Energy Policy 88 (2016) 271–277

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Measuring global oil trade dependencies: An application of the point-wise mutual information method

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HIGHLIGHTS

- We analyzed global oil trade networks using the point-wise mutual information method.
- We identified position, price, & politics as drivers of oil trade preference.
- The PMI method is useful in research on complex trade networks and dependency theory.
- A time-series analysis of PMI can track dependencies & evaluate policy decisions.

ARTICLE INFO

Article history:
Received 5 June 2015
Received in revised form
27 September 2015
Accepted 15 October 2015

Keywords:
Trade dependency
Point-wise mutual information
Crude oil trade
Network analysis
Energy policy

ABSTRACT

Oil trade is one of the most vital networks in the global economy. In this paper, we analyze the 1998–2012 oil trade networks using the point-wise mutual information (PMI) method and determine the pairwise trade preferences and dependencies. Using examples of the USA's trade partners, this research demonstrates the usefulness of the PMI method as an additional methodological tool to evaluate the outcomes from countries' decisions to engage in preferred trading partners. A positive PMI value indicates trade preference where trade is larger than would be expected. For example, in 2012 the USA imported 2,548.7 kbpd despite an expected 358.5 kbpd of oil from Canada. Conversely, a negative PMI value indicates trade dis-preference where the amount of trade is smaller than what would be expected. For example, the 15-year average of annual PMI between Saudi Arabia and the U.S.A. is -0.130 and between Russia and the USA -1.596. We reflect the three primary reasons of discrepancies between actual and neutral model trade can be related to position, price, and politics. The PMI can quantify the political success or failure of trade preferences and can more accurately account temporal variation of interdependencies.

1. Introduction

Economic trade networks constitute complex interactions which need to be described in a systematic framework. In this avenue, researchers have widely researched the theory of 'trade dependency' arising from the export of raw materials from underdeveloped countries in exchange of imports of manufactured goods from developed countries (Prebisch, 1991; Singer, 1949). The strategic policy of trade concentration has also been explored most notably by Hirschman (1945) where he discusses the economic pressures arising from trade partner concentrations. These pioneering studies developed conceptual insights into the opportunities and threats of trade dependencies.

With the increasing availability of data on trade and globalization, researchers have quantitatively examined the effects of trade concentrations (Babones and Farabee-Siers, 2012; Gasiorowski, 1985). Trade concentration is the degree to which a country engages in import/export trade with a limited number of partner countries. This is often exacerbated when dealing with commodities that have uneven spatial distributions such as rare minerals or increasingly scarce energy resources. Trade concentration is argued as having negative political and social implications and thereby to present a serious policy issue. This is especially critical in regard to trade in energy, where the nature of the traded commodity, e.g., oil, gas, and biofuels, maintains strategic and

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http://dx.doi.org/10.1016/j.enpol.2015.10.017
0301-4215/

national policy considerations. The common themes related to the security, risks, and export and import dependency of energy trade are examined in the literature using index based approaches (Ang et al., 2015; Bhattacharyya and Blake, 2010; Coq and Paltseva, 2009; Månsson et al., 2014; Yang et al., 2014). In addition to index-based approaches, researchers are increasingly using network approaches in examining energy trade. In this avenue and specific to international crude oil trade networks, researchers have examined the evolution of community structures using un-weighted and weighted models (Zhong et al., 2014) and the evolution of oil trade competition patterns using complex network theories (Zhang et al., 2014). Research on energy dependency, and more specifically oil trade dependencies, utilizing network approaches however remain few. In this paper, we attempt to assess crude oil trade dependencies by applying the concept of point-wise mutual information (PMI).

The PMI method highlights inter-dependencies between two points in a complex network. In its application to oil trade networks, it can reveal the evolution of important dependency patterns between countries which is otherwise not so easily illustrated by a simple examination of trade volumes. The PMI method therefore can be a valuable methodological scalpel for policy and decision makers to evaluate trade dependencies and trade preferences in crude oil trade. Specifically, in this paper, we address two questions: (1) how do the crude oil trade inter-dependencies change over time based on PMI values and (2) how do the actual crude oil trade values differ from those flows that generate a situation with maximal indeterminacy (i.e., zero information also referred to herein as the neutral dependency model). We also provide an evaluation of the available oil trade datasets. An analysis of PMI generated from time series trade data can reveal the changing dependencies, thereby enabling researchers to measure and track the dependency of a country's imports or exports on another country. The application of the PMI methodology is straightforward, and we demonstrate that it provides valuable information which is not found from simply examining imports and exports. This paper is organized as follows: Section 2 discusses the concept and mathematical rational of the PMI method, Section 3 discusses the data on global trade networks, results are presented in Section 4 and discussed together with an outline of future work in Section 5. A conclusion with overall policy implications is given in Section 6.

2. Point-wise mutual information

The average mutual information (AMI) of a network is a system-level metric measuring the level of efficiency or the average degrees of constraint of a network (Rutledge et al., 1976; Ulanowicz, 2009). A related concept is the point-wise mutual information (PMI) (Fano, 1961 ch. 2). The PMI measures information as the reduction in uncertainty based on the constraint between individual nodes within a network. Viewed differently, the AMI is essentially just the average of the individual values of PMI. By examining the contribution of individual flows to the system-level metric of efficiency, one is able to detail the internal workings on a pair-by-pair (point-wise) comparison within the system. Specifically, this information can be beneficial in explaining some of the underlying relations within the network that result in the system-level efficiency values.

The PMI describes the dependency of two nodes in a networked system. Although PMI is a pairwise comparison, it is nonetheless subject to system-level changes. In other words, changes at the system-level will modify the overall balance of dependencies between flow pairs, and these modifications will be reflected in the PMIs. Conversely, changes in the dependency of flows between two nodes will change the PMI between those nodes, and thereby affect the AMI.

PMI has been extensively used in the discipline of linguistics for measuring the co-occurrence of words and semantic similarities (Church and Hanks, 1990; Han et al., 2013). Researchers in this area are interested in the relationships between words in a given text corpus. One important type of relationship is a collocation, which is a sequence of words that appear more often than what is statistically expected. By comparing the probability of observing the word x and the word y together (the joint probability) to the probability of observing word x and the word y independently (statistical chance), PMI can be used to identify collocations. For example, the collocation sequence of 'strong tea' or 'big mistake' would appear more often in corpus than 'big tea' or 'strong mistake' and therefore have a higher PMI.

The concept of the mutual information was derived from considering the possible combinations of the co-occurrence of two events (Fano, 1961). To do so we define P_{ij} as the joint probability that events i and j co-occur, P_i as the probability that i occurs and P_j as the probability that j occurs. Using the measure of non-occurrence of an event (Boltzmann, 1872) we define the indeterminacy of the combinations of the co-occurrence of these two events as:

$$H_{ij} = -k\log(P_{ij}) \tag{1}$$

where k is a scaling factor. If events i and j are independent, then the probability that they co-occur would be the product of the marginal probability that i and j occur independently. This would mean that the marginal probability that i occurs for any possible j is $P_{i.} = \sum_j P_{ij}$ and the marginal probability that j occurs for any possible i is $P_{.j} = \sum_i P_{ij}$. Maximal indeterminacy would occur where event i and j are completely independent and have no influence over each other. Specifically, where the two events are independent, maximal indeterminacy can be defined as:

$$H_{ij}^{*} = -k\log(P_{i.}P_{.j}) \tag{2}$$

The difference between Eqs. (1) and (2), i.e., the maximal indeterminacy from actual indeterminacy, is described as the measure of constraint that i exerts on j and is called the point-wise mutual information:

$$H_{ij}^{*} - H_{ij} = -k\log(P_{i.}P_{.j}) - [-k\log(P_{ij})] = \log\frac{P_{ij}}{P_{i.}P_{.j}} \tag{3}$$

In a flow network, such as energy flow in ecosystems or commodity trade in economics, we can examine the transfers within a networked system by substituting the probabilities defined in Eq. (4) with the probability of the frequency of the occurrence of flow transfers in the network (Ulanowicz, 2009).

$$P_{ij} = \frac{T_{ij}}{T_{..}},\ P_{i.} = \frac{T_{i.}}{T_{..}},\ P_{.j} = \frac{T_{.j}}{T_{..}} \tag{4}$$

where T_{ij} is the flow from i to j of a conservative substance (energy, dollars, etc.), $T_{i.}$ is the sum of all flows out of i into all j, $T_{.j}$ is the sum of all flows into j from all i, and $T_{..}$ is the total sum of all flows in the network. Substituting the estimators of (4) into Eq. (3) yields the PMI of individual flow transfers i to j within a network:

$$PMI_{ij} = \log\left(\frac{T_{ij}T_{..}}{T_{i.}T_{.j}}\right) \tag{5}$$

From information theory and Jensen's inequality statement (Perlman, 1974), the average mutual information of a network is always non-negative. However, the PMI of individual flows T_{ij} measures the constraint of individual nodes and can maintain both positive and negative numbers. To better understand the possible