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Functional trade patterns in the international photovoltaic trade: Revealed by network motifs

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Abstract—International PV trade is an emerging but prosperous market, which contains high uncertainty and complexity. Functional trade patterns (FTPs) are the basic structural cooperation blocks that better contribute to the evolution trend of global PV trade pattern. In this paper, we aim at identifying functional trade patterns in the international photovoltaic trade with trade interpretations. Based on the trade data of PV commodities from 2007 to 2016, complex networks with countries as nodes and trade flows as links are modeled. FTPs are identified from PV trade networks, their roles on both global and local trade patterns are studied respectively, and countries roles are further measured by FTPs. We find that, 1) FTPs exist with certain structures and trade interpretation; 2) FTPs promote network scale and countries' centrality; 3) Countries roles measured by FTPs provide fresh perspective of countries' trade contribution. We suggest policy makers making cooperation with consideration of forming FTPs locally, and understand their countries' roles by measuring with FTPs.

Keywords—trade patterns, photovoltaic, network motifs

I. INTRODUCTION

To release the pressure and risk of traditional energy, global countries have got high interest in developing sustainable energy [1]. Especially, solar energy has got specific attention because of its advantages of production cost and the relative transportation convenience [2]. As a result, the international PV trade has been an essential part for the global solar energy development. With the increasing PV demand but limit production [3], global PV trade pattern involves increasing complexity. Certain structural characteristics of local trade patterns play functional roles in the evolution of global trade patterns. That is to say, functional trade patterns (FTPs) are the ones contributing to global trade pattern and its evolution trend. Based on this motivation, this paper aims to develop functional local trade patterns in the international photovoltaic trade.

The complex network has been widely used into the international trade to model trade flows among countries. Most previous studies pay more attention to the traditional market, including the international trade of crude oil [4], coal [5], natural gas [6], or their cumulative trade [7]. Among these studies, evolution trends [8], communities [9], potential trade links [10] are studied to explore global and local structural characteristics of trade patterns. Previous studies have made structural exploration based on the trade flows as links and the countries as nodes. However, higher-order structure gets little attention from researchers. That is to say, basic units, which play trade functions in the trade patterns, has got enough answers.

To explore functional trade patterns, we introduce the concept of motifs into our studies, which are recurring and significant inter-connections in networks [11]. Basic structural units have been revealed for certain trade patterns [12]. However, many details, like countries' roles and trade interpretations, haven't been provided. Meanwhile, as an emerging and prosperous market, the international PV trade has its own development characteristics. As a result, in this work, based on the concept of motifs, we explore functional trade patterns for the international PV trade, including the identifying significant functional local trade patterns, and countries' roles among them.

II. DATA AND METHODS

A. Data

We obtained the international PV trade data from the UN Comtrade (http://comtrade.un.org/data/). The Harmonized System (HS) codes of the PV commodities is 854140. Ten-year data from 2007 to 2016 are downloaded respectively with trade flows among countries. We keep trade values (the unit is dollar) to quantitatively represent trade volume.

B. Methods

1) *Network modeling of the international photovoltaic trade*

Complex network has been a hot method for solving interdisciplinary issues. It can be used to measure complex relations among multi agents. For the international PV trade, this work introduces complex network to model PV trade flows among countries, which reflects both global and local trade patterns. For each year, we take countries as nodes, trade flow among countries as links, and the trade value (the unit is dollar) as the weight of links. 10 complex networks are constructed for the international PV trade. We define node sets as to represent countries, so the definition of links is as follows:

$$\mathrm{L} = \begin{bmatrix} l_{1,1} & \cdots & l_{1,j} \\ \vdots & \ddots & \vdots \\ l_{i,1} & \cdots & l_{i,j} \end{bmatrix} \quad (1)$$

and

$$l_{i,j} = \begin{cases} 0 & if\ there\ is\ no\ trade\ between\ i\ and\ j \\ w_{i,j} & if\ i\ exports\ w_{i,j}\ PV\ to\ j \end{cases} \quad (2)$$

where $l_{i,i}$ represents that country i export $w_{i,i}$ dollars of PV commodities to the country j.

2) *FTPs exploration and measurement*

Motifs are basic structural units in the complex networks. Statistical significant patterns, functional units are both can be explored based on the concept of motifs [11]. As a result, motifs provide a fresh way to measure local trade patterns.

Here, we explore 3-motifs from the complex networks of the international PV trade. The module among three nodes is the most basic local structure, which has been widely studied in various application fields. Theoretically, there are 13 types of motifs with directed but unweighted links among three nodes (Figure 1). The first line in Figure 1 are all in open structure with a certain country as key mediates. The second line include seven modules with more close connections among three countries.

Z-score is an indicator used to measure the statistical significance of network motifs in real networks compared with that in random networks. Z-score can be defined as

$$Z_i = \frac{N_{real_i} - \langle N_{rand_i} \rangle}{\sigma_{rand_i}} \quad (3)$$

where N_{real_i} is the number of motif i in real network. N_{rand_i} is the number of motif i in random networks, $\langle N_{rand_i} \rangle$ is its average, and σ_{rand_i} is its standard deviation. The motif with higher Z-score value is more important to the network. Normally, the local patterns with Z-score higher than 0 are recognized as network motifs.

3) *Network indicators*

We use network indicators to measure statistical characteristics of global and local trade patterns respectively. Average degree, network density, network diameter, average clustering coefficient, average path length and modularity are selected as global indicators. In-degree, out-degree, closeness centrality, betweennesss centrality and clustering coefficient are adopted as local indicators. Here, in this draft paper, details of these indicators would not be shown, which can be referred from previous works [10,13].

4) *Pearson coefficient*

To measure the correlation between the motifs' constitution and the network structure, we introduce Pearson Correlation into our studies. The matrix of the Pearson correlation coefficient, P, is defined as follows:

$$\mathrm{P} = \begin{bmatrix} p_{11} & \cdots & p_{1N} \\ \vdots & \ddots & \vdots \\ p_{M1} & \cdots & p_{MN} \end{bmatrix} \quad (4)$$

where M and N are the length of two data series.

The equation for the Pearson correlation coefficient is as follows:

$$p_{m,n} = \frac{\sum_{i=1}^{t}(x_i^m - \overline{x^m})(y_i^n - \overline{y^n})}{\sqrt{\sum_{i=1}^{t}(x_i^m - \overline{x^m})^2}\sqrt{\sum_{i=1}^{t}(y_i^n - \overline{y^n})^2}} \quad (5)$$

where m and n are the data in two different data series, $p_{m,n}$ is the Pearson correlation coefficient between m and n, and t is the number of spot data for each variable. $\overline{x^m}$ is the average percentage value of m, which is the same as $\overline{y^n}$.

III. RESULTS AND ANALYSIS

A. Basic trade units in the PV trade network

Local trade patterns among certain countries are various with abundant structural information. Theoretically, 13 different types of local trade patterns exist among three countries. However, it is hard to say whether these local patterns are formed randomly or empirically, and whether they are functional to the evolution of local or global trade pattern. As a result, we consider statistical significance for 13 3-node motifs. It means that the local patterns with higher statistical significance are more functional to the evolution of the international PV trade.

Based on common rules, we rank the z-score for each motif from 2007 to 2016, and then select the ones with z-score>0 as FTPs. That is to say, FTPs are the local patterns that appear in the international PV trade with significant empirical characteristics.

To our surprise, even if the complexity of the international PV trade is increasing, the top FTPs are same through 10 years. We pick FTPs, and make further analysis on them, including structural features and the corresponding empirical explanation. Table 1 shows 6 FTPs in the international PV trade, which are motif 6, motif 12, motif 46, motif 164, motif 166 and motif 238, and they are ranked in the table according to their average importance during 10 years, from the highest (motif 46) to the lowest (motif 164).

From the perspective of structural features, FTPs shows different functions to the local interconnections among countries. Firstly, we know that the local pattern that widely distributes among countries may not play functional roles to the evolution of the international PV trade. For example, although motif 6 are both the common and the functional local pattern, motif 14 appears in a high percentage but not functional. In comparison with motif 14, motif 164, which describes a bilateral trade cooperation relies on one single and unilateral import source, has higher empirical typicality.

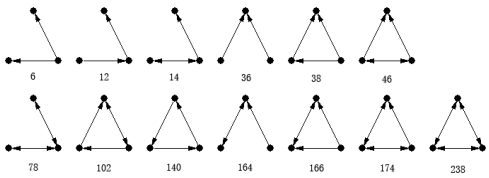

Fig. 1. 13 types of 3-motifs with directed and unweighted links

TABLE I. FTPS IN THE INTERNATIONAL PV TRADE

Motifs Code	Structural feature	Empirical meaning
46	Input from a bilateral relation	Countries with bilateral trade cooperation have common export partner.
12	Chains by intermediate node	The transmission of PV commodities exist in countries.
166	Output to a bilateral relation	Countries with bilateral trade cooperation have common import partner.
238	Bilateral relations among 3 nodes	Three countries have steady trade relations with inter-dependence
6	Output from a common node	Independent countries relies on a common import partner with single and unilateral cooperation.
164	Bilateral relation with one input	Countries with bilateral trade cooperation relies on a single and unilateral import source.

Secondly, the statistical significance of motif 46, motif 166 and motif 238 show that relative steady local interconnections promote the evolution of global trade patterns. Thirdly, motif 12 shows the importance of PV transmission on the evolution of the international PV trade.

B. *Functions on the global PV trade pattern*

From a macroscopic perspective, we try to answer whether the constitution of FTPs have correlation with the structure of global PV trade patterns. In this section, two factors used into the Pearson correlations are respectively the measurement of FTPs and the statistical properties of international PV trade networks. Considering the different meanings, we count the measurement of FTPs in two ways. One is the percentage of each FTP in the total triadic motifs (Figure 2a.), and the other is the normalized Z-scores of each FTP (Figure 2b.). There are 8 indicators used to measure the global PV trade pattern from different perspectives, which are number of nodes, number of edges, average degree, network density, network diameter, average clustering coefficient, average path length and the modularity. Each block in the Figure 2 represents the Pearson correlation between the certain FTP and the statistical indicator.

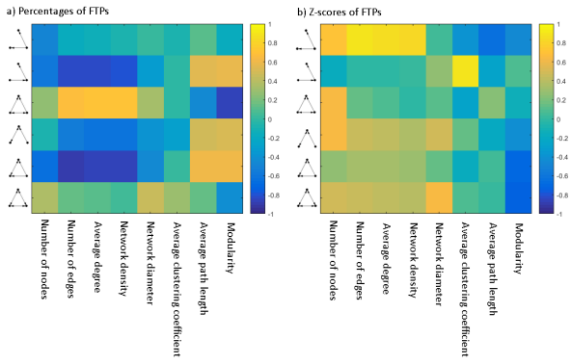

Fig. 2. 13 types of 3-motifs with directed and unweighted links

TABLE II. FTPS IN THE INTERNATIONAL PV TRADE

Indicators	Years	FTPs					
		6	12	46	164	166	238
In-Degree	2007			+***			+****
	2010	-*		+****			+****
	2013	-*		+***			+***
	2016	-*		+***			+***
Out-Degree	2007	-*		+**			+****
	2010	-*		+**			+****
	2013	-*		+*			+*
	2016	-*		+**			+****
Closeness Centrality	2007	-*					+*
	2010	-**		+*			+*
	2013	-**		+*			+**
	2016	-*		+*			+*
Betweenness Centrality	2007						
	2010						
	2013						
	2016						
Clustering Coefficient	2007						
	2010						
	2013	+*					
	2016						-*

The results shown in Figure 2 approves that the increase of FTPs' percentage or their statistical significance have different impact on the global PV trade patterns. From Figure 2a, motif 46 plays opposite functional roles compared with the motif 12, motif 164 and motif 166. The percentage of motif 46 have a positive correlation with the network scales, but have a negative correlation with the average path length and the modularity, which is totally opposite for motif 12, motif 164 and motif 166. From Figure 2b, the distribution of Pearson correlations shows more potential rules. Except motif 12, almost all 5 FTPs are more close to the number of nodes, number of edges, average degree, network density and network diameter than to the average clustering coefficient, average path length and modularity. Motif 12 have a high positive correlation with the average clustering coefficient. It means that, the structure of motif 12, which describes the transfer of PV commodities, contribute to the local closeness among countries.

C. *Functions on countries*

From a microscopic perspective, this section aims at figuring out how FTP's play functional roles on countries' global roles. We introduce the Pearson correlation into our study to measure the close relations between countries' involvement in FTPs and their global structural roles. Each country's involvement in FTPs is measured by its proportion that appears in each FTP with consideration of all triadic motifs. Countries' global structural roles are measured by five different statistical indicators, in-degree, out-degree, closeness centrality, betweenness centrality and clustering coefficient. We take the measurement in 2007, 2010, 2013 and 2016 as examples, which has been shown in Table 2.

In Table 2, the '+' or '-' character means two data series shows positive or negative correlation. The number of '*' represents the correlation degree ('*':0.5<p<0.6, '**':0.6<p<0.7, '***':0.7<p<0.8, '****':0.8<p<0.9). The results show that not all FTPs play significant roles on the local PV trade pattern, and the impact shows differences among statistical perspectives. First, motif 238, motif 46 and motif 6 play functional roles on countries' in-degree, out-degree and closeness centrality. Especially, the countries that highly involve into the motif 238, always have wide import and export partners. Similarly, the countries mostly involving in motif 46, shows wide import relations. Second, in comparison, although motif 6 is both the functional one and the most common triadic motif, but it shows limited impact on countries' local structural characters. Third, FTPs are always functional on countries' closeness with other countries, but not the bridging roles or clustering relations among countries.

D. *Countries' functional roles revealed by FTPs*

From one aspect, we've known that the involvement in FTPs have impact on countries' structural roles. However, how countries functionally to the local PV trade pattern still remain analysis, which reflects countries' functional roles in the international PV trade. For example, in motif 46, the country importing PV from other two countries, which have bilateral trade cooperation, is local export source, and has relative steady import tunnels; in motif 12, the country is local transfer trader.

Top ranking countries (at least within top 10 one time during 10 years) with structural roles or functional roles are

shown in Figure 3. Different from structural roles that are measured by traditional indicators like out-degree (Figure 3, a1), in-degree (Figure 3, b1), and betweenness centrality (Figure 3, c1), countries' functional roles are measured by their times appearing in the certain role in FTPs. Here we mainly consider three types of functional roles: 1) Exporters in motif 166 (Figure 3, a2); 2) importers in motif 46 (Figure 3, b2); 3) transfers in motif 12 (Figure 3, c2).

Figure 3 approves that the top countries playing different structural roles appear high similarities and overlap. No matter exporters, importers or transfers, China, the United States, India, Canada and several European countries play important structural roles in the international PV trade. In comparison, functional roles revealed by FTPs provide abundant and various information. First, from a local perspective, Southeastern Asian countries and several European countries that are not same as the ones with structural roles are main functional exporter for countries with bilateral cooperation. Second, countries from western South America and Africa are functional import source for steady bilateral trading countries. Finally, functional transfers locate similar with structural roles. China shoulder global PV transfer, and eastern South American countries play more functional roles. As a result, countries' functional roles revealed by FTPs provide a fresh perspective for measuring countries' contributions.

IV. Conclusions

In this paper, FTPs, which play essential roles on the evolution of both global and local trade patterns, are studied to reveal structural essence of international PV trade patterns. Based on the trade flows data among countries from 2007 to 2016, 10 directed complex networks of international PV trade are established. FTPs are explored, and their functions on global and local trade patterns are measured respectively. Further, we find that measuring countries' trade roles by FTPs provide a fresh perspective of knowing countries' trade contribution. Main conclusions are as follows:

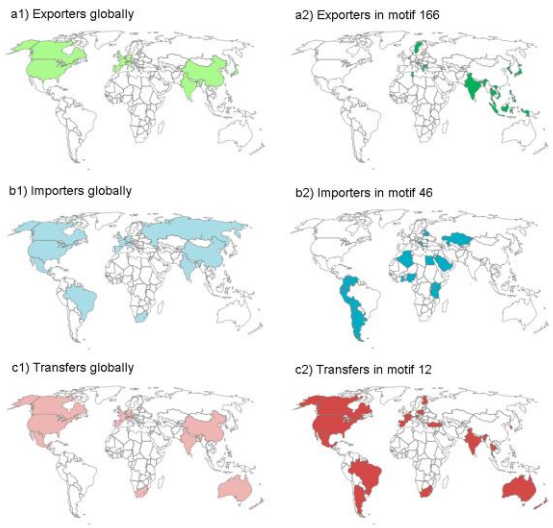

Fig. 3. 13 types of 3-motifs with directed and unweighted links

1) 13 trade patterns among three countries are explored, but only 6 of them are functional ones. The most functional ones are motif 46 and motif 166 which involve common export destination, and motif 12 which involve a key transmitter;

2) Most functional trade patterns promote network scale. Local transmittion help countries having denser cooperations. Countries with inter-cooperation would promote countries' centrality.

3) Countries' roles are better specified with FTPs. Most eastern Asian countries except China and several European countries are local key exporters, while several Latin American countries and African countries are main import destination locally. The distribution of key transmitters are decentralized, including most American countries, main producers from Europe, India, Australia, South Africa and so on.

Based on these findings, we suggest policy makers consider construct local trade cooperation more functionally, and measure countries' PV trade status with consideration of their involvement in FTPs.

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