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Structural risk evaluation of global gas trade by a network-based dynamics simulation model

Zhihua Chen [a, b, c], Haizhong An [a, b, c, *], Feng An [a, b, c], Qing Guan [a, b, c], Xiaoqing Hao [a, b, c]

[a] School of Humanities and Economic Management, China University of Geosciences, Beijing, 100083, China
[b] Key Laboratory of Carrying Capacity Assessment for Resource and Environment, Ministry of Land and Resources, Beijing, 100083, China
[c] Key Laboratory of Strategic Studies, Ministry of Land and Resources, Beijing, 100812, China

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ABSTRACT

The uneven distribution of natural gas in the world makes the gas trade between countries close, and the importance of natural gas for national economies leads to a high dependence of gas-importing countries on external natural gas resources. This dependency creates a potential structural risk in the global gas trade that can spread out along trade linkages when parts of the gas trade collapse. In this paper, we developed a simulation model for the diffusion of gas trade ruptures based on a modified bootstrap percolation network model. We used this model to detect the potential gas trade risk and observed the roles of gas trade participants in the risk transmission process. In the results, we found that Norway and Qatar have the greatest impact on price fluctuations in the risk simulation. While Russia's influence ranks lower in the global gas market, although it has larger trade partners. Meanwhile, the external gas supply risk for gas-importing countries varies greatly and shows regional characteristics (European countries are in a higher trade risk environment, while China and Japan have the largest gas supply risk in Asia). We also identified the diffusion paths of gas supply breaks and found that Singapore and India are likely to serve as the largest intermediaries, causing a wide range of trade collapse.

1. Introduction

Natural gas consumption has been largely growing over the past decade; it will remain in high demand due to national economies' need for clean energy. IEA [1] thought natural gas will grow to account for a quarter of global energy demand by 2040, becoming the second-largest fuel in the global mix after oil. Given the uneven distribution of natural gas in the world, percentage of gas consumption was done by the way of trade increased from 19% in 1995 to almost 30% in 2015 [2], which makes gas-consuming countries an increasingly dependency on international gas trade, and this dependency serves as the platform for gas trade structural risk. The structural risk indicates the different roles of countries in the trade network determined by the difference of trade structure and thus resulting systemic harmful effects. Although current regional market is in ample supply period, with the global natural gas trade integration increasing [3,4], it could lead to a wide range of trade shocks when some of the natural gas supply heavily breaks, in turn prompting serious economic problems [5] (undermining the energy support of gas consumers' economic development and financial income of gas-exporting countries). Therefore, assessing the potential gas trade collapse and the performance of countries so as to avoid the supply crisis has significant meaning for energy security and economic stability.

In theory, there is a possibility that trade relationships could break due to factors such as war, economic disputes or political conflict between countries [6]. This could be passed along the trade channel to other countries, resulting in chain reactions [7,8]. There has been one example of this phenomenon in history: after the oil crisis of 1973 resulted in an oil supply shortage, the US subsequently restricted its oil exports in 1975 to ensure domestic oil supply, which also caused supply shocks to its trade partners, including Japan and Canada. Although there has not yet been a global gas crisis in history, a scene similar to the oil crisis may appear in the future given the increasing competition of natural gas in global energy consumption.

Many studies have found that trade linkages are one of the most important crisis transmission channels [7,9–12]. Especially for countries such as Japan and China where the energy supply largely

* Corresponding author. No. 213, 4th Building, No. 29, Xueyuan Road, Beijing, 100083, China.
E-mail address: ahz369@163.com (H. An).

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depends on imports, there can be a serious impact (gas prices rise and the output of gas consumption industry declines) if the gas supply gets into trouble [13]. Moreover, due to the close relations between gas trade nations, a supply shortage in one district may trigger the same problems in other areas, known as a cascading phenomenon [14]. The main reason for the cascading phenomenon is the existence of gas-trading transfer countries that may choose to limit their gas exports when their own gas supply falls into a shortage; this behavior will lead to a wide-ranging trade risk [7]. In addition, finance crises can also be transmitted by the failure of a trade sector; Haidar [10] developed a three-country dynamic general equilibrium model to explain this phenomenon and emphasize that the effect of trade matters is in direct proportion to the trade level. Moreover, it is discovered that levels of trade volume influence the variability of price [15], and the interconnector trade has a negative impact on price volatility [16].

These studies emphasize the significance of trade linkages in the transmission of crises; however, they usually discuss this problem through a single national or regional perspective. There should be a holistic perspective to study the entire effect caused by the partial variation of trade relations in the whole trade network, which may help us understand the transmission mechanism of energy supply crisis and nations' roles in this process.

Complex network theory is a suitable method for portraying international trade relationships and studying trade pattern characteristics. The intricate worldwide LNG shipping lines and compressed gas pipelines between nations have created an interlaced gas trade network. Many studies about international gas trade have used the complex networks approach, which has proven that this method can systematically depict the features of the global natural gas trade structure. Geng, Ji [3] studied the dynamic evolution of the global gas market by using networks analysis and found that natural gas trade relationships have been increasing and becoming tighter. Meanwhile, the boom in gas trade has led to increasing competition between gas-trading countries [17]. In addition to natural gas trade, complex network theory has been used in other international trade fields, such as crude oil and mineral products [18–22]. These studies all built their network model on the real trade flows between countries, though these static models can only depict the topological structure features of the trade networks; the role and function of nations in transmission dynamic processes on the network, such as the diffusion of trade supply risk, cannot be estimated.

To simulate the potential gas supply risk and the chain reactions along gas trade linkages, we refer to dynamic models based on networks, such as the SIR (Suspicious-Infection-Recovery) epidemic model and bootstrap percolation model, etc. The SIR model is used to study the phenomenon of epidemic diffusion in a network model of population structure with specified degree distribution [23–25]. The bootstrap percolation model describes the destructive cascade on a connected graph or network [26–31], which has been used for risk diffusion in financial networks [32–34]. In the SIR model, epidemic diffusion depends on a certain infection probability, while in the bootstrap percolation model, the state change of nodes depends on a given threshold of neighbor quantities. However, these models only express the function of network structure under the initial conditions; both their settings ignore the individual (nodes in the network) differences. For example, in this study on natural gas trade, the individual differences are related to the gas industry attributes of nations, such as gas consumption demand, production capacity, imports or exports and the gas inventory. These factors need to be considered to study the risk diffusion of gas trade network.

In this paper, we modified the bootstrap percolation network model to simulate the gas trade collapse, and we focused on the potential impact of the trade ruptures from the perspective of trade structures, avoiding to discuss the intricate risk mechanism in the real trade market. By the proposed simulation model, the different roles and positions of gas-trading nations determined by the systemic structural effect can be estimated. The results can help us realize the gas trade stability and potential trade risk environment of countries, which may have implications for predictions and early warnings of a global gas trade crisis.

2. Method

In section 2.1, we built a global natural gas trade network (NGTN), which refers to the modeling method of Geng, Ji [3] and Chen, An [17]. Then, in section 2.2, a gas supplies cutoff spread model (GSCSM) simulating the spread process of gas supply cutoff was built based on the gas trade network built in section 2.1. Lastly, in section 2.3, we built a framework of statistical analysis indicators based on the NGTN and GSCSM and divided it into three aspects: gas-exporting countries, gas-importing countries and gas-trading transfer countries.

2.1. Natural gas trade network (NGTN)

The global natural gas trade system can be abstracted as a connected network $G = (V, E)$, where $V = \{v_i : i = 1, 2, \ldots, n\}$ is the set of nodes representing gas trade countries, and the edges set $E = \{(v_i, v_j); i, j = 1, 2\ldots, n\}$ represents the trade flow between country v_i and v_j. The direction of each edge is from gas-exporting country to gas-importing country; in addition, each edge was given a weight w_{ij}, which indicates the actual gas trade quantities from v_j to v_i. So far, the NGTN has been built, which is a weighted and directed network.

2.2. Gas supply cutoff spread model (GSCSM)

In the NGTN, gas exporters may embargo exports due to many reasons, such as conflict or economic sanctions. This will result in some gas import losses to gas importers. When imports were significantly affected, these gas-importing countries would also break their gas exports to ensure their own gas supply security. Given these situations, we developed GSCSM based on the gas trade network built in section 2.2.1, referring to the bootstrap percolation model of Fan, Ren [21], which has a similar application. In a typical bootstrap percolation model, nodes in a network have two statuses: inactive and active. Nodes' status changes are subject to condition $\mu(f, k)$, which means that each node is initially inactive with a given probability f, and an inactive node will become active when k neighbors are active. Applying this model to our research on international gas trade network, we modified the condition to $\mu(\varphi, w, \phi)$, which means that each gas-exporting country is selected to become active with a probability φ, and one gas-importing country becomes active if the trade sum w of its active neighbors is greater than its bearing capacity ϕ. This model is used to simulate the spreading of the potential gas supply cutoff and thus evaluate the trade risk in the current gas trade network. The detailed modeling process can be divided into the following steps:

(1) Step 1: Define the countries' statuses in gas trade network

In the gas trade network, all countries are given two statuses: normal (N) and abnormal (A) (replacing the inactive and active mentioned above). Normal status means the country is normally engaging in current gas trade activities. Abnormal status indicates the gas supply is significantly short due to gas import losses caused