Installed Capacity

Figure A2. Feature facts: (a)Electricity installed capacity; (b) Share of renewables in electricity installed capacity (%).

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