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# Costs and potentials of energy conservation in China's coal-fired power industry: A bottom-up approach considering price uncertainties

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ABSTRACT

Energy conservation technologies in the coal-fired power sector are important solutions for the environmental pollution and climate change issues. However, a unified framework for estimating their costs and potentials is still needed due to the wide technology choices, especially considering their economic feasibility under fuel and carbon price uncertainties. Therefore, this study has employed a bottom-up approach to analyze the costs and potentials of 32 key technologies' new promotions during the 13th Five-Year Plan period (2016–2020), which combines the conservation supply curve (CSC) approach and break-even analysis. Findings show that (1) these 32 technologies have a total coal conservation potential of 275.77 Mt with a cost of 238.82 billion yuan, and their break-even coal price is 866 yuan/ton. (2) steam-water circulation system has the largest energy conservation potential in the coal-fired power industry. (3) considering the co-benefits will facilitate these technologies' promotions, because their break-even coal prices will decrease by 2.35 yuan/ton when the carbon prices increase by 1 yuan/ton. (4) discount rates have the largest impacts on the technologies' cost-effectiveness, while the future generation level affect their energy conservation potentials most.

## 1. Introduction

The rapid increasing consumption of electricity has played an important role in powering China' economic growth in the past several decades. Cheng et al. (2013) estimated that China's GDP will increase by 0.6% when the national electricity production increases by 1%. However, China' power generation structure is coal dominated due to the resource endowments and technology development status, which is often blamed for its large share of national carbon emissions and related environmental pollution problems (Chen et al., 2016; Geng et al., 2010; Wen et al., 2014; Worrell et al., 2003; Zhang et al., 2015; Zhao and Ortolano, 2010).[1] Since the dominant role of coal-fired power will continue in the following decades, a higher-efficiency, cleaner, and lower-emission development of the coal-fired power industry is in desperate need to cope with these problems (IEA, 2014).

Energy conservation technologies are good solutions to achieve this goal, which will not only save energy but also reduce carbon and air pollutant emissions at the same time. Chinese government has put forward a series of policies to promote the applications of energy conservation technologies in the coal-fired power industry, such as *the action plan of upgrading and transformation of coal-fired power plants (2014–2020)*, and *the national promotion catalog of key energy conservation and low-carbon technologies*. Therefore, many technologies are now available to be employed in the coal-fired power industry, such as the Super Critical (SC) and Ultra Super Critical (USC), Circulating Fluidized Bed Combustion (CFBC) and Integrated Gasification Combined Cycle (IGCC).[2] However , different technologies have different application conditions, development potentials and promotion costs. Therefore, it is necessary to develop a unified framework to compare their cost-effectiveness and potentials, which will contribute to a more wise technology promotion portfolio in the future.

Motivated by this aim , we have employed a bottom-up approach to analyze the costs and potentials of 32 energy conservation technologies' new promotions during China's 13th Five-Year Plan period, which aims

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[1] According to the statistical data from the National Bureau of Statistics (NBS) of China, the power industry contribute to 43% of total national carbon emissions in 2014, and most of these come from coal-fired power.

[2] The acronyms and abbreviations used in this study are summarized in the Appendix A1.

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to address the following questions.

(1) What are the 32 technologies' energy conservation costs and potentials during this period, are they economically viable considering the coal price uncertainties?
(2) What are the differences among different power generating systems regarding their potentials and costs?
(3) What will happen to these technologies' economic feasibility if their co-benefits (carbon and air pollutant emission reductions) are considered?
(4) What are the impacts of discount rates, future power generation levels and technology progress on these technologies' economic feasibility?

Answers to these questions will provide quantitative results of the cost-effectiveness and potentials of these technologies, which can shed light on how to best achieve the low-carbon transition of China's coal-fired power industry.

The remainder of this paper is organized as follows : Section 2 presents the literature review. Section 3 describes the methodology. Section 4 provides the empirical results of 32 technologies' new promotions during the 13th Five-Year-Plan period, and Section 5 summarizes the conclusions and proposes some policy implications.

## 2. Literature review

Some previous studies have already been conducted about the energy conservation and carbon emission reductions in the power industry (Al-Ajlan et al., 2006; Bai and Wei, 1996; Hampf and Rødseth, 2015; Li and Wang, 2015; Lin and Yang, 2013; Strickland and Sturm, 1998; Wei et al., 2007, 2008; Yu et al., 2014). These studies can be divided into three main categories according to the methods they employed, namely a top-down approach, a bottom-up approach and a hybrid approach.

The top-down approach estimates the costs and potentials based on the power industry's macro-economic data in a national or regional level. Moreover, the most commonly used tools are the Stochastic Frontier Analysis (SFA) and Data Envelopment Analysis (DEA) (Bi et al., 2014; Ibrik and Mahmoud, 2005; Zhou et al., 2012). The estimation process can be summarized as building production frontiers, estimating efficiency, and calculating potentials and costs. For example, Hampf and Rødseth (2015) adopted DEA to estimate the $CO_2$ emission reduction potentials in the US power industry, and concluded that nearly 264 Mt $CO_2$ emissions could be reduced under four technology models.[3] Lin and Yang (2013) employed SFA to explore the energy conservation potentials of China's coal-fired power industry, and they found that 0.55 billion tons of coal equivalent can be saved from 2005 to 2010. However, these macro-level studies could not come up with detailed measures about how to achieve these potentials, which boil down to the applications of energy conservation technologies.

The bottom-up approach analyzes the costs and potentials based on the energy conservation technologies in the power industry. Most of these studies focused on evaluating the economic feasibility of a specific technology, which aimed at answering whether the benefits it brought about can offset the costs it incurred. Zhou et al. (2010) evaluated the cost-effectiveness of IGCC in the coal-fired power plants under carbon price uncertainties. Tola and Pettinau (2014) conducted a techno-economic comparison between the USC equipped with Conventional flue Gas Treatment (CGT) systems and IGCC, and found that USC is more profitable than IGCC. Zhang et al. (2014b) employed a real options model to do economic analysis of Carbon Capture and Storage (CCS) retrofitting investment for coal-fired power plants. In addition, some studies analyzed the economic feasibility of renewable energy's substitution for the coal-fired power. For example, Wesseh and Lin (2016) adopted a real options model to assess the cost-effectiveness of wind energy projects under different feed-in tariffs. However, these studies based on a single technology could provide little information about the costs and potentials for a whole industry. As to the bottom-up approaches which explore the cost-effectiveness of a group of technologies, CSC is a popular one. It is a good screening tool which not only presents the cost and potential of a single technology, but also exhibits the cumulative costs and potentials of an industry if it contained enough number of technologies. Moreover, it has already been applied in some energy-intensive or carbon-intensive industries, such as the iron and steel industry (Li and Zhu, 2014; Worrell et al., 2001; Zhang et al., 2014a) and the cement industry (Hasanbeigi et al., 2010a, 2010b, 2013; Worrell et al., 2000). However, few studies have applied the CSC approach to coal-fired power industry.

The hybrid approach combines the modeling logic of the top-down approach and the bottom-up approach, and the most famous models established are National Energy Modeling System (NEMS) (EIA, 2009) and Prospective Outlook on Long-Term Energy Systems (POLES) (Criqui, 2001). However, these models are originally designed for the whole energy system rather than specifically designed for the power sector. Moreover, they are very complex and require a lot of data inputs, which bring about challenges to their applications in the power sector (Wei et al., 2008).

In this study, the CSC approach is employed to analyze the energy conservation costs and potentials of China's power sector. We contribute to the existing literature from two main aspects. Firstly, few studies have estimated this sector' energy conservation costs and potentials from a bottom-up perspective, especially for the developing countries like China. Therefore, we attempt to bridge this gap. Secondly, most previous CSC studies made a simple assumption about the future fuel prices and carbon prices, which neglected the price uncertainties during the research periods. Therefore, we novelly incorporated a break-even analysis into the CSC models, which can be used to assess the technologies' economic feasibility under price uncertainties.

## 3. Methodology

### 3.1. Conservation supply curve and break-even analysis

CSC and break-even analysis are the two main approaches employed to conduct this study. CSC is a good screening tool that captures both the economic and engineering perspectives of energy savings, while the break-even analysis is a good approach to assess the technologies' economic performance under price uncertainties. The research framework of this study is shown in Fig. 1 and the detailed application process can be described as follows:

Step 1: Selecting energy conservation technologies in the coal-fired power industry. Based on the official files released by the government and the data availability,[4] 32 key energy conservation technologies are finally selected (see Table 1).

Step 2: Calculating the energy conservation potentials of every technology.[5] The energy conservation potentials ($ESP_{i,t}$) is a result of the total new power capacities equipped with technology $i$ ($CAP_{i,t}$) multiplying by the unit energy conservations ($UESP_i$), which is calculated as follows:

[3] The four technology models refer to Joint production (CRS), Materials balance (CRS), Joint production (VRS) and Materials balance (VRS). CRS means constant returns to scale, while VRS indicates variable returns to scale. These four models are employed to estimate the potentials of carbon emission reductions.

[4] The official files can be seen from the data source below Table 2.

[5] A simple assumption has been made that there is no interaction between different technologies with regard to their performances in the energy conservations, this is because we followed Hasanbeigi et al. (2013), who made similar assumptions concerning the energy conservation technologies in the cement industry.