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Capturing the co-benefits of energy efficiency in China — A perspective from the water-energy nexus

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ABSTRACT

To address air pollution and control greenhouse gas emissions, China has been implementing a number of national energy policies. This paper assesses the environmental and water saving co-benefit of long-run energy efficiency improvement based on a recursive multi-sectoral dynamic CGE model. A 3% and 5% energy efficiency improvement, based on using different types of energy, is imposed on all of the 47 production sectors in China. Our results show that more water will be used for energy production in the future because of the increase in energy production. Energy efficiency improvement can bring significant water saving co-benefits in addition to air pollution reduction. Energy efficiency improvements can also help the government to achieve the "3 Red Lines" goal. Such co-benefits have mostly been ignored by the government and energy production plants in their plans or cost-benefit analyses. Our study provides a new perspective for decision makers seeking to balance energy and water constraints.

1. Introduction

Energy consumption-related air pollution and greenhouse gas (GHG) mitigation is a significant issue in China today, driving energy policy reform in China in recent years (Gao et al., 2016; Meng et al., 2015; Wang et al., 2016). From 2000 to 2015, China's primary energy consumption increased by a factor of 1.9, while domestic energy production increased by 160 percent (National Bureau of Statistics of the People's Republic of China, 2016). Hence, the Chinese government has taken measures to control or slow down the growth of energy consumption. Energy efficiency improvement has become one of the core objectives of China's energy policy reform (Li et al., 2016; Liu et al., 2017). The main governmental policies have emphasized its importance. For example, the 10th, 11th, 12th and 13th Five Year Plans all established an ambitious goal of improving energy efficiency. The air pollution prevention and control action plan (State Council, 2013) and China's nationally determined contributions (NDCs) (National Development and Reform Commission, 2015) similarly exemplified the importance of energy efficiency improvement. According to the world energy research group of China Outlook, "energy efficiency in China should [not only] be the focus of policy oriented, industrial strategy and consumption patterns change but also a key indicator of energy transformation" (Research Group of World Energy China Outlook, 2015).

Energy efficiency improvement has been broadly regarded as creating multiple benefits in a cost-effective manner, and has been widely employed. In addition to providing energy savings, air pollution control and GHG emission reduction, energy efficiency can also bring various macroeconomic benefits, increased energy security, and health benefits (IEA, 2014). The computable general equilibrium (CGE) and macroeconometric models are the main methods used to assess the macroeconomic and energy impacts of energy efficiency measures (IEA, 2014; Lin and Du, 2015; Lu et al., 2017). Macroeconometric models are economy-wide models based on estimates of historical relationships, including the latent variable approach (Shao et al., 2014), the DEA approach (Gale and Joseph, 2006; Lin and Liu, 2012; Pacudan and Guzman, 2002; Xu et al., 2017), and the LMDI method (Ang, 2006; Ang et al., 1998; Zhang et al., 2016c). It is hard to apply these models to study structural changes and interactions between different sectors. CGE models are considered to be beneficial in that they provide information to simulate the response of the full economy to certain policy scenarios, such as a carbon tax (Dong et al., 2015; Dong et al., 2017). It can identify subtle linkages between different economic sectors and explicitly describe the response of economic agents to energy efficiency change. Hence, CGE models have already been used to model the energy efficiency impact worldwide (Koesler et al., 2016; Lu et al., 2017; Sorrell et al., 2009; Yu et al., 2015).

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What's more, CGE has also been widely used to study the co-benefit effect of different policies. Some studies have used CGE model to analyze the implications of climate and energy saving policies on air pollutants (Bollen, 2015; Cheng et al., 2015; Dong et al., 2015) and how they can bring about health benefits (Jensen et al., 2013; Keogh-Brown et al., 2012; Xie et al., 2016) in developed and developing countries. Besides energy and climate policies, other environmental policy co-benefits were also evaluated utilizing the CGE model, including an environmental tax (Xu and Masui, 2009). Babatunde et al. (2017) has reviewed the application of CGE to climate change mitigation policy, and found that energy efficiency and co-benefit of mitigation measures are fairly represented (Babatunde et al., 2017).

The rebound effect is an important aspect of energy efficiency studies (Liang et al., 2009; Lu et al., 2017; Turner, 2013). Moreover, the rebound effect study of energy field can contribute to a general framework in analyzing other environmental policies (Vivanco et al., 2016), which means incorporating broader efficiency changes as well as energy. The idea of rebound effect is that energy efficiency improvements may lead to additional energy consumption due to reduced prices of energy services caused by the improvement; anticipated energy savings from improved energy efficiency may thus be partly or wholly offset or even surpassed (Greening et al., 2000; Turner and Hanley, 2011). When energy efficiency improves, demand for energy input in the production will decrease, and the demand curve will move inward. But in the long-run, firms may further optimize production cost by adjusting their capital stock, which means the advantage of energy efficiency improvement may be offset by a lower capital price. However, existing studies show that the rebound effect varies widely at the economy-wide and department levels in the long and short run, from negative to more than 100% (Dimitropoulos, 2007; Lu et al., 2017; Sorrell et al., 2009).

In addition to the benefits mentioned above, the water-energy nexus provides a new perspective for understanding the impact of energy efficiency improvement. The energy consumed every day has considerable direct and indirect effects on water resources (Behren et al., 2017; Fang and Chen, 2016; Huang et al., 2016; Sovacool and Sovacool, 2009; van Vliet et al., 2016; Zhang and Anadon, 2013; Zheng et al., 2016). Water is important for different energy production, such as coal mining and washing, gas and oil extraction and electricity generation (IEA, 2015; Mekonnen et al., 2016; Zheng et al., 2016). Water constraints have already impeded energy development in China, for example, by leading to the abandonment of energy production projects in water shortage areas (Yang et al., 2013). Some regions such as Shandong and Shanxi are facing huge water stress while also producing more energy compared with other regions (see Fig. 1). In addition, with both increasing energy and water demand, conflicts between water availability and energy sector demand have been anticipated in several studies in China (Green Peace, 2017, Gu et al., 2014; Liao et al., 2016). Under a 'business as usual' scenario, the energy sector's water use might exceed the Industrial Water Allowed on a national scale in China in 2035 (Qin et al., 2015).

The water-energy nexus is supported by a rapidly growing evidence base, providing knowledge to inform stakeholders and decision-makers about the relationships and trade-offs between different sectors (Allan et al., 2015; Howarth and Monasterolo, 2016, Howells et al., 2013). However, these two resources are often poorly integrated and have been managed separately (Holland et al., 2015; Yumkella and Yillia, 2015). Over the last decade, many papers and policy reports have examined the nexus at different scales (Bergendahl et al., 2018; Fang and Chen, 2016; Zhang et al., 2016a). Inventory analysis (Cai et al., 2014; Guo et al., 2017; Liao et al., 2016; Zhang et al., 2014) and input–output analysis (Fang and Chen, 2016; Feng et al., 2014; Jin et al., 2017) are the main methods employed to quantify water demand for energy production. In addition to describing the physical linkage between different sectors (Acheampong et al., 2016; Chang et al., 2016), assessing the spillover effect of energy policies on water resources is also important, including the energy price (Gulati et al., 2013; Zhou et al., 2016), technology innovation (Allouche, 2015), and resource use efficiency (Bartos and Chester, 2014; Ringler et al., 2013). The main method to perform the assessment is scenario analysis based upon energy projections combined with water use inventories. Some studies just use energy projection results of other researches to assess the impact, such as IEA (Cai et al., 2014; Qin et al., 2015; Zhang and Anadon, 2013) and WWF (Liao et al., 2016). Other researchers have developed energy models to assess the impact of energy policies, such as CGE (Zhou et al., 2016), LEAP (Dale et al., 2015; Howells et al., 2013), and TIMES (Huang et al., 2016).

A systematic method for estimating water requirements for energy production is important to support management of both energy and water resources. In this paper, a water module is integrated into a CGE model to integrate China's energy and water system and to assess the co-benefit of energy efficiency improvement from 2015 to 2030. This study should provide some new and insightful implications for China's sustainable development, especially for the reasonable utilization of water and energy resources.

2. Material and methods

2.1. Research scope

In our study, only water withdrawal during energy production process was evaluated. Water withdrawal refers to the diversion of water from one source to another without loss, which is different from water consumption. Energy production in this study refers to primary energy extraction, processing (such as washing, refining), and electricity generation from different fuels, including coal, natural gas, nuclear, hydro, wind, and solar. Our study focuses on the impact on freshwater, so sea water use was not accounted for. Wind and solar PV operations need negligible water and were not considered in this study (McMahon and Price, 2011). Hydroelectric power generation does not withdrawal water or divert water flow and was also not considered in our study. Water withdrawal for nuclear power was not accounted because most of nuclear fuel is not produced domestically (World Nuclear Association, 2009) and all nuclear power plants in China use seawater for cooling (Zhang et al., 2016a). Water withdrawal for bioenergy production is not considered because the calculating methods and scope may bring a large amount of uncertainty (Cai et al., 2014).

Cooling technology adopted by power plants has an important influence on water withdrawal. The main cooling technologies in China are once-through cooling, recirculating cooling and air cooling (Macknick et al., 2011; Zhang et al., 2016a). Once-through cooling systems have much lower water consumption ratio than recirculating cooling systems. Water was extracted from nearby water body and discharged back to the same water body after cooling process. Water extracted by recirculating cooling systems was mostly evaporated out of the cooling tower. Air cooling has minimal water withdrawal and consumption compared with other two cooling systems (Macknick et al., 2011; Qin et al., 2015; Zhang et al., 2014). These three types of cooling systems were used in our study (Zhang et al., 2016a; Zhou et al., 2016).

Water withdrawal for energy production was calculated as following:

$$W = \sum_{1}^{n} \sum_{1}^{k} A_{i,m} \times E_{i,m} \quad (1)$$

where i indicates the fuel types from 1 to n and m designates different cooling types. W is water withdrawal of total energy production, $A_{i,m}$ is water withdrawal factor of energy i, and $E_{i,m}$ is quantity of energy i produced.