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China's future energy mix and emissions reduction potential: a scenario analysis incorporating technological learning curves

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A B S T R A C T

This paper examines the impacts of CO_2 emission reduction targets and carbon taxes on the structure of power generation in China. A model is developed to minimize the total electricity generation cost and select the optimal energy technology and resource mix for China. The model contributes to existing work by utilizing the learning curve concept (which manifests as diminishing costs of production), and includes constraints for minimum energy generation and also an emissions cap. The result shows that the introduction of the CO_2 emission reduction targets and carbon taxes both shift energy production technologies away from high carbon content fossil-fuels towards low carbon content fossil-based and renewable energies. CO_2 emission reduction targets turn out to be more effective in the early years, while carbon taxes become more effective in the later periods. Perhaps unsurprisingly, all options result in a net increase in total production costs. In addition, some scenario analyses are conducted to consider the possible roles of shale gas and improved carbon capture and storage technologies, showing the general conclusions to be robust.

1. Introduction

Ongoing and rapid growth in key parts of the world economy, such as the populous economies of India and China, is likely to result in a rapid growth in energy demand, particularly fossil fuels. It is widely reported that economically recoverable reserves may only sustain a few more decades of energy supply. According to the 2012 BP Statistical Review of World Energy (BP, 2012), total global oil reserves allow for 54 years of production if mining is maintained at the current rate, for natural gas and coal the known reserves allow for 64 and 112 years of production respectively. Excessive consumption of fossil fuel causes at the same time an excessive level of greenhouse gas (GHG) emissions, which over recent decades has had significant impacts on climate change and global environmental health. Mitigating climate change—which will bring with it reduced consumption of fossil fuels and lower GHG emissions—has become a strategic imperative of the international community, with the Kyoto Protocol in 1997 an early and clear statement of the international intention to achieve this goal.

The energy and environmental problems in China are now more serious than most other countries. According to recent estimates (NEA, 2009), the remaining recoverable reserves of oil, gas and coal could sustain current consumption for around 15, 30 and 80 years respectively. Data from the U.S. Energy Information Administration (EIA), shows that the total CO_2 emissions from the consumption of energy in China for 2012 had reached 8.106 billion tons, exceeding the 5.270 billion tons produced by the United States, and ranking the highest in the world.

China's electric power production is mainly achieved by burning fossil fuels, with coal based power sources accounting for 72% of the cumulative installed capacity in 2010, while nuclear power, hydropower, and renewable energy respectively account for 1.04%, 21.9% and 5.06% (NBS, 2011). This ratio reflects the reliance of China's power generation structure upon highly polluting coal-fired power stations (Yuan et al., 2013). Hydropower potential is not fully realized, while the development of nuclear power and renewable energy remain slow. Improving efficiency in the use of

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fossil fuels and increasing the use of renewable energy sources are among the most promising options for reducing CO_2 emissions in China (Dutt and Gaioli, 2007; Zuo et al., 2012). The existing structure of power generation is characterized by an excessive reliance on coal-fired power, which not only hinders the long-term operation and development of the electric power system, but also causes serious environmental pollution problems. Therefore, it is necessary to develop and promote alternative energy sources that maintain the energy security of China without increasing environmental impacts. According to the '*New Energy Development*' research report released by the China Electricity Council (CEC) in 2012, the cumulative installed capacity of grid-connected renewable energy had reached 51,590 MW (MW) in 2011, accounting for 4.89% of the total installed capacity. Among this, wind power and solar photovoltaic (PV) account for about 87.33% and 4.15% respectively (CEC, 2012). CEC estimates that in the future, new energy generation will gradually increase and eventually become the main power source for the 'next generation' power grid.

The aim of this paper is to develop a picture of the future power generation system in China, which is a power system undergoing significant transition. Many previous studies have researched the electric power system in the transition period, with significant proportions of renewable energy being introduced. Some have sought to understand (and implicitly, minimize) the costs associated with large-scale renewable generation (Dale et al., 2004; ILEX Energy Consulting and Strbac, 2002; Levin et al., 2010; Nguyen, 2007; Yuan and Zuo, 2011). In particular, ILEX Energy Consulting and Strbac (2002) quantify the additional system costs arising from a range of renewable power integration scenarios in Great Britain. Dale et al. (2004) consider more deeply the overall (net) cost implications of large-scale adoption of wind power in Great Britain and try to estimate both the costs and benefits of wind power when compared to fossil fuels. Nguyen (2007) and Levin et al. (2010) develop a least-cost model to examine the potential contribution of renewable energy in the future choice of fuels and technologies in the power sector.

More recent literature places a greater emphasis on the issue of how to mitigate emissions (Brown et al., 2013; Eiichi Endo and Ichinohe, 2006; Kirat and Ahamada, 2011; Mallah and Bansal, 2010; Mathur et al., 2003; Mirzaesmaeeli et al., 2010; Mondal et al., 2010, 2011; Muis et al., 2010; Sims et al., 2003). Several interesting studies including Nguyen (2007), Mondal et al. (2010, 2011) adopt a different approach to evaluating future technology options, which also integrates CO_2 emission reduction targets and carbon tax policies and in so doing reveals a range of possible co-benefits for domestic energy security. Mallah and Bansal (2010) develop a MARKAL model of the Indian electricity sector, considering a business as usual scenario against a scenario of energy conservation to forecast the optimal mix of energy supply and corresponding CO_2 emissions up to 2045. Mirzaesmaeeli et al. (2010) develop a novel deterministic multi-period mixed-integer linear programming (MILP) model with the objective of identifying the optimal mix of energy supply sources and pollutant mitigation options that meet specified electricity consumption and CO_2 emission targets at minimum cost. In an earlier study to those already mentioned, Sims et al. (2003) compare the carbon emissions and mitigation costs of fossil fuels against nuclear combined with other renewable energy resources for electricity generation, and conclude that most technologies show potential to reduce both generating costs and carbon emission avoidance by 2020, with the exception of solar energy and carbon dioxide sequestration.

This paper complements the above literature by presenting a multi-period modeling and optimization framework to support (optimal) planning of China's power sector between 2010 and 2040. The planning horizon is divided into several time intervals, over which power plants of all types can be installed, retrofitted or closed. Impacts of carbon mitigation related measures, including carbon emissions caps and implementation of trading mechanisms, as well as application of carbon capture and sequestration, are explicitly considered. Using information on various aspects of China's existing installed power generation capacity between 1997 and 2012, a case study is developed to analyze the structure change of power generation up to 2040 under a range of alternative development pathways. A year-by-year development plan of power generation sector is proposed. Based upon an empirically motivated scenario analysis of China's power structure, this paper investigates the emission reducing potential of several different policy pathways. This allows for the development of affirmatory policy recommendations to support low carbon development and optimization of power generation structure.

The main innovation of this study is to incorporate 'learning curve' effects into the simulation, which remedy one limitation of previous simulation studies. The learning curve is an important modeling concept used in managerial sciences to characterize the beneficial effects from technical change, and informing policy decisions related to energy technology (Zhao et al., 2011), reflected in smoothly declining production costs. This theory is of great significance, emphasizing the potential of naturally declining costs that have appeared in advanced solar PV technology over the first decades of the 21st century (Zwaan and Rabl, 2003). Similarly, for low-carbon technology—particularly CO_2 capture and storage (CCS), Li and Cai (2012) highlight the importance of learning effects in formulating a CCS roadmap for China.

Previous related studies exploring the optimization of power generation structure have largely ignored the possibility that the costs of energy production change with technology implementations and policy decisions. Moreover, few of the existing works allow for learning curve effects in low-carbon or renewable energy technologies. It is quite reasonable to assume that such a methodology may be of great importance in China where existing technologies often lag behind the best in industry, and use of technologies is fraught with inefficiencies. Therefore this paper develops a mathematical model of power generation structure optimization that embeds such learning curve features, describing the relationship between the cost reduction trends and the cumulative capacity of low-carbon electricity generation. This model is then used to examine the emission reduction impacts of imposing CO_2 emission reduction targets and setting carbon taxes upon the structure of power generation in China.

The paper is organized as follows: Section 2 is divided into three parts. In the first part, we present the mathematical formulation of the energy model which is based around electricity generation cost minimization, defining constraints to meet energy demand, restrict power generation capacity and set CO_2 emission limits. We also describe the treatment of the learning curve effects within the model. In the second part we introduce the data sources used. Last in the third part of Section 2 we justify and outline three policy scenarios relating to emission reduction targets and alternative carbon tax schemes. To investigate learning curve effects, two other scenarios consider the rapid exploitation of shale gas and the deployment of clean coal technology. We evaluate the model (within the Matlab 2012b software package) using a genetic algorithm and present and discuss the results in Section 3. In Section 4, the paper is concluded, outlining the relevant policy implications generated from the study.

2. Methods

2.1. Problem formulation

The existing power generation system for China is unreasonable insofar as it places too much reliance on coal fired power