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Spatial structure, inequality and trading community of renewable energy networks: A comparative study of solar and hydro energy product trades

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ABSTRACT

Renewable energy trade is booming and has formed complicated networks worldwide. However, our knowledge of the spatial structures and evolution of these networks is limited. In this paper, network analyses are used to examine the geographic characteristics of selected renewable energy trades and their evolution based on the United Nations COMTRADE Database from 1988 to 2013. The results show that the networks are expanding to include more and more countries and relationships, and scale of the networks is larger than ever. A tripartite confrontational renewable energy trading system has been forming and is strengthening. Europe, the USA, China and other Asian countries are the main players, and China has overtaken the USA and Europe as the leading player. Inequality and 'small-world' characteristics appear in renewable energy trade. Solar energy trade presents a triadic community structure with Europe, the USA and China as the dominant players, while hydro energy trade presents a smaller and more dispersed structure. The core–periphery structure strongly suggests a trade dependency between hubs and peripheral elements in renewable energy trade. Developing countries should design appropriate incentives and contribute to particular segments in renewable energy value chain to accelerate and benefit from the South–South renewable energy trade.

1. Introduction

Conventional energy sources based on oil, coal and natural gas have been shown to be highly effective driving factors for economic development (Ellabban et al., 2014). However, the utilization of conventional energy has led to serious environmental pollution. Renewable energy (typically including solar energy, wind energy, hydro energy and biomass) is now gaining popularity with national governments in order to meet the United Nations' goal of reducing greenhouse gas emissions. Renewable energy comprised 19% of total energy consumption and 22% of electricity generation in 2013 (BP, 2015). As the installation capacity of renewable energy continues to grow, and the equipment costs continue to fall, these proportions will likely increase further. The value of the green energy market is projected to increase to between US$1200 billion and US$1900 billion by 2020 (Jürgen et al., 2009). Trade is playing a positive role in this inexorable trend. Notably, developing counties are significantly increasing their exports of renewable energy equipment. For example, China's exports of solar energy devices such as solar panels and cells have reached US$10 billion, which is almost 80 times the value that China exported just ten years earlier (UNEP, 2013).

As it is now well established that trade in renewable energy is booming and is playing an increasingly important role in global economic prospects, numerous studies have been carried in this area. Many researchers have focused on renewable energy development and its influence on CO_2 emissions (Barbato et al., 2014; Ben Jebli and Ben Youssef, 2015). Some researchers have studied renewable energy consumption and economic development (Ben Jebli and Ben Youssef, 2015; Dent, 2015; Sebri and Ben-Salha, 2014), and others have investigated how renewable energy will affect energy supply and energy security (Lilliestam and Ellenbeck, 2011; Roepke, 2013). In addition, regional renewable energy development has been systematically and thoroughly discussed. For example, considerable attention has been paid to renewable energy in Africa, Europe and Asia, especially in Germany, India and China (Ben Aissa et al., 2014; Ben Jebli and Ben Youssef, 2015; Dent, 2015; Kumar and Agarwala, 2013; Li et al., 2015; Moest and Fichtner, 2010; Sebri and Ben-Salha, 2014).

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However, few analyses have been carried out on the spatial structure of the renewable energy trade network. Previous researchers have reported conflicts between domestic renewable energy supply and global trade regimes (Lewis, 2014) and examined the interrelations between domestic innovation policy and the international renewable energy trade (Kim and Kim, 2015). The differences between fossil fuel trade and renewable energy trade have also been studied (Farah and Cima, 2013; Yang, 2016). Compared with other commodity trades, we still know little about the spatial organization pattern of renewable energy trade and how it has changed over time.

Empirical studies on the spatial dynamics of trade have shown that the international trading system is becoming increasingly interconnected; the structures of 'small world' and 'flat world' are underscored by the spatial clustering of countries, and this cluster pattern reflects the dominance of industrialized countries (Yang et al., 2015; Barigozzi et al., 2011; Coe et al., 2007; Fagiolo et al., 2010; Garlaschelli et al., 2007; Kali and Reyes, 2007). Several important questions immediately present themselves. For example, do the trade networks of renewable energy, a special type of commodity, share the same spatial characteristics as other trade networks* What are the geographical characteristics of renewable energy trade networks, and how are they organized* This paper seeks to augment the existing literature by examining the spatial dynamics of international trade in renewable energy. Within the network analysis framework, the world trading system is represented through the organization of import and export relations, and the distribution of renewable energy trade across the network is elaborated upon in Section 3.

2. Methods and data

2.1. Network construction

In the complex network model, renewable energy trade relationships between countries are captured graphically by a collection of nodes and edges. Renewable energy networks are represented by the set G =(V,E), where network nodes $V = \{v_1, v_2, \ldots, v_n\}$ stand for countries, and the trade relationships are represented by network edges $E = \{e_{ij}\}$. The adjacency matrix is described as e_{ij} =1 if node v_i exports to node v_j; otherwise, e_{ij} =0. Differences in trade volume should be taken into account. In this paper, renewable energy trade flows are constructed as the weights of edges, where w_{ij} describes exports from country v_i to country v_j. If no exports are found from country v_i to v_j, w_{ij} =0. The weight-directed crude oil network matrix can then be given as follows:

$$W = \begin{bmatrix} w_{11} & \cdots & w_{1m} \\ \vdots & \ddots & \vdots \\ w_{n1} & \cdots & w_{nm} \end{bmatrix}.$$

2.2. Network measures

2.2.1. Connectivity

After reasonable abstraction of the trade network transformation, the overall network connectivity is calculated with three network density indices, which can be expressed as

$$\alpha = \frac{2(e - v+1)}{(v-1)(v-2)}, \beta = \frac{e}{v}, \quad \text{and}\gamma = \frac{2e}{v(v-1)}. \tag{1}$$

In the above equations, e denotes the edges of the directed network, and v refers to the network nodes. The values of α and γ range from 0 to 1, with 1 indicating full connectivity. In the case of β, the higher the value, the greater the connectedness of the network.

2.2.2. Network and centrality

Three centrality measures are generated by analyzing the degree (k) of the country node. Degree refers to the extent to which two nodes are graphically adjacent (connected) to one another and hence serves as a local point-based centrality measure (Scott, 2000). In effect, k measures the number of edges in an unweighted matrix. A country with a higher k is in a more important structural position because it has appreciable direct linkages with other countries. The total nodal degree k can be further divided into in-degree k_{in} (of importing country node) and out-degree k_{out} (of exporting country node):

$$k_j^{in} = \sum_{i=1}^{N} e_{ji} \text{and} k_i^{out} = \sum_{j=1}^{N} e_{ij}. \tag{2}$$

In order to assign weights to each directed trade relationship in the trade distribution, the weighted degree node is represented as strength (s), where s is the weighted version of the above nodal degree:

$$s_j^{in} = \sum_{i=1}^{N} w_{ji} \text{and} s_i^{out} = \sum_{j=1}^{N} w_{ij}. \tag{3}$$

2.2.3. Measures of equality

The Lorenz curve and the Gini coefficient are commonly used to measure the inequality in income distribution in economics, and they can be used to measure the equality (or inequality) in the renewable energy network as well. The Lorenz curve can reflect the cumulative distribution of nodes through a graphical representation. If the Lorenz curve is described by the function $Y = L(x)$, the value of the Gini coefficient can also be calculated through integration as

$$Gini=1 - 2\int_0^1 L(x)dx \tag{4}$$

In Eq. (4), $Gini\in[0, 1]$, where 0 indicates perfect equality and 1 indicates perfect inequality.

2.2.4. Community structure

The analysis of community structure is an important attribute of network research. It can be used to verify both the 'small world' and the 'flat world' properties of renewable energy trade exchanges. The relationships between nodes in the same community are usually stronger and more stable than those between nodes of different communities. While it is possible to visually obtain regional neighborhood patterns from centrality measures, the community structure is better quantified based on the notion of modularity (Newman, 2006). Up to a multiplicative constant, modularity Q refers to the number of edges falling within a group minus the expected number in an equivalent network with edges placed at random (Leicht and Newman, 2008). For directed networks, Q is expressed as follows:

$$Q = \frac{1}{m}\sum_i \sum_j \left[w_{ij} - \frac{k_j^{in} k_i^{out}}{m} \right] \delta(c_i, c_j), \tag{5}$$

where $m = \sum_i k_i^{out} = \sum_j k_j^{in}$, $\delta(c_i, c_j) = \begin{Bmatrix} 1 c_i = c_j \\ 0 c_i \neq c_j \end{Bmatrix}$, c_i shows the community to which country v_i belongs, and c_j is the community to which country node v_j belongs. If nodes v_i and v_j are in the same community, $\delta(c_i,\ c_j)$ is 1; otherwise, it is 0. Here, we calculate the community structure using the application Gephi (https://gephi.org/).

2.3. Data

International trade statistics compiled in the United Nations trade database (COMTRADE) are used in this paper. Since trade in renewable energy is not strictly defined, and there are no specific statistics for it, the trades have to be categorized in different Harmonized System (HS) subheadings. According to the COMTRADE commodity list, seven HS subheadings are relevant to renewable energy trades, including photovoltaics (solar PV), hydro energy, wind and biomass sectors. Bilateral trade flow data over the period of 1988–2013 are available. HS 854140,