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Features and evolution of international fossil fuel trade network based on value of emergy

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HIGHLIGHTS

- Number of trade relations and trade quantities follow power law distribution.
- The pattern of top relations is diversified.
- The trade density of fossil fuel is increasing.
- Coal is the "cheapest" fuel measuring by "energy cost" and is most widely traded.
- Countries with more than 20 trade relationships tend to have hierarchy structure.

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ABSTRACT

Fossil fuel is crucial to the development of modern society. The major types of fossil fuel are coal, crude oil and natural gas. The uneven distribution of the production and consumption of fossil fuel makes the fossil fuel flows between countries by international trade. This study aims to quantitatively analyse the features and evolution of the international trade of fossil fuel by complex network and emergy. We transform the trade quantity of coal, crude oil and natural gas into emergy by transformity and the sum of the three emergies is the emergy of fossil fuel. The complex network models of the integrated fossil fuel trade as well as the trade of coal, crude oil and natural gas are built up based on the value of emergy. We analyse the trade relationships, trade quantity, trade density, and hierarchy structure of the networks.

We find that the number of trade relationships and the trade quantities follow the power law distribution; countries with many export relationships tend to have many import relationships; the centralization of trade quantity is becoming more intense for fossil fuel, crude oil and coal, but less intense for natural gas; the pattern of top relationships is diversified; the trade density of fossil fuel is increasing; and countries with more than 20 trade relationships tend to have a hierarchy structure. Our findings implicate that as the hierarchy structure is becoming more ordered, the statuses of the countries are clearer, and thus it is easier for policy makers to identify the roles of their own countries or the roles of other countries. Coal is the "cheapest" fuel measuring by "energy cost" and is the most widely traded type of fossil fuel. When two countries exchange fossil fuel and money in the international trade, they should look further into the energy cost of them and reconsider the effectiveness of the trade. Our study can also reveal the trade strategy of the countries.

1. Introduction

The international trade of fossil fuel is an integrated system with three major commodities: coal, crude oil and natural gas. According to the statistics of U.S. Energy Information Administration, the three major types of fossil fuels account to 86% of the world total primary energy consumption in 2012.[1] There are numerous countries and complicated relationships in the international trade of fossil fuel which form a huge and complex system. A better understanding of the characteristics of this integrated

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[1] http://www.eia.gov/totalenergy/.

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complex system can help us understand the international fossil fuel market [1]. Previous studies on international fossil fuel trade focused on energy security [2], trade patterns [3] and political factors [4]. This study aims to quantitatively analyze the features and evolution of international fossil fuel trade by combining network analysis and emergy transformity. It provides a new perspective for the study of international trade of fossil fuel.

Complex network modeling has the advantage of analyzing the complex system of international trade. In 2003, Serrano et al. [5] introduced complex network model into the study of international trade. Then Garlaschelli et al. [6] studied the fitness-dependent topological properties of the international trade network. The study of Fagiolo et al. [7,8] provided a detailed quantitative analysis of the trade links and the role of the countries topologically and dynamically. Vidmer et al. [9] applied link prediction algorithms to predict the future evolution of the international trade network. In recent years, some scholars used complex network to analysis the international trade of energy. For example, Geng et al. [10] studied the structure and the integration of the international natural gas market by complex network. Üster et al. [11] designed an integrated large-scale mixed-integer nonlinear optimization model to analyze the natural gas transmission network. Zhong et al. [12] constructed weighted and unweighted complex network models to study the evolution of communities in the international oil trade. Ji et al. [13] introduced a global oil trade core network to analyze the overall features, regional characteristics and stability of the oil trade. Zhong et al. [13] and Zhang et al. [14] introduced complex network to analyze the competition between countries in the oil trade.

However, as far as we know, most of the previous studies on international energy trade are based on single commodity. Our study provides an integrated view of the international trade of fossil fuel by considering the trade quantity of coal, crude oil and natural gas together in the model, and reveals features of the integrated system.

A unified unit to measure the commodities of coal, crude oil and natural gas is needed because they are in different forms and qualities. Traditionally, money is applied to measure the integrated trade volume, however the fluctuating price and exchange rate [15] will affect the results. The unit of "joule" can be used to measure energy content of the fuels, however it only measures the ability to cause work. Exergy is another concept which measure the maximum useful work of the fuels [16]. These methods cannot reflect the "cost" of the energy which means how much energy is needed in order to produce a certain amount of fossil fuel. The main idea of Emergy is "energy cost" which regards the difference of energy quality and the accumulative cost of energy [17]. It measures the values of resources in common units of the solar energy used to make them (in unit of seJ) [18,19]. Transformity (in unit of seJ/J) can be used to transform the trade quantity of coal, crude oil and natural gas into emergy. The sum of the three emergies can be used to measure the emergy flow of fossil fuel. If a country exports fossil fuel, it not only exports the energy currently existing in the commodities, but also exports the energy consumed in forming, mining and producing the commodities. If a country imports fossil fuel, it also imports the embodied "energy cost" in the commodities. As far as we know, most of the previous studies of international energy trade use money, energy or exergy as trade quantity. Our study goes further in considering the accumulative amount of solar energy (Emergy) as trade quantity.

In this study, we design the integrated complex network model of fossil fuel as well as the single commodity network models of coal, crude oil and natural gas based on the emergy flows among countries. The characteristics of the international fossil fuel trade can be reflected by network analysis. Section 2 introduces the data and the process of modeling. Four indexes of network analysis are introduced: degree and strength are indicators of the individual countries, and network density and hierarchy structure are indicators of the whole network. Section 3 is the analysis of trade relationships, trade quantity, trade density, and hierarchy structure of the network. Section 4 is the discussion and conclusion remarks.

2. Data and method

2.1. Data and transformity

The data of international trade of coal, crude oil and natural gas is from the website of *UN Comtrade* which contains all the export and import flows among 226 countries. The trade volumes are measured by kilogram. We selected the annual data of all the available countries from 2000 to 2013. We transformed the trade quantities of the three fuels into emergy and the sum of them is the emergy of fossil fuel. The description of the data source, the energy content of the commodities and the transformity of coal, crude oil and natural gas are shown in Table 1. In our data, only crude oil is included in the HS Code 2709, and there are several categories of coal in the HS Code 2701. We use the average energy content and the average emergy transformity of crude oil and coal in our study.

The total emergy in fossil fuel trade increased during 2000–2008 as the world economy grew, and the total emergy declined in 2009 after the US mortgage subprime crisis.[2] The majority of fossil fuel trade emergy was contributed by crude oil, coal contributed the least emergy, and natural gas contributed a little more than coal (please see Fig. 1).

2.2. International trade network model

The complex network model $G = (V, E)$ contains the nodes V and the edges E, where $V = \{v_i{:}i = 1, 2, \ldots, n\}$, n is the number of nodes, $E = \{e_i{:}i = 1, 2, \ldots, m\}$, and m is the number of edges. In our model, the nodes are the countries, the edges are the trade relationships, the directions of the edges are the directions of the emergy flows, and the weights of the edges are the value of emergies. We constructed network models of the integrated fossil fuel trade as well as the single commodities based on the transformed data.

An example of the integrated fossil fuel trade network in 2012 is shown in Fig. 2. We filtered the network with trade quantity in order to make it more readable by showing the top 50 countries in trade quantity in the network. The size of the node is the total trade quantity of the country. The larger the node is, the more emergy the country has trade in this year. The width of the edge is the value of the emergy of this trade link. The wider the edge is, the higher value of emergy this trade link has.

2.2.1. Degree: the range of the direct impact

Degree is the number of direct trade relationships of a country. It reflects the range of a country's direct impact. The out-degree is the number of export links a country has with others, and the in-degree is the number of import links. The higher value of out-degree or in-degree indicates a wider range of the country's direct impact. These values are computed by [21]

$$k_i^{\text{out}}(t) = \sum_{j=1}^{n} d_{ij}(t) \tag{1}$$

$$k_i^{\text{in}}(t) = \sum_{j=1}^{n} d_{ji}(t) \tag{2}$$

[2] The U.S. subprime mortgage crisis was a nationwide banking emergency that coincided with the U.S. recession of December 2007–June 2009 (explanation from Wikipedia).