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A Review of Regional Energy Internet Models Considering Complex Dynamic Evolution with Time Delay

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ABSTRACT

The model research of regional energy internet is of great significance to enhance the flexible coupling transformation of smart city multi-energy system, improve the reliability of energy supply and realize the preferential consumption of renewable energy. Based on the energy self-organization and energy community, from the perspective of complex network to carry out the wisdom of the city region energy complex dynamical network model research, through summarizing the many challenges facing the complex dynamic network institute, puts forward the study area energy Internet time-delay research idea and method of complex dynamic network model, to establish scientific value and practical significance of complex dynamic network model with time-delay system research theory and method.

Keywords: smart city, regional energy internet, time-delay complex dynamic network, model, review

NONMENCLATURE

Abbreviations	
SC	smart city
SCs	smart cities
REI	regional energy internet
CNA	complex network analysis
ESO	energy self-organization
EC	energy community
ESOs	energy self-organizations
ECs	energy communities
COMM	communication
PV	photovoltaic

1. INTRODUCTION

The construction of a smart city(SC) is the need of sustainable development. Aiming at providing solutions for urban sustainable development strategies, the United Nations, the European Union and the United States have developed a number of projects, including *the Global Initiative for Resource Efficient Cities*(GI-REC)[1] from UN, *the European In-novation Partnership on Smart Cities and Communities*(EIP -SCC)[2] from EU and *the Smart City Initiative*[3] from the US, etc. Since the 18th National Congress of the Communist Party of China, China has stepped up efforts to promote a new type of human-centered urbanization[4]. “Ecological civilization, green and low-carbon” is one of the basic principles of China’s urbanization. According to “13th Five-Year Plan”, the urbanization rate of China’s permanent resident population will reach 60% by 2020, and a number of smart cities(SCs) with distinctive characteristics will be built. The United Nations development program predicts that China’s urbanization rate will reach 70% by 2030.

Cities take up the main part of energy consumption. At present, cities account for 75% of energy consumption in China, and energy demand mainly relies on fossil energy[5]. The weak complementary supporting relation of different energy supply systems, such as cooling, heating, electricity and gas, can not provide more effective sustainable development space in reducing energy consumption and improving the consumption of renewable energy. Taking the continuous adjustment of energy structure into consideration, it is estimated that the proportion of non-fossil energy dominated by wind energy, solar energy and other renewable energy will exceed 60% around 2050. Meanwhile, the transportation energy consumption will continue to grow rapidly, reaching 25%, and highways and railways will become the main driving forces of terminal energy consumption

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growth, and their power consumption will also exceed 40% and 85%[6][7]. Moreover, romoting renewable energy consumption and developing electrified transportation by relying on multi-energy coupling and complementation are new modes and forms of energy supply system in SCs in the future. Reducing energy consumption and supplying green, low-carbon and sustainable energy are the key requirements and basic objectives of energy system in SC development. Smart energy is a new starting point for the development of urban energy system, the driving force for the development of SC, as well as a powerful guarantee for advancing smart development in other fields. Based on advanced technologies such as big data and artificial intelligence, Regional energy internet(REI)[8] couples with networks such as interconnected energy, information, transportation and society, and flexibly coordinates the production, transformation, transmission, storage and utilization of different forms of energy such as cooling, heating, electricity and gas. It is expected to improve the utilization efficiency of comprehensive energy in SCs, promote the sustainable development of multi-energy consumption and give priority to the utilization of the largest proportion of renewable energy[9]. REI is essential for smart energy, which aims at achievement of coupling interaction of multi-energy, multi-information and multi-value, intelligent management, control of energy consumption in various fields and situations of cities, energy conservation, emission reduction and sustainable energy utilization. Sharing energy and information of different space-time distribution, smart energy makes the urban energy system intelligent. REI is the specific extension and practice of smart energy and the main methods to realize it.

The advantages of SC, such as deep integration of multi-network interconnection and open and shared intelligent perception, promote the formation of a complex network of energy, information, transportation and society. It realizes the conversion, transmission, distribution, storage and utilization of different forms of energy, such as cooling, heating, electricity, gas, resulting the complex network characteristics of small world, scale-free, and community structure in multi-field, multi-system and multi-scene[10]. From the perspective of complex networks, this paper studies the complex dynamic network modeling theory of REI, adapts to its requirements of multi-coupling, multi-form, multi-scale, multi-scenario and dynamic evolution of the REI. Moreover, providing support for energy transition, low-carbon environmental protection and sustainable development of SC, this paper builds a scientific , accurate and suitable complex network model and performance analysis theory to research the partial and overall coupling interaction evolution of REI.

2. THE DEVELOPMENT OF REGIONAL ENERGY INTERNET AND THE APPLICATION OF COMPLEX NETWORK ANALYSIS

REI and its demonstration projects are vigorously advocated by many countries around the world. As early as 2001, the United States put forward the development plan of the REI[11]. In European Union, the REI is regarded as the focus of the future energy efficiency and clean development framework[12]. Energy interconnection demonstration systems have been built in New Zealand's Totara Valley's HyLink[13] and Ireland[14]. China has also built REI demonstration projects in Beijing Yanqing[15], Shanghai Disneyland[16], Tianjin Eco-city[17] and Xiong'an New Area[18]. Certain results have been achieved so far, and different types and scales of REI have been established at China and abroad, mainly including industrial parks[19][20], commercial office buildings[21], communities[22][23][24], residential housing[25][26][27], public buildings[28].

The existing REI usually consists of the production, conversion, transmission, distribution, storage, and utilization of energy such as electricity, heating, cooling, and gas[29][30], however, the transportation system is usually treated as a special energy consumption system. The coupling impact of the REI and social networks is ignored, and so is the potential of renewable energy through social collaboration in systems such as electricity, heating, cooling, and transportation. With the gradual advancement of SCs, more and more studies have focused on the coupling and interconnection of networks in different fields such as energy, information, transportation, and society, and comprehensively consider the priority consumption of renewable energy[31] and promote the development of sustainable energy[32]. Conforming to the development trend of clean, electrified, networked, and intelligent urban energy systems, REI has become an important technology to face the challenges of urban energy development and provide new solutions for the green development of smart cities[33]. The REI couples and interconnects smart grids, smart heating networks(district heating and cooling), smart gas networks, transportation networks and social networks, which obviously shows complex network characteristics[34].

Different network models based on complex network analysis(CNA) can abstract and describe the urban energy system[35][36]. City is regarded as a complex network in Ref.[37] to study the dynamic evolution of its multi-energy flow, and it is applied to practical projects that prioritize the consumption of renewable energy and the promotion of co-generation systems. In Ref.[38], the structural optimization, clean replacement, network evaluation and overall system stability in the process of urban energy production, consumption, recycling and transformation are studied by means of establishing an energy metabolism ecological network model. In Ref.[39], it considers the integrated development of the Beijing-Tianjin-Hebei urban agglomeration, establishes a multi-energy flow complex network model of Beijing-Tianjin-Hebei urban agglomeration and analyzes its dynamic evolution process. A theoretical basis for the integrated development of the city is provided. Meanwhile, attention has been paid on the design model of optimized combination energy system for widely distributed renewable energy[40]. In Ref.[41], general models of electric network, gas networks, and heating networks are established. In addition, it establishes a comprehensive model of the electricity-heating-gas coupling system based on the coupling mechanism of multi-energy networks. However, this model is only suitable for small-scale and limited multi-energy coupling systems, and it is hard to adapt to the development of urban-wide energy systems. For this reason, the corresponding complex network model for the possible interaction between the urban district heating system and energy consumers is established in Ref.[42], and it has been evaluated.

Existing research results apply complex network analysis to the modeling of the REI which have achieved certain results. However, existing researches mostly focus on the static characteristics of the complex network of the energy system, and less consideration is given to the role of transportation, information, and social networks. With the promotion of electrified transportation, the coupling of transportation networks and energy networks gets closer and closer[43][44]. The coupling of energy and transportation presents more dynamic evolution characteristics. Based on CNA, the dynamic evolution mechanism of taxis in the transportation network is studied in Ref.[45]. In Ref.[46], it applies CNA to describe the complex interactive behavior of large-scale network traffic flow. In Ref.[47], it is believed that road traffic should be regarded as an interconnected system. Maximum efficiency of traffic network can be achieved by monitoring the real-time traffic flow on its network, adjusting lane direction, traffic light time and speed limit. In Ref.[48], CNA is applied to the analysis of the public transportation network in Hohhot. It achieves the minimum number of transfers for citizens' daily trips through the shortest path analysis. In Ref.[49], it studies the complexity and periodicity of the traffic dynamic flow in the intelligent transportation system, and reveals the dynamic change law of the traffic time series by analyzing the complex network model of the traffic time series. In Ref.[50], game theory and CNA are combined to study the influence of government policies on the dynamic complex network of electric vehicles of different sizes. In Ref.[51], based on time series analysis, new research ideas for traffic analysis by establishing a complex network model of traffic flow are provided. In Ref.[52], urban rail transit network in Nanjing is abstracted into a complex network, and it studies the connectivity and dynamic vulnerability of the urban rail transit network through topology analysis.

Existing research results of REI based on CNA mainly focus on static models of the coupling, interconnection and interaction of different energy networks such as cooling, heating, electricity and gas, etc. However, dynamic evolution research and a complete theoretical system of complex dynamic network research on the integration of energy networks, transportation networks, information networks, and social networks are lacking in previous studies. Taking the self-organization and self-adaptive of energy, information, transportation and social networks into consideration, it is necessary to systematically study and establish a reasonable model analysis theory of REI, so as to meet the needs of multi-scenario and multi-energy collaborative optimization of REI.

3. REI MODEL RESEARCH CHALLENGES AND KEY SCIENTIFIC ISSUES REMAINED TO BE SOLVED

3.1 Research challenges

3.1.1 Multi-field, multi-system and multi-scenario integration challenges

It is shown in Fig 1 that SC changes the inherent development model of the traditional city's subsystems independent interaction with the environment. It promotes the integration of multi-field, multi-system, multi-scenario, improves the comprehensive utilization efficiency of urban energy and the quality of clean services by mutual coupling, interdependence and collaborative optimization of different subsystems such as smart energy, smart transportation, smart industry, smart agriculture, smart architecture and smart service[53].

The REI applies technologies such as co-generation, electricity to gas, electric refrigeration, electric heating, electrified rail transit, electric vehicles/V2G, etc., to interconnect different energy networks. The open and shared informatization and the advancement of electrified transportation reform have made the coupling relation between information network, transportation network and energy network closer. In addition, influenced by the continuous deepening of market-oriented reforms, people and society have made more impact on various links in the fields of energy, information, and transportation. Coordinated and optimized operation is closely coupled with human behavior and social activities, and forms the integration of energy physical systems with information, transportation, and social networks in various situations such as industrial parks, commercial office buildings, residential buildings and public buildings, which challenges the REI analysis model.

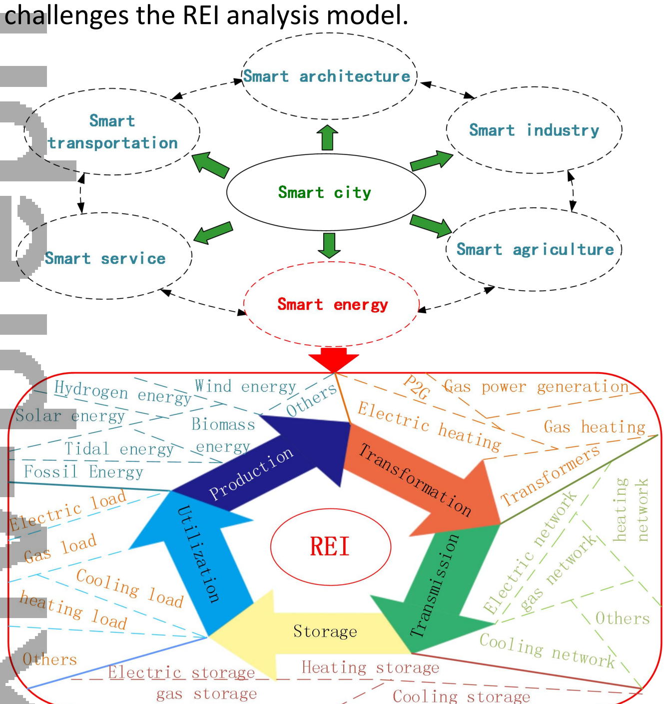


Fig 1 SC and various subsystems.

3.1.3 System network structure complexity challenge

In the REI formed by the high integration of complex networks including energy, transportation, information and society, different types and characteristics of time delay can be caused by many factors such as multi-energy flow transmission, network congestion, data collision, node failure, resource competition, information transmission and processing, comprehensive response. Different types of time delays, such as input delay, output delay, coupling delay, communication delay, and demand response delay, will have complex effects on the accurate and reasonable analysis of the complex dynamic network model of the REI.

The basis of the REI contains individual devices with different physical properties. These devices relate to different energy production, conversion, transmission, storage and utilization. Each node abstracted from a physical device can be represented as an individual in a complex network model. Based on the analysis of dynamics, the dynamic characteristics of different individuals are obviously different and have strong complexity. Those characteristics are mainly reflected in the aspects that the energy supply side and the user side have strong randomness and uncertainty, different energy coupling have various time scales, the difference among milliseconds, minutes and hours is obvious, the physical equipment of the power system has the fastest response time. Each device with different physical properties forms interconnections through coupling and conversion, which makes the relation between different individuals more complicated. Since individual devices with different physical properties are complex and diversified, and the dynamic properties are obviously different, there are many difficulties for the research on the network individual modeling of REI.

The structure of the REI from the multiple physical devices in underlying layer to the coupling of the overall multiple subsystems acts out complexity. As the scale of the REI increases, the time-delay complex dynamic network model describing the characteristics of its complex network structure has changed from a simple node-link graph to a high-order dynamic complex network model. The REI contains different subsystems, different coupling characteristics (time scale and coupling characteristics) and influencing factors (internal factors and external factors). At present, the new research direction is to describe REI by adopting different network structures to couple and interconnect and considering many factors to research its dynamic evolution. However, taking research of REI coupling with transportation network and social influence into consideration, more complex network structure appears which challenges the application of CNA and modeling research, though CNA has been applied in the field of energy.

3.1.3 Research challenges on the dynamic evolution of network individuals and structures

The REI consists of multiple energy networks such as cooling, heating, electricity, and gas, and couples interconnected information, transportation, and social networks. The deep integration among those networks with different characteristics, topological structure and dynamic changes of coupling characteristics leads to the outstanding dynamic evolution characteristics of the REI as a complex network.

The support of plug-and-play technology and the flexible coupling and interconnection of different systems lead to apparent dynamic characteristics of the network individual and structure of the REI. It is vital for studying REI to establish a dynamic model that changes over time. Dynamic network structure changes of nodes and links can provide solid theoretical foundation for research on dynamic evolution of REI.

However, in most cases, the connections among physical infrastructures and networks change dynamically over time which include coupled and interconnected operations, independent operations, and re-coupled and interconnected operations. In particular, when the scale of the REI reaches a certain level and a large number of individuals are involved in it, individuals will dynamically evolve over time and continue to change the operating states. Compared with adopting static network to describe the REI, the modeling of dynamic network faces more challenges.

3.2 Key scientific issues remained to be solved

Compared with traditional energy supply systems, REI for SCs is more closely coupled and interconnected in multiple fields, systems, and situations, and the network structure of the system is more complex. Influenced by complex and uncertain factors such as society and environment, both of the underlying system and upper system have characteristics of dynamic evolution. Therefore, in order to study the model of REI based on CNA, key scientific issues followed still remain to be solved.

(1) How to establish a complex dynamic network model suitable for the analysis of REI targeted at SC when consider its integration of multi-field, multi-system and multi-scene, time delay of multi-link and dynamic evolution of complex networked systems.

(2) How to establish a complete complex network performance metrics which is suitable for the REI on accordance with a scientific and reasonable complex network model.

(3) How to study the multi-network coupling evaluation method suitable for REI analysis in views of the shortcomings of traditional single-system evaluation method when consider the deep coupling of REI, energy information, transportation and social networks.

4. RESEARCH ON KEY ISSUES OF TIME DELAY COMPLEX DYNAMICS NETWORK MODEL

The main content of the research on the key issues of the complex dynamics network model of the REI is shown in Fig 2. Energy self-organization(ESO) and Energy community(EC) are defined in previous research[54], and ESO is the basic unit of interconnection and coupling during interaction of energy and information between the local underlying structure and the overall macro system when REI operates steadily. EC is a cluster formed by many energy self-organizations(ESOs) through direct or indirect coupling and complementary relation in a certain time and space. This paper will make a further and systematic study of complex network characteristics of ESOs and energy communities(ECs) formed through multi-energy coupling and complementation in the process of integration of energy networks, information networks, transportation networks, and social networks in SC. Based on the CNA of ESO and EC, this paper further studies the characteristics of the rule network, small-world network, scale-free network and random network of the complex dynamic network of REI, and analyzes its small world, network resilience, transitivity, clustering, power law distribution, degree distribution, and community features in order to form a complex dynamic network modeling theory suitable for analysis of coupling transmission characteristics of REI. Finally, based on the above theoretical analysis, the topological geometric properties, topological dynamic statistical laws, network coupling mechanism and network model property analysis theory of the complex dynamic network of REI are formed.

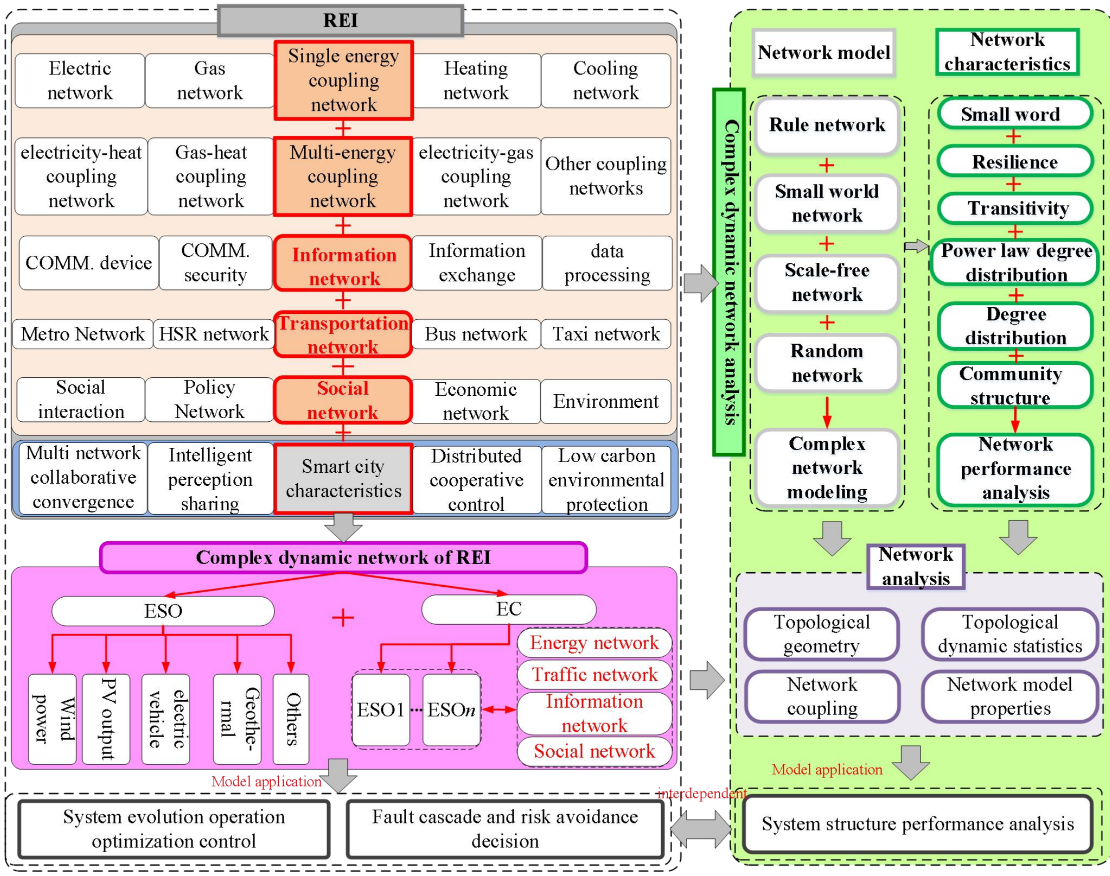


Fig 2 Research on complex dynamics network analysis theory of the REI

4.1 The research of ESOs and ECs

It is shown in Fig 3 that, as the basic components of local micro system of the underlying layer and the whole macro system of the upper layer of REI, ESOs and ECs gradually tend to integrate multiple complex networks including energy, transportation, information, and society.

In energy network, the physical equipment properties, coupling properties, transmission properties, complementary properties, distribution properties, and storage properties of the source(traditional fossil energy, renewable energy, etc.), the network(transmission, distribution, conversion and storage of energy such as cooling, heating, electricity and gas), load(multi-energy load) and storage(the energy storage of cooling, heating, electricity, gas, etc.) in different situations (industrial parks, commercial offices, residential buildings, public buildings, transportation, etc.) are mainly studied.

In transportation network, the energy supply methods (self-supply, external energy supply), coupling methods (self-coupling, coupling with other networks), load properties, planning and design methods, system and construction types, and operation modes of transportation networks including high-speed railway, subway light railway, electric vehicles, and gas vehicles are mainly studied.

In information network, the research is mainly on the effect on multi-network coupling from communication(COMM) equipment (wired, wireless COMM equipment, etc.), COMM security (sensing methods, COMM construction, etc.), information interaction methods (COMM protocols, interaction modes, etc.), and data processing (artificial intelligence, big data, cloud platform,etc.)

In social network, the research is mainly on the influence of social network formed by coupling such as social network (producers, consumers, supervisors, managers, etc.), economic networks (transaction networks, corporate and institutional networks, etc.), policy networks (national strategies, energy market policies, etc.), and the environment (natural disasters, environmental quality, etc) on energy, transportation, information and other complex network interaction and integration, collaborative and optimized operation. REI and human-centered collaborative development theory and method are also studied.

Finally, pointed at the integration trend of REI and energy, transportation, information and society networks, and based on the different system hierarchical division of ESOs and ECs, the characteristics of self-organization[55], self-optimization[56], self-operation[57], self-management[58], self-diagnosis[59], self-decision[60], and self-recovery[61] are studied, also the reliability[62], stability[63], security[64], scalability[65], high efficiency[66] and low carbon[67] of the ECs and the entire system.

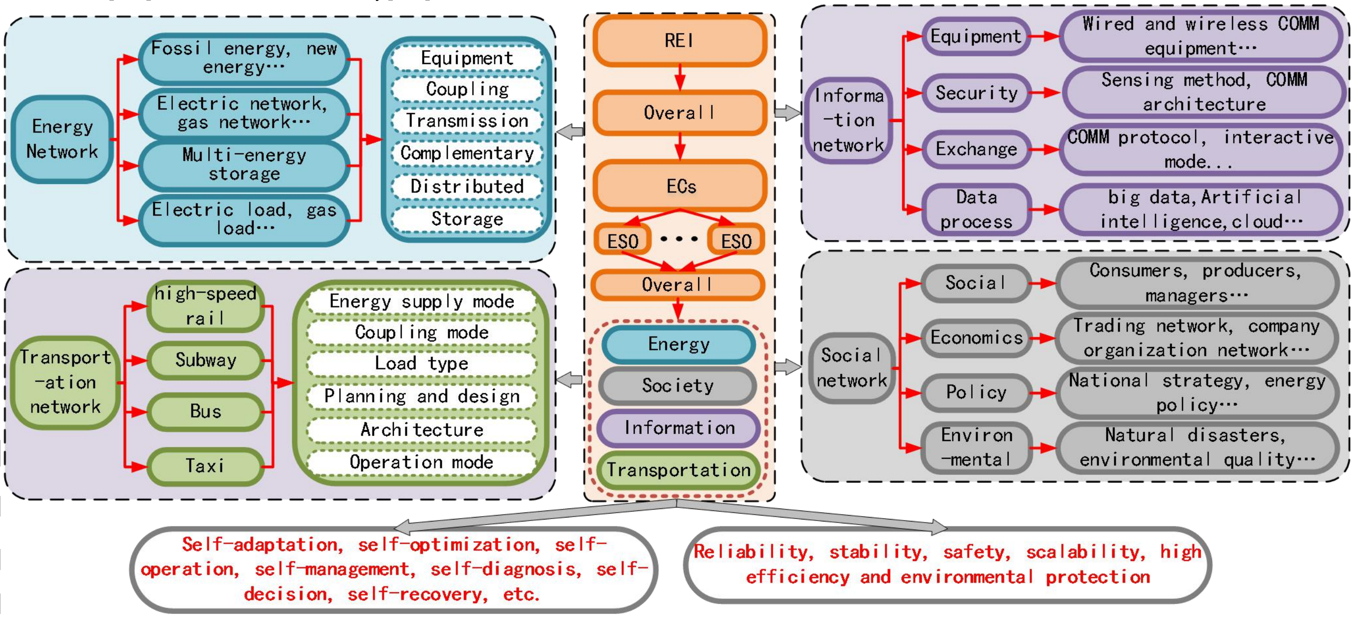


Fig 3 Research on ESO and EC.

4.2 Theoretical research on REI modeling

As shown in Fig 4, the REI modeling theory research mainly includes the single and coupled modeling theory research on energy network, information network, transportation network and social network.

The energy network modeling mainly includes the single and coupled modeling theory research on power supply network (wind, PV, geothermal, tidal, hydropower, fossil energy, etc.), heating network (photothermal, geothermal, electric heating, coal, gas, etc.), cooling network (air conditioner, refrigerator, absorption refrigeration, CO_2 refrigeration, etc.) and gas network (natural gas, hydrogen, liquefied petroleum gas, coal gas, etc.) .

Information network modeling mainly includes modeling theoretical research coupled with energy network such as information security (network security, network attacks, etc.), information interaction (interface protocols, interaction methods, etc.), and information processing (artificial intelligence, big data, cloud platforms, etc.).

The modeling of the transportation network mainly includes the research on coupling modeling theory of railway network (freight, high-speed railway, train, etc.), urban transportation network (subway, light rail, bus, taxi, etc.), personal travel transportation network (electric vehicles, fuel vehicles, etc.).

The modeling research on social network mainly includes the modeling theory of coupling influence of social network (producers, consumers, supervisors, managers, etc.), economic network (energy transactions, corporate and institutions, etc.) and policy network (national strategies, market policies, etc.) on energy network, transportation network and information network.

Taking interaction and integration of energy network, transportation network, information network and social network in REI into consideration and based on CNA (graph theory, self-organization theory, dissipative structure theory, synergetics and catastrophe theory, etc.), the structural characteristics and identification methods of ESOs are studied. Moreover, the energy coupling density, multi-dimensional application situations, hierarchical division and wide time-space distribution are also considered. Structural characteristics and identification methods of ECs are studied by adopting intelligent algorithms. The complex dynamic network modeling method of REI is studied and a complete complex dynamic network modeling theory and method including rule network, small-world network, scale-free network and random network is established through the node abstraction and coupling link equivalence of ESOs and ECs. Those studies provide a theoretical basis for the analysis of complex system structure performance, system evolution and optimal control of REI.

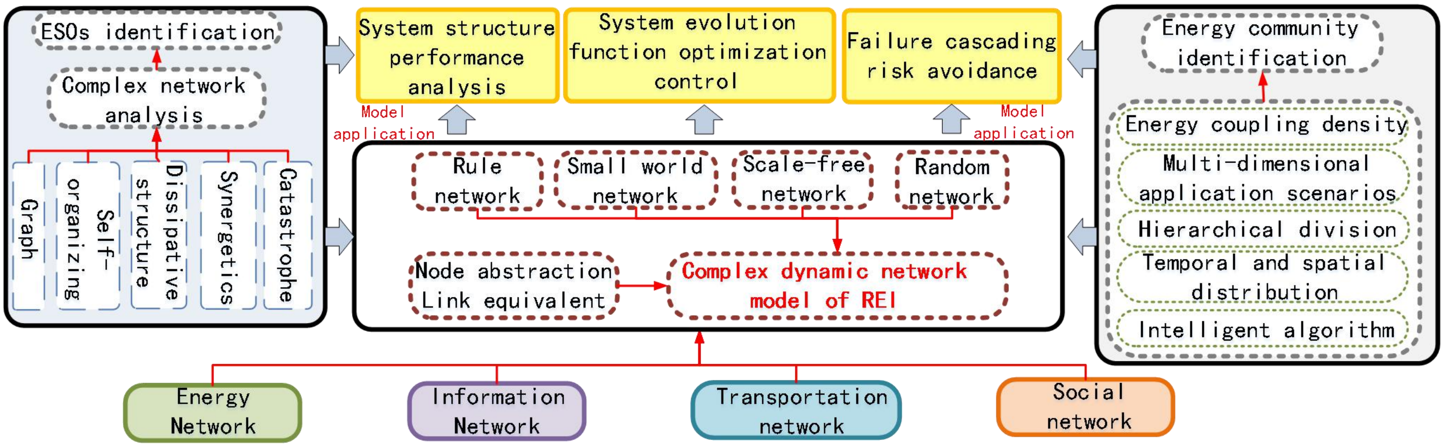


Fig 4 Modeling theoretical research on REI

4.3 Theoretical research on complex network performance analysis of REI

As shown in Fig 5, the research on the complex network performance analysis theory of the REI mainly starts from the analysis of different levels of physical infrastructure, ESOs, ECs, and the entire complex system. The specific research content is as follows.

4.3.1 Research on small world characteristics

Based on the analysis of small world characteristics, research the transmission, distribution and conversion methods of wind power, PV, geothermal, tidal, biomass and other renewable energy resources that are preferentially absorbed by multi-energy conversion technologies.

4.3.2 Research on network resilience

Based on the analysis of network resilience, the evaluation method and theory of the normal operation stability of the REI, the critical stability of the removal subsystem (or equipment), and the stability of failure recovery are studied.

4.3.3 Research on clustering characteristics

Based on the analysis of transitivity or clustering characteristics, the characteristics of multi energy-load interaction is studied and resource allocation theory and method that multi-source supplies single-load and multi-load consumes single-source are established, so as to achieve maximum energy utilization and energy supply reliability.

4.3.4 Research on centrality

Based on the analysis of degree distribution characteristics, time-space distribution characteristics of REI's energy supply center, load center, and key devices and subsystems that maintain the stability of complex system is studied.

4.3.5 Research on characteristics of community

Based on the analysis of the characteristics of ECs, the similar characteristics of energy supply, transmission, conversion, storage and consumption of multi-energy in different system levels under the coupling of energy network, transportation network, information network and social network is studied. This similarity contains not only the similarity research in a single network in a single field, but also the similarity analysis of multi-field integration and multi-network coupling.

4.3.6 Research on comprehensive evaluation methods

The comprehensive evaluation methods and theories of the REI's priority consumption of renewable energy, flexible conversion and transmission efficiency, complex system stability, economic and environmental protection, and satisfaction of social feedback are studied.

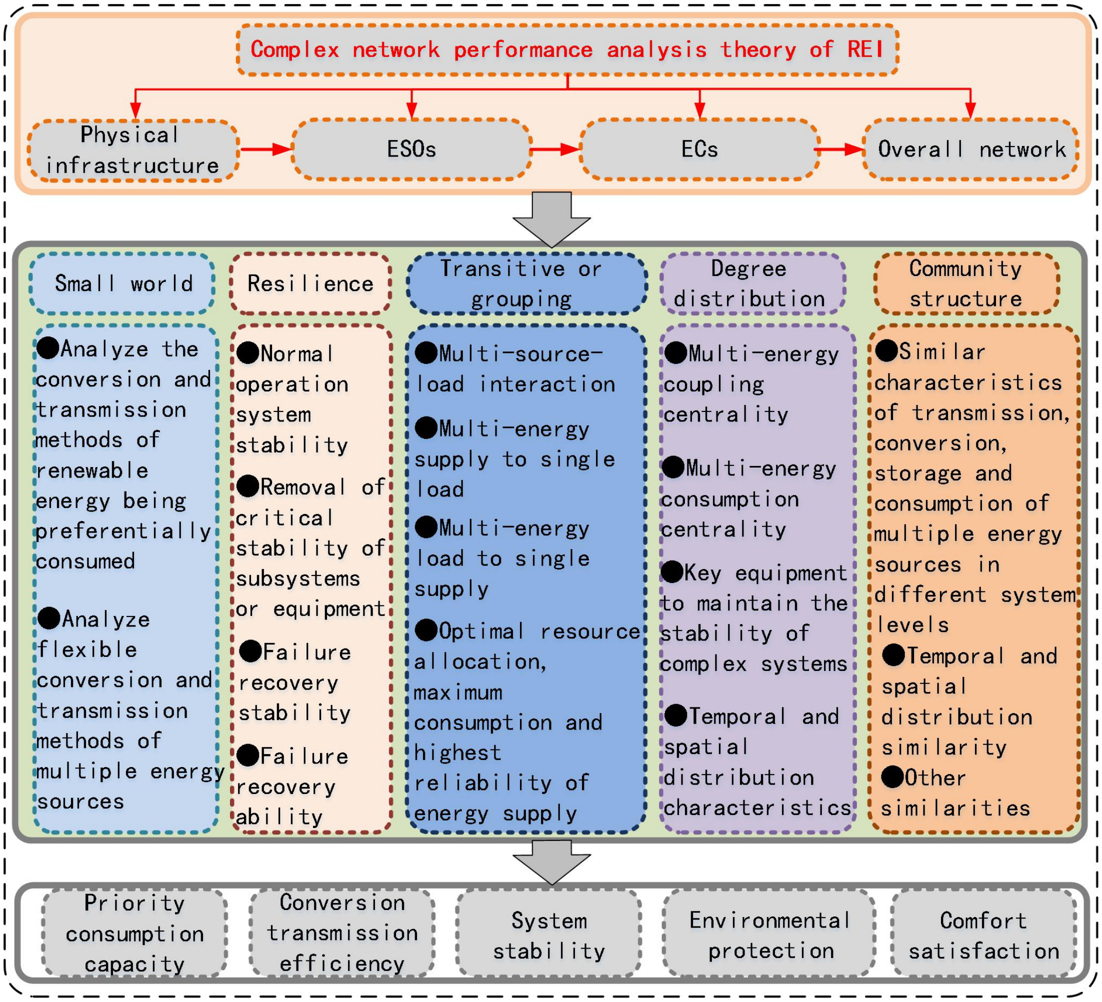


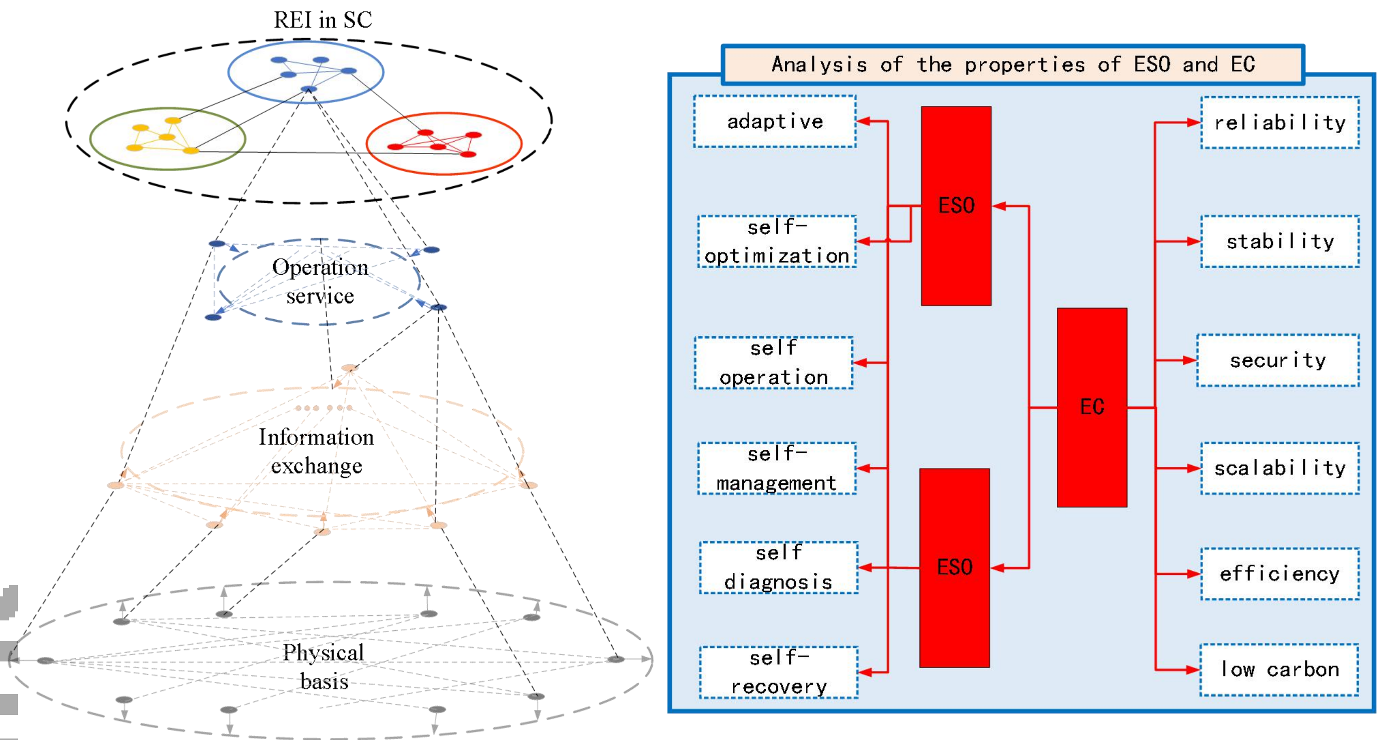
Fig 5 Theoretical research on complex network performance analysis of REI

5. RESEARCH IDEAS AND METHODS OF COMPLEX DYNAMICS NETWORK MODEL WITH TIME DELAY

The research ideas and methods proposed in this paper are as follows. The self-organization theory is used to study the properties of ESO and EC. The property of time delay of REI is studied by taking analytic hierarchy process and delay differential equation into consideration. The complex network modeling method of REI is studied by adopting graph theory considering the property of time delay, and its performance analysis method is studied based on statistical probability theory. The theory and method of complex network modeling of REI are deeply studied from the perspective of complex network.

5.1 Research ideas and methods of ESOs and ECs

(1) As shown in Fig 6, the ESO contains a large number of multi-energy sources such as cooling, heating, electricity, and gas, a large number of physical-based co-production equipment such as cogeneration units, gas boilers, heating boilers, heat pumps and other energy supply/pressurization equipment, electricity-to-gas equipment, electricity-driven refrigerators, adsorption refrigerators, heat exchange and other energy conversion equipment, storage equipment for electricity, gas, heating, as well as information exchange service systems. Based on the coupling, interconnection and interaction among them, the coupling relation among physical basic layer, information exchange layer and operation service layer is studied by adopting analytic hieraichy process[68]. The properties of self-organizing, self-optimization, self-operation, self-management, self-diagnosis, self-decision, self-recovery are studied on the basis of self-organization theory. The reliability, stability, security, scalability and efficiency of ECs are studied by considering various roles of different energy sources in typical application scenarios such as resident life, urban management, industrial and agricultural production, commercial office, public facilities, transportation and environmental tourism and adopting dynamic weighting method and fuzzy synthetic evaluation method.



(a) (b)

Fig 6 REI structure division based on ESO and EC (a) and characteristic analysis (b)

(2) Since complex network of REI formed by coupling and interconnection of energy and information, transportation and society is affected by more factors, the dynamic interaction of complex networks between energy and information, transportation and society in REI is studied by adopting differential equations (e.g formula (1)), and the impact of property of time delay (e.g formula (2)) on REI is also further studied.

$$\begin{cases} \dot{x}_i(t)=f(x_i(t))+\mu\sum\limits_{j=1}^{N}a_{ij}x_j(t)+\rho\sum\limits_{j=1}^{N}o_{ij}^{xy}y_j(t)+\gamma\sum\limits_{j=1}^{N}p_{ij}^{xz}z_j(t)+\delta\sum\limits_{j=1}^{N}q_{ij}^{xs}s_j(t) \\ \dot{y}_i(t)=g(y_i(t))+\varepsilon\sum\limits_{j=1}^{N}b_{ij}y_j(t)+\rho\sum\limits_{j=1}^{N}o_{ij}^{yx}x_j(t)+\nu\sum\limits_{j=1}^{N}\omega_{ij}^{yz}z_j(t)+\varepsilon\sum\limits_{j=1}^{N}\varsigma_{ij}^{ys}s_j(t) \\ \dot{z}_i(t)=\phi(z_i(t))+\alpha\sum\limits_{j=1}^{N}\alpha_{ij}z_j(t)+\gamma\sum\limits_{j=1}^{N}p_{ij}^{zx}z_j(t)+\nu\sum\limits_{j=1}^{N}\omega_{ij}^{zy}z_j(t)+\sigma\sum\limits_{j=1}^{N}\vartheta_{ij}^{zs}s_j(t) \\ \dot{s}_i(t)=\varphi(s_i(t))+\beta\sum\limits_{j=1}^{N}\beta_{ij}s_j(t)+\delta\sum\limits_{j=1}^{N}q_{ij}^{sx}s_j(t)+\varepsilon\sum\limits_{j=1}^{N}\varsigma_{ij}^{sy}s_j(t)+\sigma\sum\limits_{j=1}^{N}\vartheta_{ij}^{sz}s_j(t) \end{cases} \quad (1)$$

$$\begin{cases} \dot{x}_i(t)=f(x_i(t-\tau_x))+\mu\sum\limits_{j=1}^{N}a_{ij}x_j(t-\tau_x)+\rho\sum\limits_{j=1}^{N}o_{ij}^{xy}y_j(t-\tau_{xy})+\gamma\sum\limits_{j=1}^{N}p_{ij}^{xz}z_j(t-\tau_{xz})+\delta\sum\limits_{j=1}^{N}q_{ij}^{xs}s_j(t-\tau_{xs}) \\ \dot{y}_i(t)=g(y_i(t-\tau_y))+\varepsilon\sum\limits_{j=1}^{N}b_{ij}y_j(t-\tau_y)+\rho\sum\limits_{j=1}^{N}o_{ij}^{yx}x_j(t-\tau_{yx})+\nu\sum\limits_{j=1}^{N}\omega_{ij}^{yz}z_j(t-\tau_{yz})+\varepsilon\sum\limits_{j=1}^{N}\varsigma_{ij}^{ys}s_j(t-\tau_{ys}) \\ \dot{z}_i(t)=\phi(z_i(t-\tau_z))+\alpha\sum\limits_{j=1}^{N}\alpha_{ij}z_j(t-\tau_z)+\gamma\sum\limits_{j=1}^{N}p_{ij}^{zx}z_j(t-\tau_{zx})+\nu\sum\limits_{j=1}^{N}\omega_{ij}^{zy}z_j(t-\tau_{zy})+\sigma\sum\limits_{j=1}^{N}\vartheta_{ij}^{zs}s_j(t-\tau_{zs}) \\ \dot{s}_i(t)=\varphi(s_i(t-\tau_s))+\beta\sum\limits_{j=1}^{N}\beta_{ij}s_j(t-\tau_s)+\delta\sum\limits_{j=1}^{N}q_{ij}^{sx}s_j(t-\tau_{sx})+\varepsilon\sum\limits_{j=1}^{N}\varsigma_{ij}^{sy}s_j(t-\tau_{sy})+\sigma\sum\limits_{j=1}^{N}\vartheta_{ij}^{sz}s_j(t-\tau_{sz}) \end{cases} \quad (2)$$

Among them, $x_i=(x_{i1},\cdots,x_{in})^T$, $y_i=(y_{i1},\cdots,y_{in})^T$, $z_i=(z_{i1},\cdots,z_{in})^T$ are the state variable of energy network, information network and transportation network respectively; $s_i=(s_{i1},\cdots,s_{in})^T$ is the influence factor of social network on energy network, information network and transportation network;

$f, g, \phi, \varphi: R^n \to R^n$ are continuous differentiable functions; N is the number of nodes; μ, ε, α are the coupling strength within the energy network, the information network and the transportation network respectively; β is the correlation coefficient between various influencing factors of the social network; $\rho, \gamma, \delta, \nu, \varepsilon, \sigma$ are the coupling intensity between energy and information network, energy and transportation network, energy and social network information network ， transportation network, information network and social network, transportation network and social network; $(a_{ij}) \in R^{N\times N}$, $(b_{ij}) \in R^{N\times N}$, $(\alpha_{ij}) \in R^{N\times N}$, $(\beta_{ij}) \in R^{N\times N}$ are the coupling matrix elements of energy, information, transportation, and social network respectively; o_{ij}^{xy} 、 p_{ij}^{xz} 、 q_{ij}^{xs} 、 ω_{ij}^{yz} 、 ς_{ij}^{ys} 、 ϑ_{ij}^{zs} are coupling matrix elements between energy and information network, energy and transportation network, energy and social network, information network and transportation network, information network and social network, and transportation network and social network , in which a_{ii} is defined as an example, that is, $a_{ii} = -\sum_{j=1, j\neq i}^{N} a_{ij}$, other diagonal elements have the same definition, and the coupling matrix is a symmetric matrix.

(3) Pointed at the complex network structure of REI which is shown in Fig 7 and the different properties of ESO and EC, the main features of different scenes, energy flow density[69] and space distribution[70] are extracted based on clustering[71], deep confidence network and convolution neural network[72]. ESO (e.g Taking the penetration of renewable energy into consideration, the breaking of red switch can be regarded as the independent operation and mutual coupling operation of ESO) and EC (e.g Many red switches closed) are identified and divided by adopting convolution neural[73] and clustering algorithm[74].

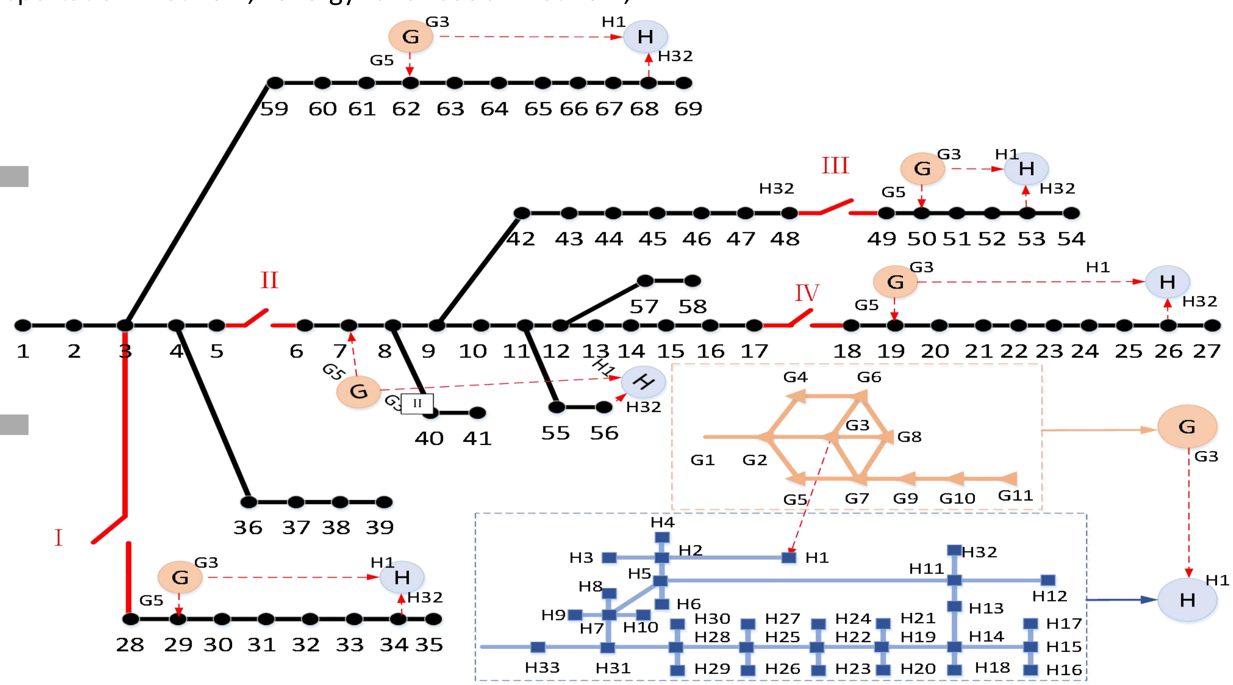


Fig 7 division of ESOs and ECs

5.2 Research ideas and methods of REI modeling theory

(1) As shown in Fig 8, modeling methods with rule networks, random networks, small-world networks, and scale-free networks, and applications of different modeling methods in REI are studied by considering the hierarchical structure of ESO. Subsystems in REI conformed to the properties of random, small world, scale-free, and rules at different levels are analyzed and its complex network modeling method is formed.

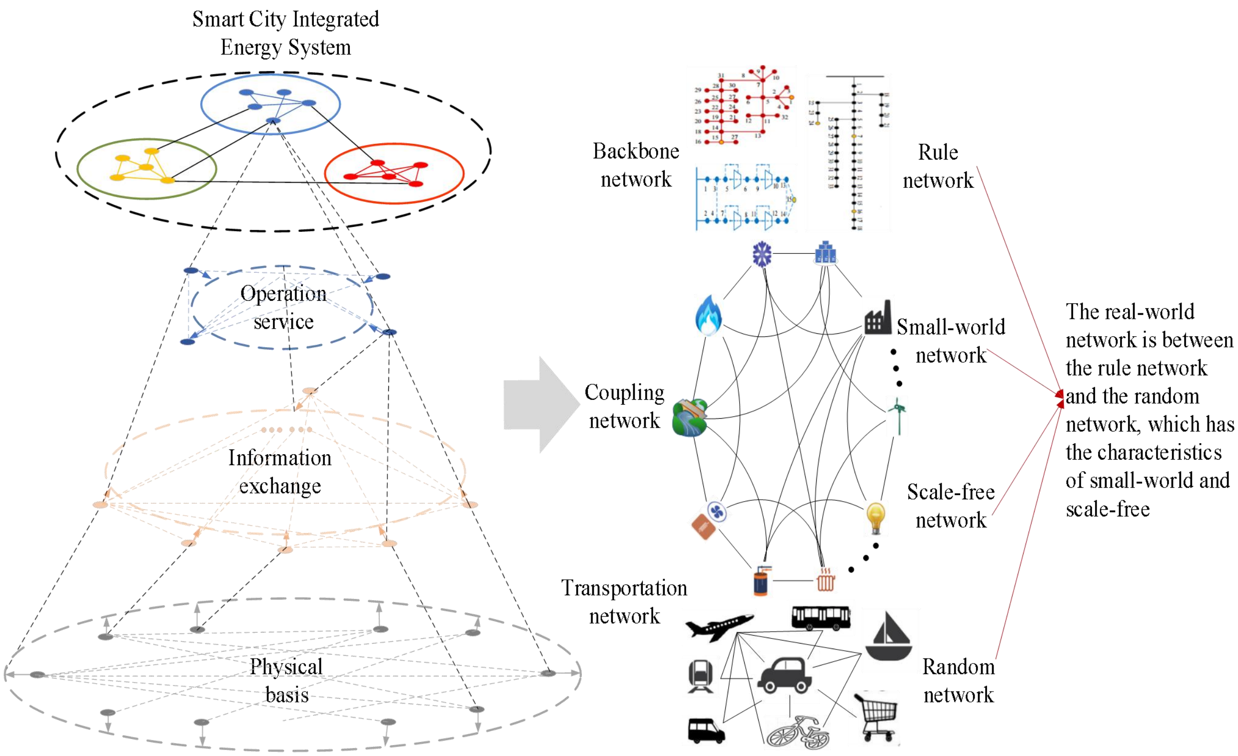


Fig 8 Research ideas on layered architecture and complex network modeling of REI.

(2) As shown in Fig 9, based on the study of the coupling network relation among different types of physical infrastructure, information interaction system and service system, a complete complex network modeling system of REI is formed. Node abstraction with rules, random, small world and scale-free properties of REI and directed graph and undirected graph visual model of multi-energy flow diagram equivalent complex network are established in order to represent the relation of ESO and EC.

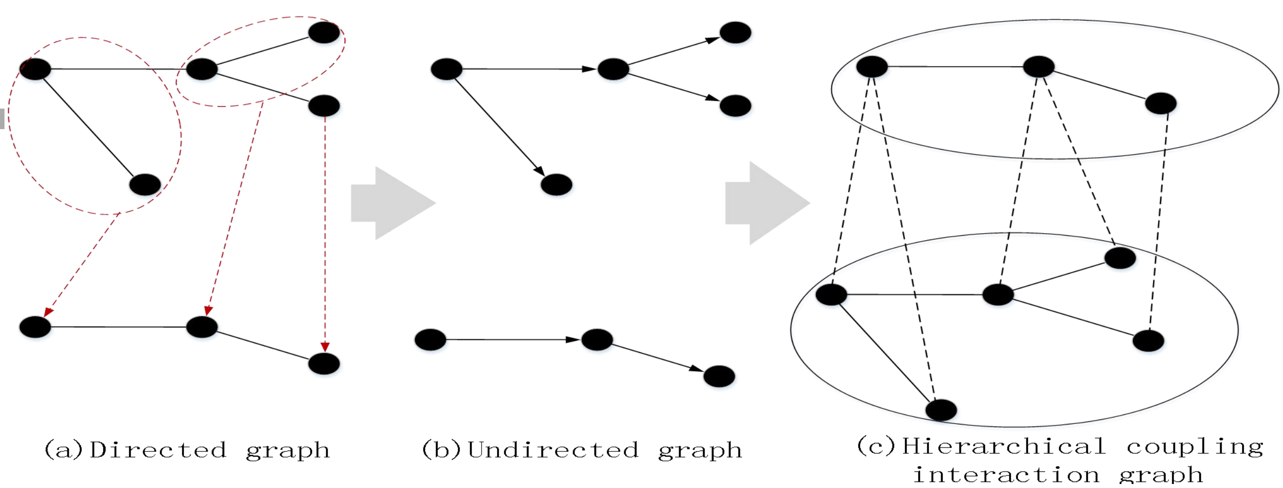


Fig 9 Complex network visualization model of REI based on ESOs and ECs: (a)undirected graph, (b)directed graph, (c)layered graph-the upper layer is based on the ECs network model, the underlying layer is based on the ESOs network model

(3) Based on the research of properties of ESOs and ECs, different basic models of complex network, and visual model of multi-energy flow diagram, the topology model of multi-energy flow diagram equivalent complex network is established by adopting nonlinear stochastic partial differential equations and time-delay nonlinear stochastic partial differential equations and expressing coupling relations and property of time delay in formula (3). Among them, the basic component node of the underlying microstructure network model is ESOs, and the basic component node of the upper macrostructure network model is ECs.

$$
\begin{cases}
\dot{x}^{ESO}(t)=f_1(x_i^{ESO}(t))+\mu^{ESO}\sum_{j=1}^{N}a_{ij}^{ESO}x_j^{ESO}(t)+\mu_{ij}^{ESO-EC}\sum_{j=1}^{N}a_{ij}^{ESO-EC}x^{EC}(t) \\
\dot{x}^{EC}(t)=f_2(x_i^{EC}(t))+\mu^{EC}\sum_{j=1}^{N}a_{ij}^{EC}x_j^{EC}(t)+\mu_{ij}^{ESO-EC}\sum_{j=1}^{N}a_{ij}^{ESO-EC}x^{EC}(t)+\mu_{ij}^{EC-EC}\sum_{j=1}^{N}a_{ij}^{EC-EC}x^{EC}(t)
\end{cases} \tag{3}
$$

Among them, $x_i^{ESO}=(x_{i1}^{ESO},\cdots,x_{in}^{ESO})^T$ 、 $x_i^{EC}=(x_{i1}^{EC},\cdots,x_{in}^{EC})^T$ represent the state variable of ESO and EC, $f_1,f_2:R^n\to R^n$ are a continuous differentiable function, N is the number of nodes, μ^{ESO}, μ^{EC} are the coupling intensity within ESO and EC, and μ^{ESO-EC} 、 μ^{EC-EC} are coupling intensity between ESO and EC and ECs with themselves. $(a_{ij}^{ESO})\in R^{N\times N}$, $(a_{ij}^{EC})\in R^{N\times N}$ are the coupling matrix elements of ESOs and ECs respectively, $(a_{ij}^{ESO-EC})\in R^{N\times N}$, $(a_{ij}^{EC-EC})\in R^{N\times N}$ are coupling matrix elements between ESOs and ECs, and between ECs and ECs, its definition is same as $a_{ii}=-\sum_{j=1,j\neq i}^{N}a_{ij}$, the other diagonal elements have same definition, and the coupling matrix is a symmetric matrix.

5.3 Research ideas and methods of complex network performance analysis of REI

(1) As shown in Fig 10, according to the node abstraction and the equivalent network topology structure (including random, small world, scale-free and rule networks) of the multi-energy flow graph, the complex network probabilistic statistical performance analysis indicators of REI is studied starting from different levels of physical infrastructure, ESOs, ECs and the entire complex system, which contains node degree, average node degree, degree distribution, path length, average path length, clustering coefficient, average clustering coefficient, betweenness and modularity and other important indicators (see Ref.[54] for specific definitions).

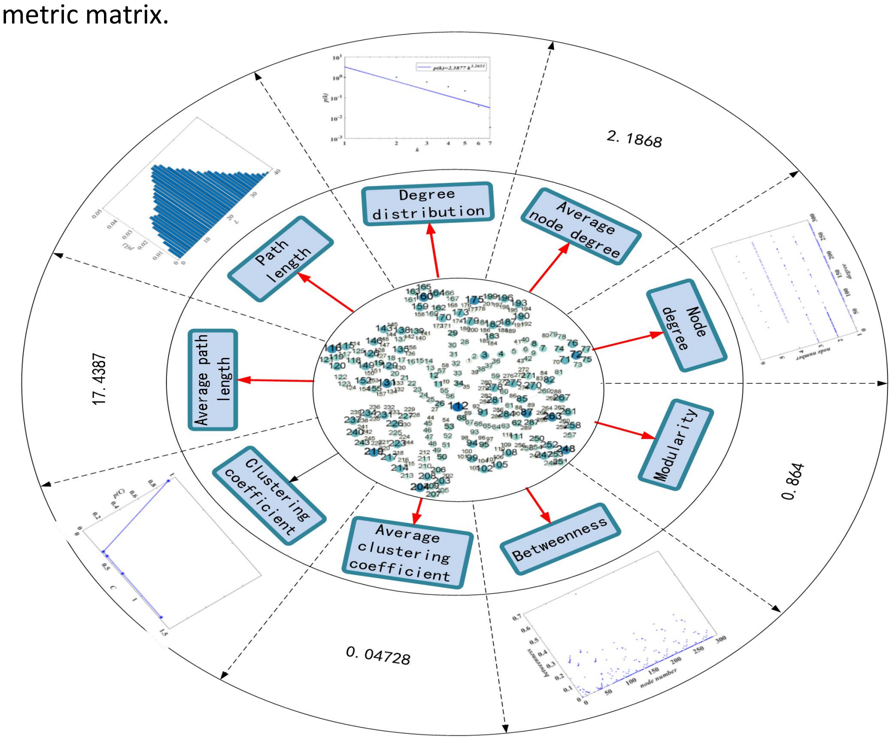


Fig 10 Basic metrics for complex networks of REI.

(2) As shown in Fig 11, According to graph theory and CNA, pointed at complex network model of the REI and based on indicators such as node degree, average node degree, degree distribution, path length, average path length, clustering coefficient, average clustering coefficient, betweenness and modularity, complex network performance analysis indicators of REI are further studied, including reliability, economy[75], vulnerability and centrality[76].

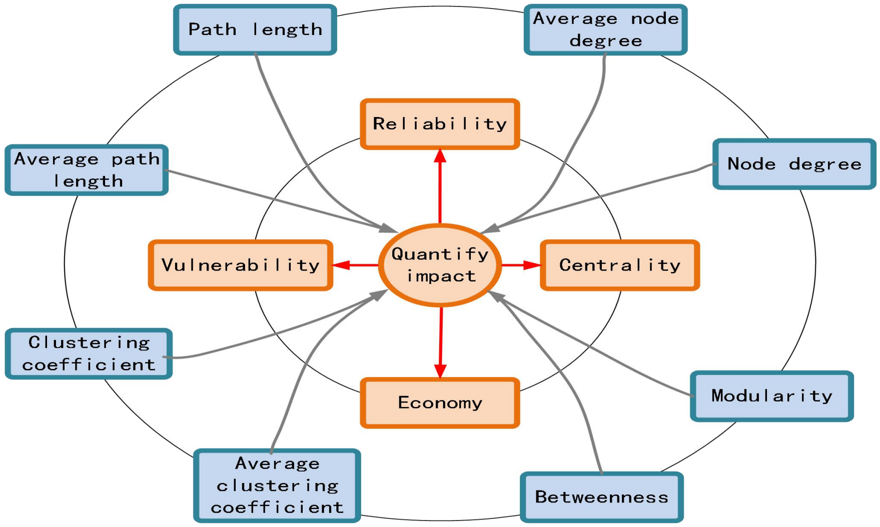


Fig 11 Metrics for REI.

According to the mutual coupling, connection and interaction of multi-energy flow between ESOs and ECs, REI is evaluated and quantitatively analyzed in a reasonable, scientific and objective way based on evaluation methods such as data envelopment analysis (DEA)[77], ecological network analysis (ENA)[78], hierarchical process method[79], entropy weight method, incidence matrix, analytic hierarchy process + least square support vector machine (LS-SVM)[80], combined weighting method[81], ANP-fuzzy comprehensive evaluation[82]. It provides scientific basis and advanced technical support for the development of REI and the transformation of urban clean energy.

6. CONCLUSIONS

Aiming at REI for SCs, this paper analyzes the complex dynamic network characteristics of the REI and builds a basic model system, reveals the interaction mechanism of the integration of different networks such as energy, information, transportation and society, and establishes a complete and complex dynamic network analysis theory of REI from the perspective of complex networks. Aiming at the properties of REI such as multi-link complex coupling with variable time delay, multiple time scales, strong nonlinearity, high dimensionality, and multiple uncertainties, theory and analysis method system of REI complex dynamic network model are researched under the background of the highly integrated complex network of energy, information, transportation, and society. It can provide strong theoretical and methodological support for the efficient, clean and renewable development of SCs, and promote the energy-saving, emission-reduction and low-carbon development of the whole society, therefore it has important theoretical and practical significance.

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