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Features and evolution of international fossil energy trade relationships: A weighted multilayer network analysis

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HIGHLIGHTS

- The international fossil energy trade is analyzed using multilayer network theory.
- Both the ETMN and energy-specific networks display scale-free distributions.
- The natural gas network has the largest number of communities and stability.
- Internationalization of natural gas trade is influenced by geopolitical environment.
- Status of renewable energy increases with its development obviously in the ETMN.

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ABSTRACT

From June 2014 to January 2015, the slumped price of crude oil mainly be caused by the increasing shale gas in the U.S. The market of crude oil was altered by the variation of natural gas trade patterns. It implies that the international fossil energy trade is a multilayer structure, and each layer is a complex system with numerous countries and complicated relations. In this paper, we build the international fossil energy trade multilayer network (ETMN), and study the evolutionary characteristics of networks during 2002–2013. The generalization of several important indicators, including degree distribution, community, stability of communities and the time-varying evolution of main countries' importance were discussed. Our conclusions suggest that: Firstly, the ETMN and three energy-specific networks including coal, oil, and natural gas display the scale-free characteristic in un-weighted and weighted networks. However, it shows that even if a few countries have major trading partners, there are not always a few countries that play critical roles in trade intensity. Secondly, the natural gas network has the largest number of communities and stability compared with networks of coal and oil, and the volatility of stability lagged one year than the other two networks for the specific form of pipeline transportation. Thirdly, studying on the stability of networks shows that geopolitical environment is the most important influenced factor, but the status of renewable and new energy increases with its development obviously. Fourthly, the evolutionary characteristics of three major countries' importance, including United States, China and Japan, are analyzed in detail. At last, some policy suggestions were pointed out according to the results.

1. Introduction

The international fossil energy trade pattern is decided by the uneven distribution of mineral fuels production and consumption. As one of the most important commodities for national development and people's life, fossil energy is concerned by researchers and policy makers increasingly.

At present, most researches on energy prices, markets, risks, and policy optimization are qualitative. Actually, the real international trade is a complex system with numerous countries and complicated relations. Thus, the development of complex network theory has offered an effective tool for the study of international trade. Complex network theory can analyze the world-wide trade system at global and local levels, so as to reveal many new features

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of the international trade topologically and dynamically [1–3]. Currently, complex network theory have been proposed to solve problems in international fossil energy trade. Sun and Fang [4,5] proposed a universal bipartite model based on an energy supply–demand network, and the properties of the coal supply–demand market in the US and China were investigated. Chen [6] proposed a refined random network model, the Block Configuration Model, and utilized it in an agent-based energy consumption simulation. Zhong et al. [7] studied the evolution of communities of the international oil trade network by setting up un-weighted and weighted oil trade network models based on complex network theory using data from 2002 to 2011, and analyzed their evolutionary properties and stabilities over time. Zhang et al. [8] studied the competition among oil importers using complex network theory, combined with several alternative measures of competition intensity, to analyze the evolution of the pattern and transmission of oil-trading competition. Lu et al. [9] established an original network model based on ecological network analysis to holistically evaluate the security of the crude oil supply in China, and found that the security of the crude oil supply in China generally increased from 2001 to 2010. Ji et al. [10,11] constructed a global oil trade core network to analyze the overall features, regional characteristics and stability of the oil trade by using complex network theory. The results indicated that the global oil export core network displays a scale-free behavior. An et al. [12] established a trading-based network model of international crude oil trade and studied their evolution of scales, stability, hierarchy structure and partition over time. Hao et al. [13,14] built a global fossil energy exergy flow network and analyzed the distribution of countries, the overall structure, major countries and major exergy flow paths from 1996 to 2012. The results showed that even if the fossil energy trade becomes more frequent and larger, there are always a few trade relationships and countries that play critical roles. Geng et al. [15] analyzed the evolution characteristics of the international natural gas trade structure and the integration of the international natural gas market by using complex network theory, and found that both the LNG and pipeline gas import and export trade networks display scale-free distributions while the countries in the LNG trade network are linked more closely than those in the pipeline gas trade network. Üster [16] developed an integrated large-scale mixed-integer nonlinear optimization model to determine pipelines in a new natural gas transmission network. Their analysis provided insights into sensitivity of network configuration and operation to the number of periods as well as into strategic decision making for design and expansion of natural gas networks. An et al. [17] adopted a complex network approach to examine the dynamics of the co-movement between crude oil futures and spot prices, and defined the co-movement modes by a coarse-graining procedure and analyzed the transformation characteristics between the modes by weighted complex network evolutionary models. Bale [18] reviewed the application of complexity science methods in understanding energy systems and system changes, and showed that modeling of systems using network theory is a thriving field of investigation and helps with the identification of network robustness and network resilience by exploring the direction of connectedness of edges, the strength of network ties and cascading effects of node failure.

The existing literature has provided a solid empirical investigation and a good reference to understand the evolution of a certain energy trade network, but some problems still need to be further examined. For instance, the status of countries varies in different energy-specific networks, and it is the comprehensive energy status in the multilayer network rather than the energy-specific networks. Therefore, this paper aims to empirically explore these issues above, which may present some favorable implications for investors and policymakers.

In this paper, we explore the topological structure of the ETMN studying which is a novel framework to research. Detecting the features, evolutionary characteristics and the relationships among fossil energy trade networks. Identifying important countries and uncovering some stylized facts about the actual interdependencies among countries. Four main contributions are as follows: (1) In order to take into account the existing heterogeneity in the capacity and intensity of connections, the thought of gravity equation model is used to construct the energy-specific networks including coal, oil and natural gas. (2) The international ETMN is constructed with complex network theory to analyze the topological structure and evolutionary characteristics of international fossil energy trade patterns. (3) The evolution of degree distribution between the ETMN and the energy-specific networks are studied. (4) The stability of the four networks are studied by measuring the change of communities and the Normalized Mutual Information (NMI).

The remainder of this paper is organized as follows: in Section 2, the international ETMN are constructed, and the topological properties are analyzed. In Section 3, the relationship between the overall features of the ETMN and energy-specific trade pattern is studied, and the evolutionary characteristics of major countries' importance are analyzed in detail. Section 4 provides concluding remarks.

2. Methodology

2.1. Energy-specific network model

Actual import–export flows greatly differ when they are computed as shares of the importing/exporting country size (measured e.g. by its gross domestic product, GDP). It is considered widely in gravity equation model to study the determinants of bilateral international-trade flows [19,20]. In order to take into account the existing heterogeneity in the capacity and intensity of connections, a weighted-network analysis of energy-specific trade can instead be performed.

In the energy-specific network, the nodes represent the countries, and the edges represent the fact that there are relationships between each of the countries. To build adjacency and weight matrices, we followed the flow of goods. This means that rows represent exporters, whereas columns stand for importers. We define a "energy trade relationship" if and only if exports from country i to country j (labeled by e_{ij}) are strictly positive. The weights of the connecting edges are instead defined as, $w'_{ij} = e_{ij}/\mathrm{GDP}_i$ i.e. exports over GDP of the exporter [20]. It reflects the potential supply capacity of exporters. As the undirected network, the generic entry of the symmetrized weight matrix W is defined as

$$w_{ij} = (w'_{ij} + w'_{ji})/2$$

where w_{ij} represents the weight of edge ij, and we call it the trade intensity between the nodes i and j. Finally, in order to have $w_{ij} \in [0,1]$ and to remove all trend-related factors for all (i,j), we renormalize all entries in W by their maximum value $w_{ij}^{\max} = \max_{i,j=1}^{N}\{w_{ij}\}$.

Two remarks are in order. First, the number of countries are available different over the years. Second, the size of country sample must be as large as possible to achieve statistical significance.

2.2. Energy trade multilayer network model

We build a time sequence of weighted, undirected energy-specific networks of coal, oil, and natural gas trade respectively, each characterized by links of 3 different colors, see Fig. 1(a). In networks, the countries are taken as the nodes and trade relationships as the edges. In this case, three layers $\alpha = 1, 2, 3$ can be