Energy conservation and CO₂ mitigation potentials in the Chinese pulp and paper industry

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Abstract

China's paper production accounted for nearly a quarter of the world's total paper production in 2010. In this study, 23 energy saving technologies applicable to the pulping and papermaking process in China are identified and analyzed. The Conservation Supply Curve (CSC) method is employed to assess the technical and economic aspects of energy conservation. The fuel CSC for Chinese pulp and paper industry shows the cost-effective and technical fuel conservation potential is 180 PJ and 254 PJ, accounting for 27% and 38% of total fuel used in 2010, respectively. The CO₂ mitigation potential related to the cost-effective fuel efficiency is 17 Mt CO₂ and the technical potential is 24 Mt CO₂. The electricity CSC shows the technical electricity conservation potential is 2,316 GWh, representing 4% of total electricity consumption. All of the electricity efficiency measures are shown to be cost-effective in this study. The CO₂ mitigation resulted from electricity efficiency is around 2 Mt CO₂. In addition, sensitivity analyses for the parameters of penetration rate, discount rate, and energy price are conducted to assess their influence on the final results.

Keywords: Energy conservation; CO₂ mitigation; Conservation supply curve; Pulp and paper industry

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1. Introduction

The Chinese pulp and paper industry has grown rapidly since 2000, with the average annual growth rate of about 12% (CPA, 2001-2011). Meanwhile, the total final energy consumed by this industry increased by 7.3% per year (NBS, 2009-2011). As one of the largest pulp and paper producers, China manufactured nearly a quarter of the world's total paper in 2010 (FAO, 2012). Around 834 petajoules (PJ) of final energy was consumed to produce this quantity of paper. It is predicted that the average paper production in China will continue to increase at a rate of 4.6% annually until 2015 (NDRC, 2011a). Consequently, there will be a corresponding increase in total energy consumption and carbon dioxide (CO₂) emissions for this industrial sector in China.

China has undertaken a series of measures to improve industrial energy efficiency during the last decades. Energy efficiency in this paper means using less energy to provide the same service or output without compromising the productivity or product quality. The specific energy consumption of the pulp and paper product declined by approximately 2.7% per year from 2000 to 2010 (NDRC, 2007, 2011a). However, there is still a wide gap between some developed economies and China in this sector with respect to the average industrial energy efficiency. In 2011, the Chinese government announced a 20% reduction in specific energy consumption for the pulp and paper industry in the 12th Five-year Plan (FYP) (2011-2015) (NDRC, 2011b). There are still many works need to be done in order to achieve this ambitious target.

Several studies have identified the potentials for energy efficiency improvement in the pulp and paper industry from the national level, e.g. Canada (Jaccard, 1996), the U.S. (Kramer et al., 2009; Martin et al., 2000), Sweden (Möllersten et al., 2003), Germany (Fleiter et al., 2012), India (Schumacher and Sathaye, 1999), and Brazil (Fracaro et al., 2012). Schumacher and Sathaye (1999) assessed 60% of energy efficiency improvement potential in India's pulp and paper industry. Martin et al. (2000) identified 16%-24% of cost-effective energy savings in the U.S. pulp and paper industry. Fleiter et al. (2012) assessed opportunities for improving energy efficiency in the German pulp and paper industry and identified a technical saving potential of 21% for fuel and 16% for electricity by 2035. Zafeiris (2010) studied the technical potentials of energy

and CO₂ emissions reduction for dominant pulp and paper countries up to 2030 and found the greatest CO₂ mitigation potential was located in China, followed by U.S. and Canada. From above studies, significant energy conservation and CO₂ mitigation potentials are still available in the pulp and paper industry. However, such studies that specialize in the Chinese pulp and paper industry are seldom.

Aimed at identifying some knowledge gap in this field, we analyse the potential energy conservation and CO₂ emissions reduction of 23 energy efficiency measures for the Chinese pulp and paper industry. We evaluate to which extent these measures are already implemented and subsequently calculate the cost-effective and technical savings potentials based on the energy conservation supply curve.

2. The pulp and paper industry in China

2.1 Overview of the Chinese pulp and paper industry

The Chinese pulp and paper industry has developed rapidly since 1978, with the greatest growth during the past decade, as shown in Fig. 1. As of 2008, China overtook the U.S. to become the world's largest paper manufacturing country (FAO, 2012). The number of paper mills in China increased at a rate of 4.3% per year, while the number of employees in the Chinese pulp and paper industry decreased by 0.5% per year from 2000 to 2010. To some extent, this trend reflects the modernization of the Chinese pulp and paper industry during this period. There exist 3,724 paper mills that employed 737,000 workers in China. In 2010, the Chinese paper industry generated 585 billion RMB (equal to \$86.4 billion in 2010 U.S. dollars (US\$)) in gross output. This is more than five times the output value in 2000 (CPA, 2001-2011).

Fig. 1. The pulp and paper production in China (CTAPI, 2011)

Shandong, Guangdong, Zhejiang, and Jiangsu province each produce more than 11 megatonne (Mt); these four provinces together represented 58% of the China's total paper production in 2010

(CPA, 2001-2011). The ten largest companies (more than 1 Mt of paper productivity) manufactured 26.7 Mt paper in 2010, representing 28.8% of total paper production in China. However, the average annual production capacity of China paper mills was only 24.9 kilotonne in 2010. Although some of the world's largest and most modern pulp and paper mills were located in China and about 10 Mt of inefficiency capacity was phased out during the 11th FYP, there still are plenty of small- and medium-size paper mills (CTAPI, 2011).

2.2 Energy use and CO₂ emissions in the Chinese pulp and paper industry

In 2007, the Chinese pulp and paper industry consumed 750 petajoules (PJ) of final energy¹, equivalent to 11% of the global pulp and paper industry's final energy consumption in the same year (Kong et al., 2013a). The energy consumed by the pulp and paper industry increased by 7.3% annually between 2000 and 2010, corresponding the rapid expansion in the industry during this period. Fig. 2 presents the total energy consumed by the pulp and paper industry in China between 2000 and 2010.

Fig. 2. Energy consumption in China's pulp and paper industry (NBS, 2009-2011)

In addition consuming fossil fuel, pulping and papermaking process also uses a large amount of secondary energy in the form of steam and electricity. From 2000 to 2010, coal and electricity accounted for 60% and 20%, respectively, of total final energy use. Other energy sources are purchased steam, natural gas, oil, and coke (self-generated biomass energy is not included in these statistics).

As the result of the increase in energy use, energy-related CO₂ emissions from China's pulp and paper industry increased at an average annual rate of 6.3% from 2000 to 2010. In 2007, this industrial sector emitted approximately 85 Mt energy-related CO₂, accounts for 21% of total world pulp and paper industry CO₂ emissions. Fig. 3 shows the total CO₂ emissions from the Chinese pulp and paper industry. In 2010, the total CO₂ emissions reached around 100 Mt CO₂.

¹ The energy use shown in this paper does not include biomass energy unless specifically noted because biomass use is not included in the official statistics for China's pulp and paper industry.

Nearly 90% of the CO₂ emissions were from coal and electricity use.

Fig. 3. CO₂ emissions from the Chinese pulp and paper industry²

During the 11th FYP, China took a series of measures to improve its industrial energy efficiency, which resulted in the specific energy consumption of the pulp decreased from 16.1 gigajoules (GJ)/tonne to 13.2 GJ/tonne and the specific energy consumption of paper reduced to 19.9 GJ/tonne from 24.3 GJ/tonne (NDRC, 2007, 2011a). However, there are still numerous opportunities to further reduce energy consumption and CO₂ emissions. Energy efficiency improvement will be one of the most important and cost-effective means to achieve the goal of 20% reduction in the sector's specific energy consumption in the 12th FYP.

3. Methodology

We apply the energy conservation supply curve (CSC) method to evaluate energy conservation and CO₂ mitigation potentials in the Chinese pulp and paper industry. The CSC has proven its worth for various other national industrial sectors in earlier work by estimating the cost effectiveness of energy saving measures (Hasanbeigi et al., 2010b, 2010c, 2010d, 2011, 2013a, 2013b; Worrell et al., 2000, 2001). In this section, a quick overview of the steps employed is first presented, followed by a detailed explanation of the CSC. Afterwards, the data collection and conversion factors used to construct the CSC is also presented.

3.1 Overview of the steps

The following five steps are employed to construct the CSC in order to evaluate the cost-effective and technical potentials for energy conservation and CO₂ emissions reduction in the Chinese pulp and paper industry.

1. Establish the base year for energy, material use, and production in the Chinese pulp and paper

² CO₂ emissions are calculated based on energy use data from China Energy Statistical Yearbook 2008-2010 (NBS, 2009-2011) and the CO₂ emissions factor from 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006).

industry. We choose 2010 as the base year considering it is the latest year for which energy statistics are published by China's National Bureau of Statistics when preparing this work.

2. Develop a list of commercially available energy efficiency technologies and measures for the pulp and paper industry to include in the construction of the CSC. The information on the capital cost, operations and maintenance cost, energy savings, and CO₂ emissions reduction of these technologies and measures is compiled during this step. None of the adopted measures are interacted with each other in this study. In other words, the application of one measure will not have an impact on the results of energy saving potential for the rest of the measures. In this study, a total of 23 energy efficiency technologies and measures are included based on their applicability to the Chinese pulp and paper industry as well as data availability.

3. Determine the potential adoption rate of these energy efficiency technologies in China in the base year. Generally, the potential adoption rate can be estimated through the results of filed surveys or the responses of the delivered questionnaires. As a result of the resource accessibility, we estimated the potential adoption rate based on the responses of the delivered questionnaires from some Chinese pulp and paper experts in this paper.

4. Construct the fuel and electricity CSC respectively to capture the accumulated cost-effective and total technical fuel and electricity conservation potentials. For this purpose, the cost of conserved energy (CCE) is first calculated separately for each technology. After that, we ranked the measures by ascending CCE to construct the fuel or electricity CSC, respectively. Because average energy price for in 2010 were different from one another and some technologies only save one kind of energy (e.g. fuel or electricity), it is suggested to separate the fuel and electricity saving measures. There are also some measures save both fuel and electricity, and some increase electricity consumption as a result of saving fuel. For these measures, when a technology's fuel savings account for the larger portion of total primary energy savings, we include this technology in the fuel CSC and vice versa.

5. Calculate the cost-effective and technical potential savings for both energy and CO₂

emissions. From the constructed energy CSC, we can estimate the cost-effective energy conservation and CO₂ mitigation potentials from the energy efficiency measures that fall below the energy price line because the cost of investing in them to save 1 GJ of fuel or 1 MWh of electricity is less than purchasing the same amount of fuel or electricity at the given energy price. Consequently, the cost-effective measures indicate those with the CCE less than the average energy price shown in the CSC. Furthermore, the technical potential savings for energy and CO₂ reductions can be accumulated from all the applicable saving measures.

3.2 Energy conservation supply curve

The energy CSC is an analytical tool that captures both the engineering and economic perspectives of energy conservation (Meier, 1982). The curve implies the energy conservation potential as a function of the marginal CCE. It has been used to assess energy efficiency potentials in different industrial sectors recently (Hasanbeigi et al., 2010b, 2010c, 2010d, 2011, 2013a, 2013b; Worrell et al., 2000, 2001). The energy CSC shows the total technical and cost-effective potential of energy conservation accumulated from all the applicable measures. On the curve, the width of each measure indicates the energy saved by that measure during the period covered in the analysis. The height means the CCE of each measure (Meier, 1982).

In general, the CCE is calculated from Equation 1 with the unit of US\$/GJ for fuel savings and US\$/MWh for electricity savings.

$$CCE = \frac{\text{Annualized Capital Cost} + \text{Annual Change in O\&M Costs}}{\text{Annual Energy Savings}} \quad (1)$$

The *Annual Energy Savings* in Equation (1) is calculated as follows with the unit of GJ or MWh,

$$\text{Annual Energy Savings} = \text{Production} \times \text{Energy Savings per tonne production} \times \text{Potential Adoption Rate} \quad (2)$$

The *Potential Adoption Rate* (in percentage) here defines the maximum possible adoption rate of a specific energy efficiency measure that could be reached after several years' commercialization. There are always technical and plant-specific situations that make it not possible to adopt certain

energy efficiency measures by the pulp and/or paper mill(s) in China, e.g. technical complications, small capacity, use of older technologies with different process configuration, etc. The term of *Technical Applicability* with the dimension of percentage is introduced to calculate the potential adoption rate by Equation (3).

$$Potential\ Adoption\ Rate = (100\% - Penetration\ Rate) \times \frac{Technical\ Applicability}{100\%} \quad (3)$$

Where *Penetration Rate* (in percentage) is actual adoption rate of a specific energy efficiency technology or measure in the base year, i.e. 2010 for this study. *Technical Applicability* (in percentage) is defined as the extent to which the remaining penetration potential of the technology can be technically adopted by the Chinese pulp and paper industry. The data of penetration rate and technical applicability is obtained based on the responses of the delivered questionnaires from experts in the field of China's pulp and paper industry, which will be explained in detail in the section 3.3.

The *Annualized Capital Cost* can be calculated from Equation 4 with the unit of US\$.

$$Annualized\ Capital\ Cost = Capital\ Cost \times \frac{d}{(1 - (1 + d)^{-n})} \quad (4)$$

Where d is the discount rate (in percentage) and n is the economic lifetime of the energy efficiency measures (in years). In this study, we use a discount rate of 30% as the base scenario.

3.3 Data collection and conversion factors

Several technologies and measures exist that can reduce energy consumption and CO₂ emissions in pulping and papermaking processes. The analysis in this report is based on the energy efficiency measures and technologies adopted in the pulp and paper industry. Many of the energy efficiency measures examined in Lawrence Berkeley National Laboratory publications and reports are used in this study for providing consistent and comprehensive data on capital cost, operations and maintenance cost, energy savings, and CO₂ emissions reduction of the measures

(Martin et al., 2000; Kramer et al., 2009). The China's domestic technologies are derived from some energy efficiency projects conducted in some specific paper mills in China (Kong et al., 2013a). The energy efficiency measures that used to evaluate the saving potentials for the Chinese pulp and paper industry are presented in Table 1. The production capacity of the Chinese pulp and paper industry in the base year is obtained from the Almanac of China Paper Industry (CTAPI, 2011).

From the equation (2), the potential adoption rate is prerequisite to calculate the annual energy savings. The potential adoption rate can be derived from penetration rate and technical applicability through the equation (3). Thus, we should know the data of penetration rate and technical applicability of each energy efficiency measure to estimate the CCE. In this paper, a comprehensive questionnaire is designed to obtain the data of penetration rate and technical applicability of each energy efficiency measure.

There are two questions for each measure included in the questionnaire, i.e. what is the penetration rate of energy efficiency measure A? what is the technical applicability of energy efficiency measure A? The total questions included in the questionnaire are 46 because it collected information on 23 energy efficiency measures in total. The questionnaire is then delivered to approximately ten experts in the field of China's pulp and paper sector. Eventually, we got responses from six of the experts contacted, based on which, we estimated the penetration rate and technical applicability of each measure. The experts responded to the questions based on their best knowledge of the Chinese pulp and paper industry. Using the input from six different experts make it possible to reduce the uncertainty. However, we are aware of the fact that still the penetration rates used in the analysis encompasses certain level of uncertainty. That is why we conducted sensitivity analysis to quantify the effect of variations in the penetration rate data used on the final results.

A conversion factor of 2.9 is employed to convert electricity from final energy to primary energy. This is equal to the national average net heat rate of thermal power generation of 0.333 kilograms of coal equivalent (kgce) per kilowatt hour (kWh) in 2010, including transmission and

distribution losses of 6.53% (CEPP, 2011). Costs are reported in the Chinese Renminbi (RMB) and US\$. We use a conversion factor of 6.77 RMB/US\$ to convert the costs from RMB to US\$ (NBS, 2009-2011). The lower heating value of the fuel is used in this work.

The carbon conversion factors for fuels used for calculating CO₂ emissions from energy consumption are taken from the 2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories (IPCC, 2006). The emissions factor for grid electricity in 2010 is assumed to be 0.770 kg CO₂/kWh (Hasanbeigi et al., 2013b). More than 90% of the fossil fuel used in China's pulp and paper industry is coal. Therefore, we use the weighted average CO₂ emission factor for raw coal, cleaned coal, and other washed coal consumed in the pulp and paper industry in 2010 as the CO₂ emission factor for fuel in the base year of our analysis. It is assumed the electricity that purchased by pulp and paper industry from the grid is generated by coal-fired power plants in China.

The average unit price of coal with 23 megajoules (MJ) per tonne for industrial use in 2010, 4.8 US\$/GJ, is used as the fuel price. We use 91.3 US\$/megawatt hour (MWh) as the average unit price of electricity in the base year (CEPC, 2011).

3.4 Potential energy efficiency measures for China's pulp and paper industry

To analyze the potential for energy conservation and CO₂ mitigation, we assessed 23 energy saving measures applicable to the pulping and papermaking process in China (Martin et al., 2000; Kramer et al., 2009; Kong et al., 2013a). Table 1 shows the energy savings, capital costs, change in annual operations and maintenance costs, CO₂ emissions reduction, and potential adoption rate of these potential technologies and measures in 2010. Except the potential adoption rates that are estimated based on the responses of the delivered questionnaires, the other data of the energy efficiency measures are from the literatures review (see section 3.3). The production capacity of each stage in the pulping and papermaking process at the national level is also presented in Table 1. A brief description of the technologies or measures evaluated in this study can be found at Kong et al. (2013b).

Table 1. Energy savings and costs for energy efficiency measures applied to the Chinese pulp and paper industry

4. Results and discussion

Based on the method mentioned above and the data shown in Table 1, we constructed the fuel and electricity CSC separately for China's pulp and paper industry. Of the investigated 23 energy efficiency measures, 18 of them are fuel conservation measures, the rest are electricity saving measures.

4.1 Fuel conservation and CO₂ reduction potential

From Fig. 4 and Table 2, it can be seen that 12 out of 18 fuel saving measures in the fuel CSC fall below the average fuel price line (4.8 US\$/GJ). Namely, the CCE of these measures is less than the average fuel price. They are regarded as cost-effective measures in this paper because the cost of employing these measures to save 1 GJ of energy is less than the cost of purchasing 1 GJ of fuel at the given price. The other six measures (numbers 13-18 in Table 2) have CCEs higher than the average fuel price line. They are technically applicable but not cost-effective, so their implementation might require financial incentives beyond energy savings alone.

Fig. 4. Fuel CSC for the Chinese pulp and paper industry

Table 2 presents the fuel efficiency measures applicable to the Chinese pulp and paper industry by CCE. The table also shows the fuel conservation and CO₂ emissions reduction resulted from each measure. Installing stationary siphons, maintaining/upgrading steam traps, and installing turbulent bars are the top three most cost-effective measures. Moreover, steam traps maintenance saves the most amount of energy among all of the energy efficiency measures. However, it should be noted that these saving are at the country-level. At the plant-level, the quantity of energy savings achieved by the implementation of energy efficiency measures studied in this paper depends on the plant-specific situation and the efficiency of current facilities.

Table 2. Fuel efficiency measures for the Chinese pulp and paper industry by CCE

The amounts provided for fuel savings and CO₂ mitigation are given for 2010 in Table 2. This also goes for other tables across this paper. The cost-effective fuel efficiency improvement potential for the Chinese pulp and paper industry in 2010 is 180 PJ, representing approximately 27% of this industry's total fuel consumption in 2010. The technical fuel conservation potential is 254 PJ, equal to approximately 38% of China's pulp and paper industry's total fuel use in 2010 (Table 3). The CO₂ emissions reduction potential related to cost-effective measures 17 Mt CO₂, and the total CO₂ emissions reduction potential is 24 Mt CO₂. As shown in Table 3, the cost-effective and technical CO₂ mitigation potentials are equal to 17% and 24%, respectively, of the total CO₂ reductions from China's pulp and paper industry in 2010.

Table 3. Fuel conservation and CO₂ mitigation potentials in China's pulp and paper industry

4.2 Electricity conservation and CO₂ reduction potential

Five energy efficiency measures are included in the electricity CSC. Fig. 5 and Table 4 present that all the five electricity efficiency measures below the average electricity price line (91.3 US\$/MWh). Namely, the CCE of these measures is less than the average unit price of electricity. Therefore, these five measures can be considered cost-effective because the cost of investing in them to save 1 MWh of electricity is less than purchasing the same amount of electricity at the given electricity price.

Fig. 5. Electricity CSC for the Chinese pulp and paper industry

Table 4 shows the electricity efficiency measures applicable to the Chinese pulp and paper industry, ranked by CCE, as well as the electricity savings and CO₂ reductions achieved by applying each measure. Among them, the top three cost-effective energy efficiency measures include optimizing the vacuum system, installing high-efficiency double-disc refiners, and improving refiners performance.

Table 4. Electricity efficiency measures for the Chinese pulp and paper industry by CCE

The total electricity efficiency improvement potential is 2,316 GWh in China's pulp and paper industry, which accounts for approximately 4% of total electricity use by this industrial sector in 2010. All of the electricity efficiency measures are cost-effective. As Table 5 shows, the related CO₂ emissions reduction potential is about 2 Mt CO₂, representing 2% of the total CO₂ emissions from this sector in 2010.

Table 5. Electricity conservation and CO₂ mitigation potentials in China's pulp and paper industry

4.3 Energy conservation potential

Table 6 shows the potentials for energy conservation and CO₂ mitigation from all of the measures. As it shows, the cost-effective and total technical final energy conservation potentials are estimated to be 188 PJ and 263 PJ, which is around 22% and 30% of total final energy used in 2010, respectively. The cost-effective and technical primary energy conservation potentials are 204 PJ and 279 PJ, respectively, representing 17% and 23% of the total primary energy use in 2010. Besides, the CO₂ emissions reduction potential associated with the cost-effective measures is 19 Mt CO₂ and the total CO₂ mitigation potential is 26 Mt CO₂. The actual energy conservation and CO₂ mitigation potentials may be higher since not all the energy efficiency measures are included due to data availability in this study. With a comparison, the technical and cost-effective primary energy saving potentials are 31% and 16% of total primary energy consumption in the U.S. pulp and paper industry³, the corresponding CO₂ emissions reduction from energy savings is 25% and 14% for technical and cost-effective potential, respectively.

Table 6. Energy conservation and CO₂ mitigation potentials in China's pulp and paper industry

Of the total technical energy conservation potential, 72% is cost effective, however, these measures have not been adopted by this industry for financial, technical, and other reasons. These

³ The energy use and CO₂ emissions in the U.S. pulp and paper industry is from Martin et al. (2000).

reasons are crucial to be investigated and addressed, and could be a good topic for future studies. We cited one of our co-author's previous research on barriers to energy efficiency in industry (Hasanbeigi et al., 2010a). Because the purpose of this paper, we did not conduct this kind of research.

Compared to the Canadian pulp and paper industry which consumed 580 PJ of final energy in 2010 (NRC, 2013), the cost-effective and technical final energy saving potentials of the Chinese pulp and paper industry is 32% and 45% of total energy used in Canada's pulp and paper industry. In addition, we also compared the final energy conservation potential in China's pulp and paper industry and the total final energy use in the world pulp and paper industry. The world pulp and paper industry consumed 6.87 exajoules (EJ) of final energy and emitted about 400 Mt CO₂ in that year (IEA, 2010). From Table 6, we can see that the cost-effective and total technical final energy conservation potential are equal to 3% and 4%, respectively, of world pulp and paper industry final energy consumption in 2007. The CO₂ mitigation potentials related to the cost-effective and total final energy savings are equal to approximately 5% and 6%, respectively, of CO₂ emissions from the global pulp and paper industry in 2007. One of the reasons that China's share of world CO₂ emissions reduction is greater than the share of world final energy conservation potential is that the Chinese pulp and paper sector depends heavily on fossil fuel compared with other countries. Consequently, China could reduce its CO₂ emissions from the sector further by switching fuels supposing more renewable and sustainable energy related policies will be initiated and implemented in the following years. Regarding CO₂ reduction potential from fuel switching, it is beyond the scope of this paper because there are different issues to consider, e.g. technology, availability, and cost, etc.

4.4 Sensitivity analysis

In the previous sections, the cost-effective and technical energy efficiency and associated CO₂ emissions reduction potentials in the Chinese pulp and paper industry were presented and discussed. However, the estimated results may be affected by some factors due to the uncertainties and limitations of the methodology applied and data used, e.g. penetration rate, discount rate, and

energy price, sensitivity analyses were performed on these three parameters to see how changes in these parameters can influence the results. It should be noted that the variation of these parameters only affect the cost-effective energy conservation and CO₂ mitigation potentials while the total technical potentials will keep constant. In addition, although the capital cost, energy savings and CO₂ emissions reduction of each measure also has a influence on the results, we do not consider them in this section because they are the fundamental data for the analysis and are assumed as constant in this study.

Table 7 shows how changes of the penetration rate can influence the cost-effective energy savings and associated CO₂ emissions reduction potential while the other parameters (i.e., discount rate and energy price) are assumed to be constant. The changes to the penetration rate (e.g. +20%) are given as a percentage change compared to the default penetration rate, i.e. 30%, used in the main analysis. For this specific study, the cost-effective energy-saving potential changes from 218 PJ to 141 PJ when the penetration rate changes from -20% to +20% of the current base scenario. In addition, the cost-effective electricity savings will also reduced, from 2,610 GWh to 2,022 GWh accordingly. The penetration rate of the energy efficiency measure has a great impact on the cost-effective savings potential. In general, the increment increasing of penetration rate will lead to lower the cost-effective energy savings and associated Thus, the results of the base scenario analysis shown in this paper should be used with caution.

Table 7. Effect of penetration rate cost-effective energy conservation and CO₂ mitigation potentials

Table 8 shows the effect of applied various discount rate on the cost-effective energy savings and CO₂ emissions reduction potential, keeping other parameters (i.e., penetration rate and energy price) constant. It indicates that the change of discount rate from 30% to 25% will not affect cost-effective energy savings and related CO₂ reduction. When changed to 15%, the fuel-efficiency and CO₂ emissions reduction potential will rise up to 236 PJ and 23 Mt. No obvious affection of discount rate between 15% and 5% was observed on the results of energy savings and CO₂ emissions reduction. Furthermore, the change of discount rate from 30% to 5%

will not influence electricity savings and associated CO₂ emissions reduction. The reason behind this is that the variation of discount rate within the investigated range will not make the CCE higher than the average electricity price for all the cases used in this study.

Table 8. Effect of discount rate on cost-effective energy conservation and CO₂ mitigation potentials

Energy price can directly influence the cost effectiveness of energy-saving potentials. A higher energy price could result in more energy efficiency measures being cost-effective and could increase the number of instances in which the CCE falls below the energy price line on the CSC. We performed a sensitivity analysis of the impact of changing electricity and fuel prices by assuming 10%, 20%, and 30% increases as well as a 10% decrease in energy prices. However, the result shows that neither the cost-effective fuel savings nor the electricity savings will change under different energy price scenarios. This is because a change of fuel price in this range does not change the positions of the CCEs of the measures relative to the fuel price line. In other words, the ranking of the measures in relation to the average fuel price line does not change. Thus, we did not give the table to show the sensitivity analysis result for various energy prices applied herein.

Although the CSC we developed is a good screening tool for evaluating potential energy efficiency improvements, the actual costs and energy savings of each energy efficiency measure may vary depending on several factors such as raw material quality, technology provider, production capacity, byproducts, and time period of the analysis. Furthermore, it should be noted that some energy efficiency measures in this paper provide additional productivity and environmental benefits that are difficult or impossible to quantify. There are also some other energy efficiency options for the Chinese pulp and paper industry sector which were not considered in this paper due to lack of data. Thus, we intend to conduct a initial potential analysis for energy conservation and CO₂ reductions on the basis of above mentioned 23 energy efficiency measures. A thorough field survey on the Chinese pulp and paper industry is indispensable to analyse the energy efficiency potentials more concisely.

5. Conclusions

Pulp and paper industry is one of the most energy-intensive industries in China. In 2010, the industry's specific energy consumption was 13.2 GJ/tonne pulp and 19.9 GJ/tonne paper, final energy use was 834 PJ, primary energy use was 1,143 PJ, and CO₂ emissions were around 100 Mt CO₂. This study uses energy CSC to estimate the potential for 23 energy efficiency measures to improve the energy efficiency and reduce CO₂ emissions in the Chinese pulp and paper sector.

The results show that the cost-effective fuel conservation potential for the industry is estimated to be 180 PJ, and the total technical fuel conservation potential is 254 PJ, which are equal, respectively, to 27% and 38% of total fuel consumption by this industry in 2010. The associated cost-effective and technical CO₂ emissions reduction potentials are 17 Mt CO₂ and 24 Mt CO₂, equal to 17% and 24%, respectively, of total CO₂ emissions from the Chinese pulp and paper industry. The electricity saving potential is 2,316 GWh, representing 4% of the industry's total electricity use. All of the electricity efficiency measures are presented to be cost-effective. The CO₂ mitigation potential associated with electricity efficiency approximates 2 Mt. The cost-effective and technical primary energy conservation potentials in the Chinese pulp and paper industry represent 17% and 23%, respectively, of total primary energy consumption in 2010.

The CSC used in this study could be used as a screening tool in assessing the energy saving potentials. The fuel CSC shows that maintaining or upgrading steam traps, enclosing the paper machine hood and installing stationary siphons are three of the most promising fuel-savings technologies since they are both cost-effective and result in significant energy savings. Three promising electricity efficiency measures based on cost-effectiveness and high energy conservation criteria are employing high-efficiency double-disc refiners, installation of variable frequency drives and energy-efficient lighting. Energy conservation potentials and the cost of energy efficiency measures may vary according to various conditions. In other words, the implementation of energy efficiency measures might be limited by various technical and non-technical barriers. For the country-level analysis as is presented in this study, certain level of

generalization and making some assumptions are required. However, more detailed and plant-specific data is the prerequisite for conducting the plant-level analysis with investment purposes.

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Table 1. Energy savings and costs for energy efficiency measures applied to the Chinese pulp and paper industry

No.	Energy Efficiency Technology/Measure ^a	Production capacity in 2010 (Mt/year)	Electricity savings (kWh/t product)	Fuel savings (GJ/t product)	Final energy savings (GJ/t product)	Primary energy savings (GJ/t product)	Typical Capital cost (US\$/t product)	Change in annual O&M cost (US\$/t product)	CO ₂ emissions reduction (kg CO ₂ /t product)	Potential adoption rate (%)
Chemical Pulping										
1	Batch digester modifications	6.69	0	3.20	3.20	3.2	6.60	0.49	302.72	40%
2	Continuous digester modifications	10.04	0	0.97	0.97	0.97	1.25	0.16	91.76	36%
Chemical Recovery										
3	Falling film black liquor evaporation	16.06	0	0.80	0.80	0.80	90.00	0	75.68	18%
4	Black liquor concentration	16.06	0	0.76	0.76	0.76	31.76	0	71.9	24%
5	Lime kiln modifications	16.06	0	0.46	0.46	0.46	2.50	0	43.52	28%
Mechanical Pulping										
6	Refiner improvements	2.27	305	0	1.10	3.18	7.70	2.60	234.85	48%
7	Heat recovery in TMP mill	2.27	-149 ^e	3.20	2.66	1.64	21.00	18.00	187.99	25%
Pulp Bleaching										
8	Chlorine dioxide preheating	16.88	0	0.59	0.59	0.59	2.06	0	55.81	40%
Papermaking										
9	High-efficiency double-disc refiners ^b	92.7	17	0	0.06	0.18	0.89	0	13.09	53%
10	Shoe press ^{b, c}	86.5	-17.63 ^e	1.56	1.49	1.37	30.24	0.75	133.82	42%
11	Stationary siphons	92.7	0	0.89	0.89	0.89	0.05	0	84.19	25%

12	Turbulent bars	92.7	0	0.59	0.59	0.59	0.50	0	55.34	32%
13	Enclose paper machine hood ^{b, c}	86.5	7.44	1.56	1.59	1.64	7.93	0	153.3	28%
14	Air system optimization ^{b, c}	86.5	0	0.20	0.20	0.20	1.68	0.07	18.94	30%
15	Waste heat recovery	92.7	0	0.50	0.50	0.50	17.6	1.60	47.3	27%
16	Anaerobic wastewater treatment and methane utilization ^b	92.7	-2.52 ^e	0.21	0.20	0.18	3.72	0.22	17.93	36%
17	Sludge recovery and utilization ^b	92.7	0.65	0.28	0.28	0.29	1.26	0	26.99	56%
18	Vacuum system optimization	92.7	5.56	0	0.02	0.06	0	0	4.28	48%
General Measures										
19	Adjustable-speed drives	92.7	10.5	0	0.04	0.11	0.95	0	8.09	40%
20	Energy-efficient lighting	92.7	14	0	0.05	0.15	1.20	0.01	10.78	40%
21	Steam traps maintenance	92.7	0	1.79	1.79	1.79	1.24	0.06	169.33	27%
22	Condensate return	92.7	0	0.21	0.21	0.21	1.18	0	20.12	18%
23	Real-time energy management system ^d	92.7	0	0.40	0.40	0.40	4.41	0	37.71	43%

^a The description of the above 23 measures can be found in this report (Kong et al., 2013a).

^b The data for the measures were obtained from projects implemented in China, the costs are given in RMB, and we used an exchange rate of 6.77 (RMB/US\$) to convert the costs to U.S. dollars.

^c Household and sanitary paper production are excluded from these three measures.

^d Electricity savings for this measure are already included in fuel savings.

^e A negative value for electricity savings indicates that although this measure saves fuel, it will increase electricity consumption. However, the total final and primary energy savings of these measures is positive.

Table 2. Fuel efficiency measures for the Chinese pulp and paper industry by CCF

CCF Rank	Energy Efficiency Technology/Measure	Fuel savings* (PJ)	CCF (US\$/GJ saved)	CO ₂ mitigation* (Mt CO ₂)
1	Stationary siphons	20.6	0.02	2.0
2	Steam traps maintenance	44.8	0.25	4.2
3	Install turbulent bars	17.1	0.26	1.6
4	Continuous digester modifications	3.5	0.55	0.3
5	Batch digester modifications	8.6	0.78	0.8
6	Chlorine dioxide preheating	4.0	1.07	0.4
7	Sludge recovery and utilization	14.9	1.33	1.4
8	Enclose paper machine hood	39.7	1.45	3.7
9	Lime kiln modifications	2.0	1.66	0.2
10	Condensate return	3.5	1.69	0.3
11	Optimize air system	5.2	2.92	0.5
12	Real-time energy-management system	15.7	3.34	1.5
13	Shoe press	49.9	7.16	4.9
14	Anaerobic wastewater treatment	6.1	7.31	0.6
15	Black liquor concentration	2.9	12.61	0.3
16	Waste heat recovery	12.5	13.82	1.2
17	Heat recovery in TMP mill	0.9	14.78	0.1
18	Falling film BL evaporation	2.3	33.80	0.2

* The amounts provided for fuel savings and CO₂ mitigation are given for 2010 in this paper, which also applies for the following tables.

Table 3. Fuel conservation and CO₂ mitigation potentials in China's pulp and paper industry

	Fuel savings (PJ)		CO ₂ mitigation (Mt CO ₂)	
	Cost-effective	Technical	Cost-effective	Technical
Savings potential for 2010	180	254	17	24
Share of China's pulp and paper industry in 2010	27%	38%	17%	24%

Table 4. Electricity efficiency measures for the Chinese pulp and paper industry by CCE

CCE Rank	Energy Efficiency Technology/Measure	Electricity savings		CCE (US\$/MWh saved)	CO ₂ mitigation (Mt CO ₂)
		GWh	PJ*		
1	Vacuum system optimization	247	0.9	0.00	0.2
2	High-efficiency double-disc refiners	827	3.0	15.79	0.6
3	Refiner improvements	333	1.2	16.11	0.3
4	Adjustable-speed drives	389	1.4	27.68	0.3
5	Energy-efficient lighting	519	1.9	28.44	0.4

* The electricity savings expressed in PJ is final energy converted from electricity that expressed in GWh.

Table 5. Electricity conservation and CO₂ mitigation potentials in China's pulp and paper industry

	Electricity savings (GWh)		CO ₂ mitigation (Mt CO ₂)	
	Cost-effective	Technical	Cost-effective	Technical
Savings potential for 2010	2,316*	2,316	2	2
Share of China's pulp and paper industry in 2010	4%	4%	2%	2%

* Both cost-effective and technical electricity savings is 8.3 PJ if expressed in PJ instead of GWh.

Table 6. Energy conservation and CO₂ mitigation potentials in China's pulp and paper industry

	Final energy-savings potential (PJ)		Primary energy-savings potential (PJ)		CO ₂ mitigation (Mt CO ₂)	
	Cost-effective	Technical	Cost-effective	Technical	Cost-effective	Technical
Saving potential in 2010	188	263	204	279	19	26
Share from China pulp and paper industry in 2010	22%	30%	17%	23%	19%	26%
Share from World pulp and paper industry in 2007*	3%	4%	N/A	N/A	5%	6%

* The most recent available data on world pulp and paper final energy use is for 2007 (IEA, 2010).

Table 7. Effect of penetration rate on cost-effective energy conservation and CO₂ mitigation potentials

Penetration rate (±%)	Fuel		Electricity		
	Fuel savings (PJ)	CO ₂ mitigations (Mt CO ₂)	<u>Electricity savings</u> GWh	PJ**	CO ₂ mitigation (Mt CO ₂)
-20%	218	21	2,610	9.7	2.0
-10%	199	19	2,463	8.9	1.9
*	180	17	2,316	8.3	1.8
+10%	161	15	2,169	7.8	1.7
+20%	141	13	2,022	7.3	1.6

* The penetration rate from questionnaire survey is acted as the base scenario which is used in the main analysis presented in the previous sections.

** The electricity savings expressed in PJ is final energy converted from electricity that expressed in GWh.

Table 8. Effect of discount rate on cost-effective energy conservation and CO₂ mitigation potentials

Discount rate (%)	Fuel		Electricity	
	Fuel savings (PJ)	CO ₂ mitigation (Mt CO ₂)	Electricity savings(GWh)**	Cost-effective CO ₂ mitigation (Mt CO ₂)
5%	239	23	2,316	1.8
15%	236	22	2,316	1.8
25%	180	17	2,316	1.8
30%*	180	17	2,316	1.8

* The discount rate (30%) is the base scenario which is used in the main analysis presented in the previous sections.

** The electricity savings is 8.3 PJ for all the scenarios if expressed in PJ instead of GWh.

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Fig. 1. The pulp and paper production in China from 1978 to 2010

Fig. 2. Energy consumption in China's pulp and paper industry

Fig. 3. CO₂ emissions from the Chinese pulp and paper industry

Fig. 4. Fuel CSC for the Chinese pulp and paper industry

Fig. 5. Electricity CSC for the Chinese pulp and paper industry

Fig. 1. The pulp and paper production in China from 1978 to 2010 (CTAPI, 2011)

Fig. 2. Energy consumption in China's pulp and paper industry (NBS, 2009-2011)

Fig. 3. CO₂ emissions from the Chinese pulp and paper industry¹

¹ CO₂ emissions are calculated based on energy use data from China Energy Statistical Yearbook 2008-2010 (NBS, 2009-2011) and the CO₂ emissions factor from 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006).

Fig. 4. Fuel CSC for the Chinese pulp and paper industry

Fig. 5. Electricity CSC for the Chinese pulp and paper industry