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Urban energy transition in China: Insights from trends, socioeconomic drivers, and environmental impacts of Beijing

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ABSTRACT

The coal-dominated energy structure has not only fueled China's rapid economic development, but also brought great pressure on China. Promoting energy transition is among the great challenges for China. As one of the most developed megacities in China, Beijing promotes energy transition intensively. In this study, we explored the trends, socioeconomic drivers and environmental impacts of the energy transition process in Beijing during the decades. We found that Beijing's energy transition has gone through four typical stages. After a parallel growth between the economy and coal-dominated energy consumption at beginning, the growth rate of energy consumption has gradually slowed down since 1996. Between 2000 and 2007, the energy structure became relatively balanced and diversified, driven by the changes of energy intensity, energy structure, and final demand composition, along with the economic structure's shift from heavy manufacturing to service. Thereafter, economic development was seriously decoupled from direct energy consumption, and the de-coal trend had made remarkable achievements. SO_2 and NO_x emissions have declined significantly since 2007. Diversified energy structure based on the de-coal trend, cleaner energy, and economic restructuring promotes energy transition. Meanwhile the feasibility of implementation also should be considered in other cities' energy transition process in China.

1. Introduction

China has been heavily dependent on burning coal to fuel its spectacular growing economy (Heinberg and Fridley, 2010; Liu et al., 2013). Although the share of coal in the energy structure has declined since 1978, coal is still the dominant energy source in China, with a 64.0% share of the energy structure in 2015. This energy situation in China has led to three serious problems. First, the single-energy-source dependence and limited fossil energy in China threaten the country's energy security. Second, the coal-dominated energy structure has caused serious domestic air pollution, and the large amounts of SO_2, NO_x, and $PM_{2.5}$ in the air caused by coal combustion pose great health risks to the Chinese. Third, China is under great pressure to curb its soaring CO_2 emissions, and the coal-dominated energy structure is the main source of CO_2 emissions in China (Liu and Diamond, 2005; Kan and Wu, 2013; Dong et al., 2014). Hence, promoting energy transition toward a clean, low-carbon, and safe energy structure is an urgent and essential task for China.

Urban areas are the centers of production and consumption, and hence also the centers of energy consumption, accounting for about 66.7% of primary energy demand and 70% of the total energy consumption-related CO_2 emissions in the world (International Energy Agency (IEA), 2016). Thus, transitioning urban energy is important for shaping the national energy transition. As one of the most developed megacities in China, Beijing is in pursuit of energy transition. Beijing currently suffers from heavy $PM_{2.5}$ pollution. As the capital city representing the image of China, there is great pressure on Beijing to improve its air quality, and energy transition is among the most important solutions. However, strong financial support is required to promote energy transition, especially to promote clean and low-carbon energy. As one of the most developed cities in China, Beijing has recognized the importance of energy transition earlier and has begun to advance its process intensively; it also has the capability to support its energy transition. Beijing has implemented a number of forceful energy policies and laws to adjust the energy mix (Li et al., 2016a) and taken measures to deal with air pollution issues, especially since the Olympic Games in 2008. Hence, it is worth discussing the characteristics and implications of Beijing's energy transition in-depth to provide examples and lessons for the energy transition, energy saving, and emission reduction efforts in other regions of China.

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Energy transition has gradually attracted increasing attention from science and politics (Verbong and Geels, 2007). Over the years, numerous authors have studied energy transition based on its features, definitions, and components (Grübler et al., 1999; Geels and Schot, 2007). Smil (2003) held that energy transition should be flexible to adapt to the various changes and uncertainties of the socioeconomic system. Verbong and Geels (2010) and Zhang (2010) argued that energy transition was not achieved easily. Bridge et al. (2013) and Sovacool (2014) both asserted that energy transition could not be a uniform process at different levels or scales. The literature on the definitions and components of energy transition has also blossomed in the last 20 years. Fouquet and Pearson (2012) deemed that energy transition comprised sets of structural changes in energy production and consumption. Other studies argued that energy transition consisted of not only major progress in technological innovation (World Energy Council (WEC), 2014; Darby, 2017), but also a series of vital adjustments and changes in energy prices, policies, and social factors (Chabrol, 2016; Fouquet, 2016; Iychettira et al., 2017; Van Leeuwen et al., 2017). Specifically, it involves lower-carbon and cleaner-energy alternatives (such as natural gas), nuclear phase-out, increasing renewable energy input, distributing energy resources, and smart energy systems that can adapt to and support socioeconomic development (Osorio and van Ackere, 2016; Chen and Geng, 2017; Rodríguez-Huerta et al., 2017; Carley et al., 2018). Thus, energy transition in this paper is defined as a transition in the long-term amount of energy supply and demand, fundamental energy structure, energy consumption volume, environmental impacts of energy consumption changes, and associated underlying driving forces.

The pathways of energy transition have been a subject of major research interest (Grübler et al., 1999; Batoletto and Rubio, 2008; Geels et al., 2016). Previous studies about developed countries have largely focused on the transition to a renewable energy system (Moriarty and Honnery, 2011), as most such countries have already gone through the energy transition from fossil fuels to clean energy (Lund, 2000; Blazejczak et al., 2014). Meanwhile, the energy transitions of developing countries have only begun. In the case of China, researchers have tended to focus on one aspect of the energy transition, such as China's energy consumption, energy intensity, or energy structure problems (Li et al., 2013b; Yuan et al., 2014; Zhang and Lahr, 2014). First, socioeconomic development requires massive energy resources, and energy consumption increases sharply. In recent years, many studies have examined China's energy consumption, with focuses such as decoupling analysis between energy consumption and economic growth (Dong et al., 2016; Chen et al., 2017), the driving forces of energy consumption (Xie, 2014; Wu and Zhang, 2016), and the reasons for the increase in energy use (Du and Lin, 2015). Second, energy intensity plays an important role in the measurement and assessment of a country's energy efficiency and technological level (Sun, 2002). The Chinese government has attached great importance to energy intensity reduction, and much research has been done on energy intensity, its trends (Yang et al., 2016), management system (Li et al., 2016b), and influence factors, such as urbanization, technical change (Yan, 2015), and final demand (Zeng et al., 2014). Third, energy structure change has been a powerful symbol of energy transition and propitious for improving environmental status. Wang et al. (2016) simulated the structure of China's future energy roadmap and found that the total energy consumption of coal peaked in 2024 and decreased to 43.0% in 2050. Some researchers have adopted three-scale input-output modeling to calculate the embodied energy, water consumption, and carbon emissions in Beijing (Chen et al., 2013; Han et al., 2015; Li et al., 2016b). In addition, scholars have also comprehensively analyzed CO_2, $PM_{2.5}$, and mercury emissions (He et al., 2001; Li et al., 2013a, 2017) to examine the effects of resource-environment, and the relative energy policies that drive these energy consumption trends and low-carbon development (Ang, 2004; Dhakal, 2009; Liu and Li, 2011).

Although major research on energy transition has been conducted, there is still a lack of systemic, comprehensive, and detailed analysis of the whole urban energy transition process in China, especially in terms of a comprehensive evaluation of the trends, socioeconomic drivers, and environmental impacts of the urban energy transition process. In this study, by taking Beijing as an example, we attempt to answer the following questions: (1) What has been Beijing's energy transition process during the decades? (2) What drives this transition? (3) What is the impact of the transition on air pollution? And (4) What can other cities in China learn from the energy transition in Beijing?

The rest of this paper is organized as follows. Section 2 outlines the methods adopted in this study and how we compiled the data. In Section 3, we present the results of the study. Section 4 discusses the features, key factors, and environmental impacts of energy transition in Beijing and provides policy implications. Section 5 concludes the paper.

2. Methodology and data

2.1. Sankey diagram

The Sankey diagram is a widely accepted analytical tool for sorting out and displaying energy systems (Cullen and Allwood, 2010; Ma et al., 2012; Zhang and Wang, 2012; Chong et al., 2015). With the aid of the Sankey diagram, it is possible to explore the detailed energy transition at the sectoral level from both supply and demand perspectives.

The whole chain in our Sankey diagram included three stages: energy supply, energy transformation, and energy demand. In the case of Beijing, it contained four energy types: coal, petroleum, natural gas, and electricity. Coal was further divided into local raw coal supply and coal imported from other domestic regions. In addition to its use for direct consumption, some coal was used for thermal power. Petroleum comprised crude oil imported from other domestic regions and refined product imported from domestic regions and abroad. Similar to coal, parts of the petroleum and natural gas supply were also used for thermal power. Natural gas depended on import from other regions of China. Notably, electricity was the secondary energy source here, in addition to hydro power. Moreover, thermal power was produced locally from combustion of coal, natural gas, and petroleum and a large amount of electricity included local hydro power and other thermal power imported from other domestic regions. From the supply side to the demand side, the diagram could comprehensively depict the changes in energy flow. The width of the energy flow signified the quantity of energy, and the color of each flow signified the energy type.

2.2. Structural decomposition analysis approach

Structural decomposition analysis (SDA) is a widely accepted method for assessing the contributions of different driving factors to changes in energy consumption and pollutant emissions (Wood, 2009; Wang et al., 2013; Tian et al., 2014). For example, Mi et al. (2017a) used the SDA approach to investigate the driving factors that affected the changes in embodied CO_2 emission based on China's domestic and international trade between 2007 and 2012. SDA is based on the input-output (I-O) model (Leontief, 1936; Hendrickson et al., 1998; Miller and Blair, 2009), which can not only analyze energy consumption and pollutant emissions into factors that researchers are interested in according to their real needs, but also account for indirect energy consumption and demonstrate the details of sectoral effect and final demand categories on the change in driving factors (Yamakawa and Peters, 2011; Wang et al., 2014; Mi et al., 2017b).

According to the theory of the I-O model, the main row balance can be expressed mathematically as

$$x = Ax + y, \tag{1}$$

$$x = (I - A)^{-1}y = Ly, \tag{2}$$

where $x = (x_i)_{n\times 1}$ denotes the vector of total outputs; x_i indicates the