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Analysis of the distribution and evolution of energy supply and demand centers of gravity in China

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HIGHLIGHTS

- We studied China's coal, oil, gas, and electricity distribution from 1997 to 2009.
- We quantified the evolution of the energy supply and demand centers of gravity.
- The study revealed spatial variations in the gap between energy supply and demand.
- The pattern was closely related to energy strategies and resource reserves.
- The results provide support for coordinating regional development.

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ABSTRACT

Using a center of gravity model and GIS software, we measured how China's energy production and consumption centers changed (positions, movements, distances, and rates) from 1997 to 2009, thereby revealing regional differences in the relationship between supply and demand. We found that the centers of gravity for raw coal consumption, crude oil production and consumption, and electricity production and consumption moved southwest during the study period, whereas those of raw coal and natural gas production moved northwest and that of natural gas consumption moved southeast. The distances moved were largest for natural gas, followed by crude oil, but the distances were small for raw coal and electricity, indicating that their supply and demand pattern changed little during the study period. The gaps between supply and demand for raw coal, crude oil, and natural gas were large, and tended to increase. The production centers were northwest of the consumption centers, indicating that China's energy production is concentrated in the northwest, whereas consumption was concentrated in the southeast. This pattern resulted from the distribution of China's energy resource reserves and its energy development strategies. Recommendations are provided to reduce the gap between supply and demand.

1. Introduction

As a result of China's continuous and rapid economic development in the last several decades, energy shortages have become increasingly prominent. Although China is a major energy producer and consumer, there is a big gap between its energy supply and demand (Chang et al., 2003). In 2010, China's share of global energy consumption (20.3%) was the world's largest (British Petroleum (BP), 2011); as a result, the production of several energy types cannot meet the demand created by the growth in domestic consumption. China is self-sufficient in terms of its raw coal consumption, but for other energy types, there is a large gap between supply and demand. For example, 52.7% of crude oil and 11.2% of natural gas is imported (British Petroleum (BP), 2011). China is excessively dependent on imports of crude oil (Asif and Muneer, 2007).

Safeguarding the security of China's energy supply has been the key to ensure sustainable development (Ni and Johansson, 2004), and has been the focus of international attention (Downs, 2004; Kennedy, 2010). In addition to national energy security, regional energy security cannot be ignored. Some provinces have a severe imbalance between supply and demand because of excessive consumption or surplus production. Crude oil provides a good example. Although China depends strongly on crude oil imports at a national level, six provinces (i.e., Beijing, Zhejiang, Fujian, Jiangxi, Hunan, and Chongqing) imported 100% of their crude oil, whereas Tianjin and Qinghai provinces exported more than 50% of their indigenous production to other provinces in

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2009 (National Bureau of Statistics of China (NBSC), 1991–2010). Raw coal provides an another good example. Although China imports no raw coal, Tianjin, Shanghai, Guangdong, and Hainan provinces imported 100% of their raw coal from other provinces, whereas Inner Mongolia and Shaanxi Province exported more than 50% of their raw coal production to other provinces in 2009 (National Bureau of Statistics of China (NBSC), 1991–2010). These serious imbalances in energy supply and demand within China make it important to understand the problems that arise from the spatial patterns of energy supply and demand, the relationships between them, and how the patterns have evolved over time.

In recent years, several studies have examined the spatial variations in energy consumption. For instance, Liang and Zhang (2010) adopted the Theil index (Theil, 1966, 1967) to measure the spatial inequality of urban energy consumption in China. Jia et al. (2011) employed statistical methods to discern spatial differences in global energy consumption. Li et al. (2010) applied cluster analysis to probe the changes in the spatial pattern of rural energy consumption in China. However, these studies only considered energy consumption, and did not account for energy production. To analyze the relationship between energy supply and demand, Zhang and Huang (2009) used the gap between energy production and consumption, the degree of self-sufficiency, and the transportation distance to analyze the changing pattern of regional energy supply and demand in China. All of these studies revealed regional differences in energy consumption or an imbalance between supply and demand in most provinces, but none of these authors quantified the distances between centers of supply and demand or how these distances changed over time. In 1872, the American scholar Hilgard used the concept of a center of gravity for the first time to study population problems in the United States and found that this approach provided a concise, accurate method for studying population distributions (Hilgard, 1872). The concept of a center of gravity derives from physics, and represents the point at which the distribution would balance if it were represented by weighted points on a weightless line, plane, or sphere (Kumler and Goodchild, 1992). Since Hilgard's innovation, his approach has been commonly used in the study of geographic distributions (Lefever, 1926; Sviatlovsky and Eells, 1937; Jones, 1980).

After this early success, the center of gravity concept became increasingly widely applied in the field of economics. For example, the theory has been used to study the movement of centers of gravity related to economic parameters (Feng and Huang, 2006; Grether and Mathys, 2010; Hui et al., 2011; Klein, 2009; Sun, 2001; Qiao and Li, 2005), population (Aboufadel and Austin, 2006; Chen et al., 2007; Duan et al., 2008), food provision (Wang et al., 2012), land utilization (Chen and Zhou, 2011), consumption goods (Fu et al., 2011), ecosystem services (He et al., 2011), farmland (Gao et al., 1998), and environmental pollution (Peng and Lin, 2010; Wang et al., 2009). Based on knowledge of the importance of spatial differences, some scholars have also introduced the theory of centers of gravity to study the pattern of movement of energy consumption (Fesharaki, 1996; Wang et al., 2006). However, there have been no studies of the movement vectors (initial position, distance moved, direction of movement, and movement rate) for energy production and consumption centers of gravity or of the relationship between energy supply and demand that results from differences in these movements.

Because China's provinces vary so greatly in their energy resource endowment, level of economic development, industrial structure, and level of technical development, their socioeconomic development has not been balanced. There is a large distance between the energy production and consumption centers of gravity, and this distance has changed over time because these centers change constantly in response to changes in the provincial economies and energy resource development policies. In the present study, we focused on the major primary energy sources in China: Raw coal, crude oil, and natural gas accounted for 81.7%, 10.4%, and 4.4%, respectively, of total primary energy production in 2009 (National Bureau of Statistics of China (NBSC), 1991–2010). These types of primary energy are particularly important because each can be used in final consumption, or can be consumed to generate secondary energy. We also included electricity in our analysis because it is the major form of secondary energy, and can be produced both by combustion of primary energy types (coal, oil, and gas) and by hydroelectric power, thermal power, nuclear power, and other sources such as wind. The power-generation sector is a major component of China's energy sector, and the production and consumption of electricity is a crucial part of this sector.

In this paper, we used geographical information system (GIS) technology to analyze the evolution of the patterns of raw coal, crude oil, natural gas, and electricity production and consumption in China based on their centers of gravity from 1997 to 2009. The results revealed trends in the movement vectors for energy supply and demand, and spatial variations in the gap between energy supply and demand. By understanding the reasons behind these patterns, it will become possible to provide guidance for the development of policies intended to improve China's national and regional energy security.

This paper is organized as follows: Section 2 describes the methods and data used to conduct this study. In Section 3, we discuss the results and their implications for regional energy resource endowments and energy development strategies. In Section 4, we present the conclusions that can be drawn from this study, along with the study's limitations and directions for further study.

2. Data used and methodology

2.1. Methodology

In this paper, we used center of gravity theory to analyze the spatial distribution and centers of gravity for China's energy production and consumption and to determine how they have changed over time. In our calculations, we assumed that each administrative region at a provincial level (including provinces, autonomous regions, and province-level municipalities) was located on a homogeneous plane (i.e., that the analysis was conducted in two dimensions, without accounting for the third dimension of altitude), and that the energy production and consumption by each region was concentrated in the provincial capital cities. Although the latter is clearly a simplifying assumption, it ensured consistency among regions with different levels of detail in the available data, and can be justified by the fact that most of the province's energy production and consumption are concentrated in or near the capital as a result of rapid urbanization in the past several decades. Each provincial capital city then acts as a particle on the plane, with weights determined based on the energy production and consumption quantities. This simplification is also necessary because finer-grained data (e.g., at a county level) is not yet available throughout China.

The position of the center of gravity was then calculated using a combination of the geographical coordinates of the 30 cities and their corresponding energy production and consumption weights. The difference in the positions of the centers for production and consumption represent imbalances between the two parameters, and differences in the movement of these centers of gravity represent changes in the balance over time. The position of the center of gravity was expressed in terms of longitude and latitude,