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Analysis of Energy-Efficiency Opportunities for the Pulp and Paper Industry in China

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Abstract

The pulp and paper industry in China has been developing rapidly since 2000 with an average annual increase in production of about 12 percent per year through 2010. In 2008, China surpassed the United States to become the world's largest paper producer. China manufactured 11.2 percent of the world's virgin pulp and 24.5 percent of the world's paper in 2010. Although more than 18 million tonnes (Mt) of inefficient production capacity will be phased out during the 12th Five-year Plan (FYP) (2011-2015), China's total paper production is estimated to grow from 92.7 to 116 Mt during this period.

The total final energy consumption of China's pulp and paper industry was 750 petajoules (PJ) in 2007, representing 11 percent of global pulp and paper industry final energy consumption in that year. As energy prices and climate change awareness increase, improving energy efficiency is an effective way for the pulp and paper industry to reduce energy consumption and carbon dioxide (CO_2) emissions. During the 11 FYP, the average energy intensity of China's pulp and paper industry dropped by 18 percent. The energy intensity of the pulp and paper industry is predicted to drop by 20 percent by the end of 2015 compared to the intensity in 2010. Nonetheless, a wide gap exists between China and other developed economies in the best available technologies in use in the pulp and paper sector.

This study assesses the impact of 23 energy-efficiency measures that could be applied in China's pulp and paper industry. We analyze the fuel- and electricity-efficiency improvement potential of these technologies for the year 2010 using a bottom-up conservation supply curve (CSC) model. The fuel CSC model shows that the cost-effective fuel efficiency improvement potential for China's pulp and paper industry is 179.6 PJ, and the total technical fuel-savings potential is 254.3 PJ. These figures represent 26.8 percent and 38.0 percent, respectively, of total fuel used in China's pulp and paper industry in 2010. The CO_2 emissions reduction potential associated with

the cost-effective fuel savings is 16.9 Mt CO_2, and the total technical potential for CO_2 emissions reduction is 24.2 Mt CO_2. The electricity CSC model shows that the total technical electricity-efficiency potential to 2,316 gigawatt-hours (GWh) or 4.3 percent of total electricity use in the pulp and paper industry in 2010. All of the electricity-efficiency potential is cost effective. The CO_2 emissions reduction potential associated with the total electricity savings is 1.8 Mt CO_2.

Sensitivity analyses for adoption rate, discount rate, electricity and fuel prices, investment costs, and the energy savings from each measure show that these parameters have significant influence on the results. Therefore, the results presented in this report should be interpreted with caution.

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Acronyms

CCE	cost of conserved energy
CCF	cost of conserved fuel
CO_2	carbon dioxide
CSC	conservation supply curve
ECSC	energy conservation supply curve
EJ	exajoule
FCSC	fuel conservation supply curve
FYP	five-year plan
GJ	gigajoule
GWh	gigawatt-hours
IEA	International Energy Agency
kg	kilogram
kt	kiloton
kWh	kilowatt hour
LBNL	Lawrence Berkeley National Laboratory
Mt	million tonnes
MWh	megawatt hour
NDRC	National Development and Reform Commission
PJ	petajoule
RMB	renminbi
TJ	terajoule

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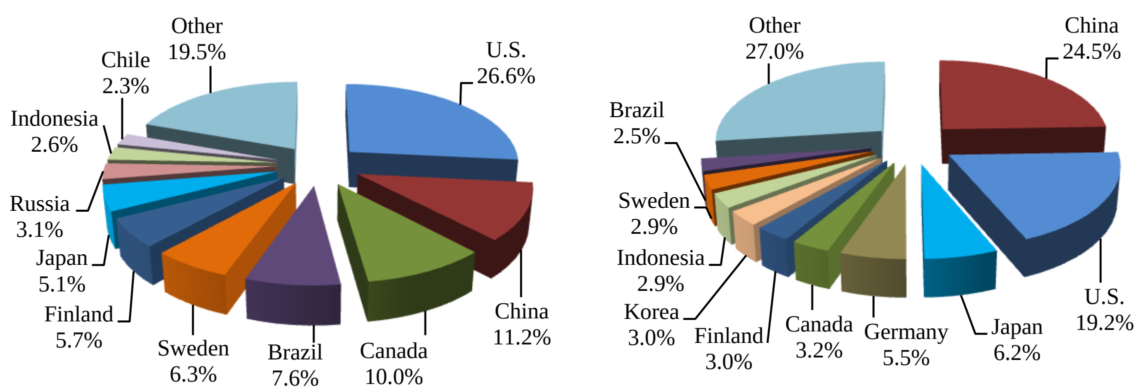
1. Introduction

The pulp and paper industry has been developing since the first continuous paper machine was invented by Fourdrinier brothers in 1806 (Vickerman 1995). According to the International Energy Agency (IEA), annual global paper production is expected to grow from approximately 365 million tonnes (Mt) in 2006 to between 700 Mt (low estimate) and 900 Mt (high estimate) in 2050 (IEA 2009).

In China, the pulp and paper industry has been developing rapidly since the beginning of the 10th Five-year Plan (FYP) (2001-2005). China is currently one of the largest pulp and paper product manufacturers in the world. As Figure 1 shows, China manufactured 11.2 percent of pulp and 24.5 percent of paper globally in 2010 (FAO 2012). Figure 1 lists the top 10 pulp and paper manufacturing countries worldwide in 2010. Approximately 50 percent of the total global pulp and paper production capacity is located in China, the United States (U.S.), and Canada. China's average annual pulp and paper production increased by about 12 percent per year from 2000 to 2010 (CPA 2001-2011). World paper demand is expected to grow by about 2.1 percent per year until 2020, and China will play a crucial role in the future paper market growth (Szabó *et al.* 2009).



(a) Pulp production[1] (b) Paper production

Figure 1. Top 10 pulp and paper manufacturing countries in 2010 (FAO 2012)

[1] Pulp production refers only to virgin pulp, not include recycled fiber pulp.

Pulp and paper manufacturing is one of the most capital- and energy-intensive industries. Globally, pulp and paper production is the fourth most energy-intensive industry, after chemicals, iron and steel, and nonmetallic minerals (EIA 2011). The pulp and paper industry accounts for 5 percent of total global industrial final energy consumption and contributes 2 percent of global direct industrial carbon dioxide (CO_2) emissions (IEA 2011). With the dramatic expansion of pulp and paper production in China during the past decade, the total final energy consumption of China's pulp and paper industry increased by 6.1 percent per year from 2000 to 2010 (NBS 2009, 2011a). China's average paper production is expected to increase at a rate of approximately 4.6 percent annually until 2015 (NDRC 2011a). There will be a corresponding increase in the industry's absolute energy use and CO_2 emissions.

During the past decade, China has undertaken a series of measures to improve industrial energy efficiency. According to the National Development and Reform Commission (NDRC), the energy intensity of the pulp and paper industry declined by 18 percent in the 11 FYP (NDRC 2007, 2011a). However, there is still a wide gap between China's average industrial energy efficiency and that of other developed economies. The energy intensity[2] of the pulp and paper industry is predicted to drop by 20 percent by end of 2015 compared to the intensity in 2010 (NDRC 2011b). Many studies as well as actual experience show that there are numerous opportunities to reduce energy consumption and CO_2 emissions in this industry. Improving energy efficiency has been demonstrated to be the most important and cost-effective means of reducing energy consumption and CO_2 emissions in many industries, especially in the near and medium term (Worrell *et al.* 2009).

We analyze energy savings and CO_2 reductions associated with implementation of 23 energy-efficiency technologies for the pulp and paper industry in China. The report is organized as follows: we begin with an overview of China's pulp and paper industry and then describe historical energy use and CO_2 emissions of the industry between 2000 and 2010. Next, we describe the 23 energy-efficiency improvement technologies and measures, including typical savings and cost data. The list of technologies and measures analyzed is not exhaustive, and there are others that could improve energy efficiency and reduce the CO_2 emissions of China's pulp and paper industry. However, we include only those for which we could ascertain adoption rates in China as of 2010. Fuel- and electricity-efficiency improvement potentials are analyzed using a bottom-up conservation supply curve (CSC) model. Sensitivity analyses are also performed for adoption rate, discount rate, electricity and fuel prices, investment costs, and the energy savings of each measure.

[2] Energy intensity discussed in this report means the energy consumption per tonne of product, but not the energy consumption per unit of gross domestic product.

2. Overview of the Pulp and Paper Industry in China

As noted above, China manufactured 11.2 percent of the world's pulp and 24.5 percent of the world's paper in 2010 and has become one of the largest global producers of pulp and paper. This section presents an overview of pulp and paper production, energy consumption, and CO_2 emissions in China.

2.1 Description of the Pulp and Paper Industry in China

China's pulp and paper industry comprises pulp mills, paper mills, and integrated pulp and paper mills. Pulp mills produce market pulp from wood (softwood and/or hardwood) or non-wood sources (e.g., straw, bamboo, bagasse). Paper mills manufacture paper or paperboard from market pulp or recycled paper pulp. Integrated mills produce both pulp and paper or paperboard.

The pulp and paper industry has developed rapidly in China since 1978, with the greatest growth during the past decade, as shown in Figure 2. Both pulp and paper production[3] increased with an average annual growth rate of about 10 percent since 1978. Pulp production jumped from 3.46 Mt in 1978 to 73.1 Mt in 2010 and paper production increased to 92.7 Mt in 2010 from 4.66 Mt (CTAPI 2011). As of 2008, China overtook the U.S. to become the world's largest paper manufacturing country (FAO 2012).

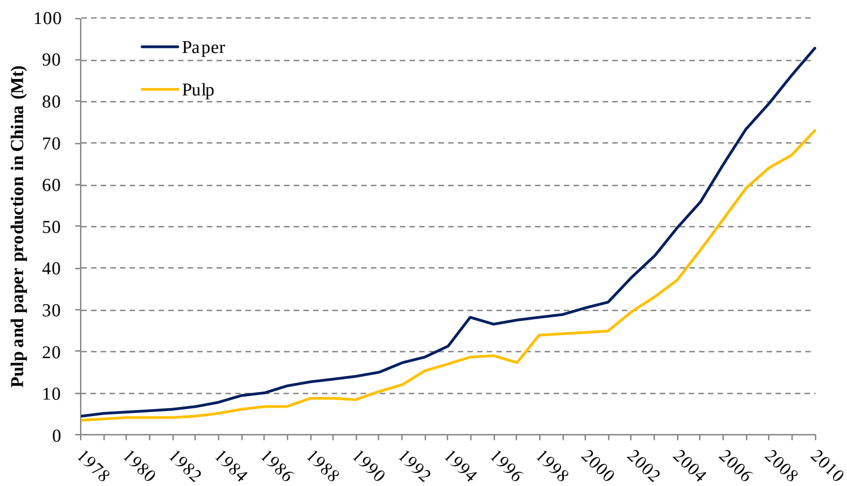


Figure 2. Pulp and paper production in China, 1978-2010 (CTAPI 2011)

The number of paper mills in China increased at a rate of 4.3 percent per year between 2000 and 2010 even though some small mills were phased out during this period. There were 3,724 paper mills in China in 2010 compared with 2,456 mills in 2000. However, the number of employees in China's pulp and paper industry decreased by 0.5 percent per year, from 783,000 in 2000 to 737,000 in 2010. To some extent, this trend reflects the modernization of China's pulp and paper

[3] "Total pulp production" encompasses both virgin and recycled paper pulp, except where specifically noted.

industry during this period, which reduced the need for workers. In 2010, China's paper industry generated 585 billion renminbi (RMB) (equal to $86.4 billion in 2010 U.S. dollars) in gross output. This is more than five times the output value in 2000 (CPA 2001-2011). Table 1 shows the total number of paper mills and employees, the gross output value, and the average production capacity of the pulp and paper industry in China between 2000 and 2010.

Table 1. Overview of the development of China's paper industry, 2000-2010 (CPA 2001-2011)

	Unit	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Paper mills	-	2,456	2,620	2,587	2,766	3,009	3,342	3,388	3,465	3,494	3,686	3,724
Gross output	Billion RMB	106	120	140	171	210	262	312	383	457	466	585
Employees	1,000 persons	783	781	779	768	760	763	747	742	752	711	737
Average annual capacity	kilotons per mill	12	12	15	16	16	17	19	21	23	23	25

Figure 3. Geographical distribution of China's paper production in 2010 (Unit: Mt) (NBS 2011b)[4]

[4] The paper production data in Figure 3 are from China's National Bureau of Statistic (NBS 2011). The NBS values are higher than those from the China Paper Association (CPA) or China Technical Association of Paper Industry

The majority (71.6 percent) of paper and paperboard production is in China’s eastern region where Shandong, Guangdong, and several other developed provinces are located. The country’s central region produces for 20.1 percent of the total production capacity, and only 8.3 percent is manufactured in the western region. Figure 3 shows the detailed production of each province. Figure 4 shows the top 10 paper making provinces in China and the capacity shares of each. Shandong, Guangdong, Zhejiang, and Jiangsu province each produce more than 11 Mt; these four provinces together represented 58 percent of the China's total paper production in 2010.

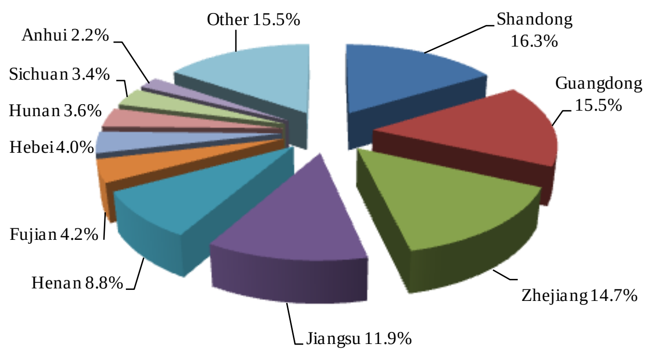


Figure 4. Top 10 paper-making provinces in China, 2010 (CPA 2011)

Although some of the world's largest and most modern pulp and paper mills are located in China and about 10 Mt of inefficient capacity was phased out during the 11th FYP (2006-2010), China still has a large share of small- and medium-size paper mills (Li 2006; CPA 2011; CTAPI 2011). The majority (96 percent) of China’s paper mills still produce less than 100 kilotons (kt)/year. It is estimated that only 0.3 percent of China’s paper mills produced more than 1,000 kt in 2010, and 0.5 percent produced between 400 and 1,000 kt[5]. In some facilities, old technologies installed during the 1970s or 1980s are still in service. This is one reason for the low energy efficiency of China's pulp and paper industry compared to the developed countries and best available technologies.

(CTAPI). However, NBS is the only source that breaks down data by province; the Annual Report of China Paper Industry (CPA 2001-2011) and Almanac of China Paper Industry (CTAPI 2011) do not break down production by province. Therefore, we use the NBS data in Figure 3. However, in the rest of this report, we use CPA data because Chinese pulp and paper industry experts perceive those data to be more accurate.

[5] The production share presented here is estimated based on the information from the Almanac of China Paper Industry (CTAPI 2011). At the IEA-WBCSD Workshop on Energy Efficient Technologies and CO_2 Reduction Potentials in the Pulp and Paper Industry, held in Paris in 2006, Li (2006), representing the China Cleaner Production Centre of Light Industry, stated that 0.2 percent of pulp and paper mills had capacity greater 1,000 kt, 0.8 percent of mills had a capacity greater than 200 kt, 2.8 percent had a capacity greater than 10 kt, and 96.2 percent had capacity of less than 10 kt (Li 2006).

2.2 Pulp and Paper Production in China

Pulp Production

The pulp and paper industry consumes large amounts of raw materials. The basic pulp types are wood pulp (made from hardwood or softwood), non-wood pulp (made from straw, bamboo, bagasse, reeds etc.), and recycled paper pulp (made from waste paper). In China, recycled waste paper pulp and non-wood pulp accounted for 90 percent of total pulp production in 2010; the remaining 10 percent was wood pulp. China also imports market wood pulp from other countries for use in papermaking. Figure 5 shows China's total pulp production from 2000 to 2010, by pulp type.

As of 2008, China surpassed Canada to become the world's second-largest virgin pulp producer, after the U.S. (CPA 2011; FAO 2012). China's total virgin and recycled paper pulp production increased from 24.6 Mt in 2000 to 73.1Mt in 2010, with an average annual growth rate of 12 percent. The primary change during this period was a decline in non-wood pulp production and an increase in recycled and wood pulp production. In 2000, China's production was 46 percent recycled pulp, 45 percent non-wood pulp, and 8 percent wood pulp (see Figure 5). The share of pulp made from waste paper rose to 73 percent in 2010, and the share of non-wood pulp fell to 18 percent as a result of Chinese government policies and limitation on the construction of non-wood pulp mills. The percentage of wood pulp remained relatively stable during this period, increasing by only 2 percent. Even though non-wood pulp accounts for only 18 percent of China's total production, China is the largest non-wood pulp manufacturing country in the world. China's total production of non-wood pulp was 12.97 Mt in 2010.

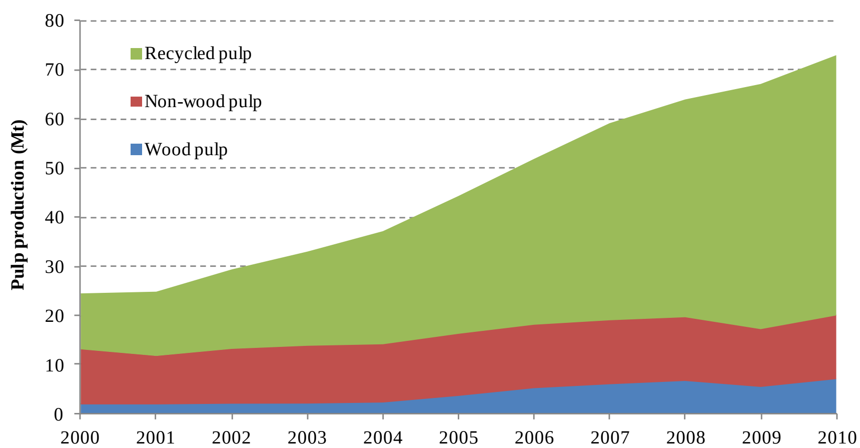


Figure 5. China's pulp production by type, 2000-2010 (CPA 2001-2011)

Paper Production

Figure 6 shows China's production of paper by type between 2000 and 2010. The categories of paper and paperboard used in this report, which are based on FAO (2011), are: newsprint, printing and writing paper, household and sanitary paper, wrapping and packaging paper and paperboard, and other paper and paperboard (FAO 2011). Paper production in China consists primarily of wrapping and packaging paper and paperboard as well as printing and writing paper, which together accounted for 84.8 percent of total paper production in 2010. The rest of China's production is household and sanitary paper (6.7 percent), newsprint (4.6 percent), and other paper and paperboard (3.9 percent) (CPA 2001-2011).

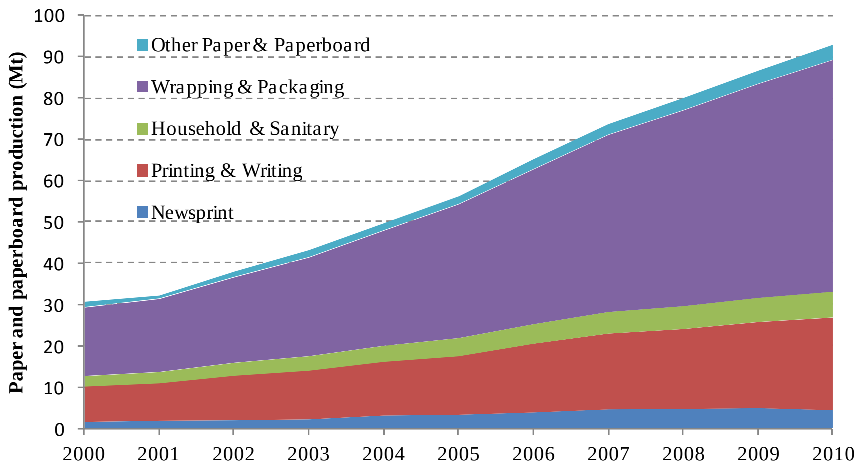


Figure 6. China's paper production by type, 2000-2010 (CPA 2001-2011)

China's paper production increased sharply, by 12 percent per year, from 30.5 Mt in 2000 to 92.7 Mt in 2010. In 2000, the shares of paper by type were as follows: 54.1 percent wrapping and packaging paper and paperboard, 28.9 percent printing and writing paper, 8.2 percent household and sanitary paper, 4.8 percent newsprint, and 4.1 percent other paper and paperboard (see Figure 6). During this period, the only major changes in the relative shares of types of paper produced were: the share of printing and writing paper declined by 4.5 percent, and the share of wrapping and packaging paper and paperboard increased by 6.3 percent.

More than 18 Mt of inefficient pulp and paper production capacity will be phased out in China during the 12th FYP. However, total paper production in China is expected to increase to 116 Mt in 2015 from 92.7 Mt in 2010 according to NDRC (NDRC 2011a). As a result, the Chinese pulp and paper industry's absolute energy use and CO_2 emissions will continue to increase in the mid and long term.

2.3 Energy Consumption of China's Pulp and Paper Industry

The production of pulp and paper is highly energy intensive (EIA 2011; IEA 2011). In 2007, China's pulp and paper industry consumed 750 petajoules (PJ) of final energy[6], equivalent to 11 percent of the global pulp and paper industry's final energy consumption in the same year (NBS 2009; IEA 2010). The energy consumed by China's pulp and paper industry increased by 7.3

[6] The energy use shown in this report 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.

percent annually between 2000 and 2010, corresponding the rapid expansion in the industry during this period (NBS 2009, 2011a). Figure 7 shows the total primary and final energy consumption by China's pulp and paper industry between 2000 and 2010. Total final and primary energy use almost doubled during that period, to 834 PJ and 1,143 PJ, respectively, in 2010.

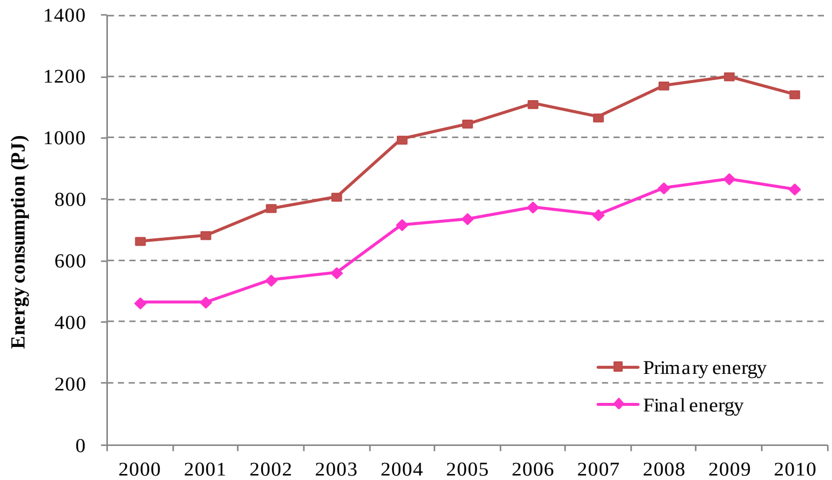


Figure 7. Energy consumption in China's pulp and paper industry, 2000-2010[7] (NBS 2009-2011)

In addition consuming fossil fuel, pulp and paper making also uses a large amount of secondary energy in the form of steam and electricity. Thermal energy is usually used for electricity generation, process stream heat, and water evaporation. Electricity is mainly used for various motors, fans, and pumping systems and for stock preparation operations such as beating or refining. In larger and/or modern paper mills, almost all secondary energy is self-generated from fossil fuel. However some small- and medium-size mills purchase some electricity and heat from utilities either because self-generated energy cannot meet their requirements or for economic reasons. Figure 8 shows the final energy mix in China's pulp and paper industry. Between 2000 and 2010, coal accounted for 60 percent of total final energy use, and electricity made up approximately 20 percent of total final energy consumption (NBS 2009-2011). Other energy sources are purchased steam, natural gas, oil, and coke (self-generated biomass energy is not included in these statistics). Although the energy mix shows a trend toward cleaner production, the pulp and paper industry in China still depends heavily on coal if the predominance of coal-fired power plants is also taken into account.

[7] Energy consumption figures do not include biomass energy because biomass use was not reported in official data sources.

Figure 8. Final energy mix in China's pulp and paper industry, 2000-2010 (NBS 2009-2011)

During the 11th FYP, China took a series of steps to improve industrial energy efficiency. For the pulp and paper industry, the energy intensity of the pulp decreased from 16.1 gigajoules (GJ)/tonne to 13.2 GJ/tonne and the energy intensity of paper reduced to 19.9 GJ/tonne from 24.3 GJ/tonne[8] (NDRC 2007, 2011a). However, there are still numerous opportunities to further reduce energy use and CO_2 emissions in the pulp and paper sector. There is also a wide gap in average pulp and paper industry energy efficiency between China and other developed economies. Energy efficiency improvement is one of the most important and cost effective means of achieving the goal of 20-percent reduction in the pulp and paper industry's energy intensity during the 12th FYP, in addition to phasing out outdated production capacity.

2.4 CO_2 Emissions from China's Pulp and Paper Industry

CO_2 emissions from the pulp and paper industry can be broken down into energy-related and non-energy-related emissions. Energy-related CO_2 emissions are from on-site fuel combustion and purchased electricity or steam. Non-energy-related CO_2 emissions include emissions from chemical reactions in the lime kiln and wastewater treatment plant. This report focuses only on energy-related CO_2 emissions.

As the result of the rapid increase in energy use, CO_2 emissions from China's pulp and paper industry increased at an average annual rate of 6.3 percent from 2000 to 2010. In 2007, the industry emitted approximately 85 Mt CO_2 emissions, representing 21 percent of total world pulp and paper industry CO_2 emissions in that year. Figure 9 shows the total CO_2 emissions from China's pulp and paper industry between 2000 and 2010 as well as the emissions sources. Total CO_2 emissions reached a high of 99 Mt CO_2 in 2010, up from 54 Mt CO_2 in 2000. Nearly 90 percent of the CO_2 emissions were from coal and electricity use.

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[8] Part of the energy intensity reductions in China's pulp and paper industry are attributed to phase-out of some inefficient mills between 2000 and 2010.

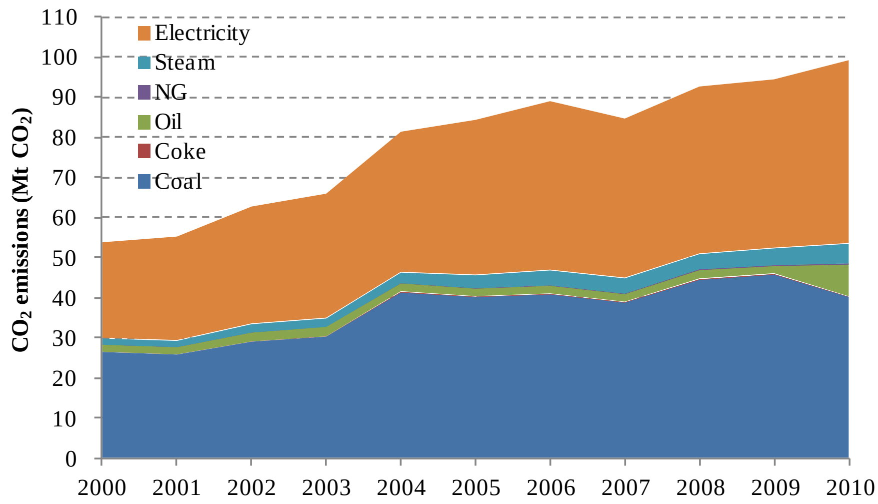

Figure 9. CO_2 emissions from China's pulp and paper industry[9]

Modern pulp mills, which efficiently utilize black liquor and other waste biomass for energy production, are fully energy self-sufficient and can even provide significant amounts of surplus energy (steam and/or electricity) to the community or other third parties. In these mills, fossil fuels are only needed for start-up and for back-up fuel and other emergency uses. Theoretically, fossil-fuel derived CO_2 emissions could be avoided in these modern mills if sufficient biomass is used and black liquor is converted into electricity with sufficient efficiency (IEA 2007). Overall in China, CO_2 intensity reduced between 2000 and 2010 as a result of decreasing energy intensity.

3. Methodology

This chapter describes our data collection method, the basic conversion factors and assumptions in our study, as well as the CSC approach we used to analyze the energy-efficiency opportunities for the pulp and paper industry in China. The base year for our analysis is 2010. Figure 10 shows the steps in our analysis.

3.1 Data Collection

The data collection effort for this report draws upon Lawrence Berkeley National Laboratory (LBNL) assessments of the energy efficiency and CO_2 emissions reduction potentials of the U.S. pulp and paper industry (Martin *et al.* 2000; Kramer *et al.* 2009) and South China University of Technology research on energy-efficiency improvement projects in specific paper mills located in China, among other references.

[9] CO_2 emissions are calculated based on energy use data from China NBS (2009-2011) and the CO_2 emissions factor from the Intergovernmental Panel on Climate Change (IPCC 2006).

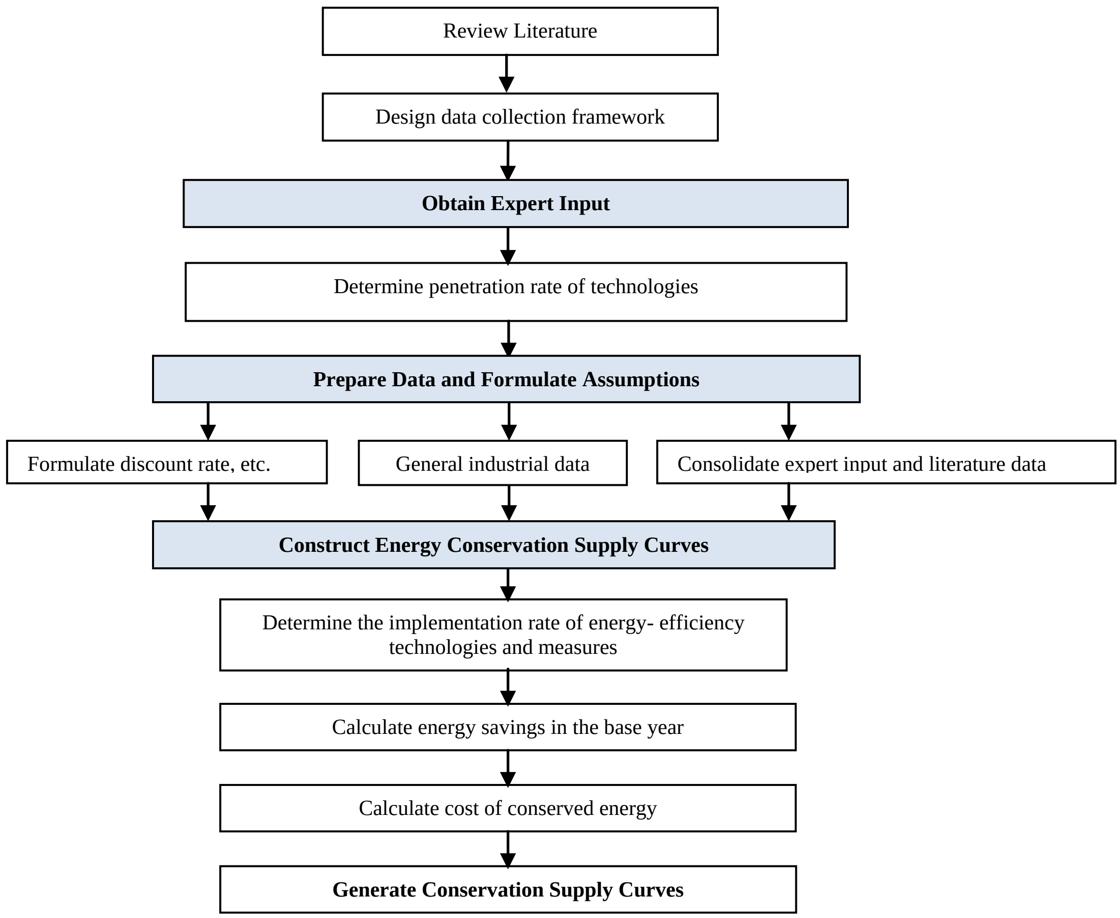

Figure 10. Overview of analysis methodology

The analysis in this report is based on both international and domestic Chinese technologies for the pulp and paper industry. Many of the energy-efficient technologies examined in LBNL publications and reports are used in this analysis because other studies on energy efficiency in the pulp and paper industry do not provide consistent and comprehensive data on energy savings, costs, and lifetimes of different technologies. For some technologies, information was obtained from other studies (EC 2001; FOE 2005; NEDO 2008; Kong *et al.* 2012). Furthermore, the methodology used for this analysis, i.e. construction of the energy CSC and abatement cost curve, is also used by LBNL for the U.S. and China iron and steel industry, Thai and China cement industry as well as the U.S. pulp and paper industry (Martin *et al.* 2000; Worrell *et al.* 2001; Hasanbeigi *et al.* 2010a; Hasanbeigi *et al.* 2010b; Hasanbeigi *et al.* 2012a; Hasanbeigi *et al.* 2012b).

We use 2010 as the base year throughout our analysis because that is the latest year for which energy statistics are published by China's *National Bureau of Statistics* (NBS). Data on the total production of different products by China's pulp and paper industry was obtained from the *Almanac of China Paper Industry* (CTAPI 2011). For the penetration rate of energy-efficiency measures, we developed a questionnaire and sent it to pulp and paper industrial experts in China.

In addition, we obtained some data from a recent China *Energy Research Institute* study of key industrial energy-efficient and emissions reduction technologies (ERI 2011).

3.2 Conversion Factors and Assumptions

We use a conversion factor of 2.9 to convert electricity from final to primary energy. This is equivalent to China's national average net heat rate for fossil fuel-fired power generation of 0.333 kilograms of coal equivalent (kgce) per kilowatt hour (kWh) in 2010 plus national average transmission and distribution losses of approximately 6.53 percent (SERC 2010). The lower heating value of the fuel is used in this analysis. To convert costs reported in RMB to U.S. dollars (US$), we use an average exchange rate of 6.77 RMB/US$ (NBS 2011b).

The carbon conversion factors for fuels used for calculating CO_2 emissions from energy consumption are taken from the 2006 Intergovernmental Panel on Climate Change Guidelines for National Greenhouse Gas Inventories (IPCC 2006). The emissions factor for grid electricity in 2010 is assumed to be 0.770 kg CO_2/kWh (Hasanbeigi *et al.* 2012b). More than 90 percent of the fossil fuel used in China's pulp and paper industry is coal. Therefore, we use the weighted average CO_2 emission factor for raw coal, cleaned coal, and other washed coal consumed in the pulp and paper industry in 2010 as the CO_2 emission factor for fuel in the base year of our analysis. This value is 94.6 kg CO_2/GJ. It is assumed that the electricity purchased by pulp and paper industry is generate power from coal-fired power plants, which generate more than 80 percent of the power in China.

We use 91.3US$/megawatt hour (MWh) as the average unit price of electricity in the base year (SERC 2011b). The average unit price of coal with 5,500 kilocalories per tonne for industrial use in 2010 (SERC 2011a) is used as the fuel price in the fuel CSC.

An important variable in our analysis is the future electricity grid emissions factor. Electricity that is more or less carbon intensive than is the case today will affect future CO_2 emissions reduction potential. Similarly, the emissions factor of the future fuel mix used in the pulp and paper industry will affect the future CO_2 mitigation potential. In this study, however, we have not conducted the future scenario analysis and we rather calculated the energy efficiency potential exist in the base year.

3.3 Energy Conservation Supply Curves

We use the concept of CSC to construct a bottom-up model for estimating the cost-effective and technical potential for energy-efficiency improvements and CO_2 emissions reduction in China's pulp and paper sector. The CSC approach is an analytical tool that captures both the engineering and the economic perspectives of energy conservation (Meier 1982). The curve shows energy conservation potential as a function of the marginal cost of conserved energy (CCE) and has been used to assess energy-efficiency potentials in different industries (Martin *et al.* 2000; Worrell *et al.* 2000; Worrell *et al.* 2001; Hasanbeigi *et al.* 2010a; Hasanbeigi *et al.* 2010b; Sathaye *et al.*

2010; Xu *et al.* 2010; Hasanbeigi *et al.* 2011; Hasanbeigi *et al.* 2012a; Hasanbeigi *et al.* 2012b). The CSC can be developed for a plant, a group of plants, an industry, or an entire economic sector.

The CCE required for constructing the CSC can be calculated from Equation 1:

$$CCE = \frac{Annualized\ Captial\ Cost\ +\ Annual\ Change\ in\ O\&M\ Costs}{Annual\ Energy\ Savings} \tag{1}$$

Where *O&M* is operations and maintenance.

The annual energy savings are calculated as follows,

$$Annual\ Energy\ Savings = Production \times Energy\ Savings\ per\ tonne\ production \times Potential\ Adoption\ Rate \tag{2}$$

We have the current penetration rate of each energy efficiency measure which shows the adoption rate of each measure in the base year. However, for most of the energy efficiency measures, the remainder of the adoption rate can not be 100 percent implemented because of mostly technical and plan-specific reasons. Thus, we calculated the "potential adoption rate" to be used in our analysis using equation 4.

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

Where:

Potential adoption rate: adoption rate potential that will be used in the calculation of energy saving potential used in CSC.

Penetration rate: penetration rate of the technology in the base year

Technical applicability: the extent to which the remaining penetration potential of the technology can be technically adopted in Chinese pulp and paper industry. These rates are obtained based on consultation with Chinese pulp and paper industry experts.

Take the energy-efficiency measure #1 as an example. The penetration rate of this measure in the Chinese pulp and paper industry was 20 percent in 2010. If this measure could totally be adopted in every Chinese pulp and paper mill, then its theoretical adoption rate would be 80 percent. However, in reality technical and plant-specific barriers hinder the applicability of the efficiency measures in some plants. Assuming 50 percent technical applicability for this measure, the potential adoption rate for this measure is equal to 40 percent [(100%-20%)*(50%/100%)].

The annualized capital cost can be calculated from Equation 4:

$$\text{Annualized capital cost} = \text{Capital Cost}^*(d/\ (1-(1+d)^{-n}) \tag{4}$$

Where *d* is the discount rate (in *percentage*) and *n* is the lifetime of the energy-efficiency measures (in *years*).

In this study, a real discount rate of 30 percent is used for the base-case analysis to reflect the barriers to energy-efficiency investment in China's pulp and paper industry. These barriers include perceived risk, lack of information, management concerns about production and other issues, capital constraints, opportunity cost, and preference for short payback periods and high internal rates of return (Hasanbeigi *et al.* 2010b; Hasanbeigi *et al.* 2011). After calculating the CCE for each energy-efficiency measure separately, we construct the energy CSC by ranking all of the measures in ascending order according to their CCEs. For each CSC, we determine an energy price line. This line is the weighted average fuel price in the fuel CSC (FSCS) and average electricity price in the electricity CSC (ECSC) for this industry. All measures that fall below the energy price line are considered cost effective. Furthermore, the CSC also shows the total technical potential for electricity or fuel savings accumulated from all the applicable measures. On the curve, the width of each measure (plotted on the x-axis) represents the energy saved by that measure during the period covered in the analysis. The height (plotted on the y-axis) shows the measure's CCE, calculated as explained above.

To construct the CSC, we did the following:

1. Establish 2010 as the base year for energy, material use, and production in the pulp and paper industry in China.
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 conservation supply curve. We assumed that the measures are mutually exclusive, and there is no interaction between them. A total of 23 energy-efficiency technologies and measures are included in this study based on their applicability to China's pulp and paper industry as well as the data availability[10].
3. Determine the potential adoption rate of these energy-efficiency technologies and measures in China in the base year, based on information collected from China's pulp and paper companies, expert engineering judgment, and literature review. The method is explained above.
4. Construct an electricity CSC (ECSC) and a fuel CSC (FSCS) separately to capture the accumulated cost effectiveness and total technical potential for electricity- and fuel-efficiency improvements. For this purpose, we calculated the CCE or cost of conserved fuel (CCF) separately for each technology. After calculating the CCE or CCF for all the measures, we ranked the measures by ascending CCE or CCF to construct the ECSC or FCSC, respectively. The reason to construct two separate supply curves for electricity and fuel is that the cost effectiveness of energy-efficiency measures depends heavily on the energy price. Because average electricity and fuel prices for the pulp and paper industry in 2010 were different from one another, and because many technologies save only electricity or only fuel, it is appropriate to separate the electricity- and fuel-saving measures. Thus, the ECSC with

[10] We listed 61 energy-efficiency technologies and measures in the questionnaire. However, we were only able to get information on penetration rates for 23 technologies. Thus, these 23 energy-efficiency measures and technologies are used in this study to analyze the energy-efficiency improvement potential in the pulp and paper industry.

average unit price of electricity plots technologies that primarily save electrical energy, and the FCSC with average unit price of fuel plots technologies that primarily save fuel. There are also some measures save both electricity and fuel, and some increase electricity consumption as a result of saving fuel. For those measures, we noted that the fuel savings accounted for the major portion of the total primary energy savings and included them in the FCSC, taking into account their primary energy savings.

Although the CSC model we developed is a good screening tool for evaluating potential energy-efficiency improvements, the actual cost and energy savings potential of each energy-efficiency measure in an individual pulp and/or paper mill may vary depending on several factors such as raw material quality, technology provider, production capacity, byproducts, and time period of the analysis. Moreover, it should be noted that some energy-efficiency measures provide additional productivity and environmental benefits that are difficult or sometimes impossible to quantify. Including quantified estimates of these other benefits could significantly reduce the CCE for some energy-efficiency measures (Worrell *et al.* 2003; Lung *et al.* 2005).

4. Energy-Efficiency Technologies and Measures

In this study, we analyze 23 the potential energy-efficiency improvements applicable to the pulp and paper industry in China. Appendix A briefly describes the 23 measures. More detailed description about these energy-efficiency technologies and measures can be found in Martin et al. (2000), EC (2001), and Kramer et al. (2009).

Table 2 presents, for the 23 measures analyzed, the energy savings, capital costs, change in annual operations and maintenance (O&M) costs, and potential adoption rate in 2010. It also presents data on the production capacity for each step of the pulping and papermaking process in China.

Table 2. Energy savings and costs for energy-efficient technologies and 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)	Capital cost (US$/t product)	Change in O&M cost (US$/t product)	Typical life time (year)	Potential adoption rate (%)
Chemical Pulping									
1	Batch digester modifications	6.69	0	3.20	3.20	6.60	0.49	20	40%
2	Continuous digester modifications	10.04	0	0.97	0.97	1.25	0.16	20	36%
Chemical Recovery									
3	Falling film black liquor evaporation	16.06	0	0.80	0.80	90.00	0	25	18%
4	Black liquor concentration	16.06	0	0.76	0.76	31.76	0	20	24%
5	Lime kiln modifications	16.06	0	0.46	0.46	2.50	0	15	28%
Mechanical Pulping									
6	Refiner improvements	2.27	305	0	1.10	7.70	2.60	25	48%
7	Heat recovery in TMP mill	2.27	-149[e]	3.20	2.66	21.00	18.00	25	25%
Pulp Bleaching									
8	Chlorine dioxide preheating	16.88	0	0.59	0.59	2.06	0	15	40%
Papermaking									
9	High-efficiency double-disc refiners [b]	92.7	17	0	0.06	0.89	0	20	53%
10	Shoe press [b, c]	86.5	-17.63[e]	1.56	1.49	30.24	0.75	25	42%
11	Stationary siphons	92.7	0	0.89	0.89	0.05	0	20	25%
12	Turbulent bars	92.7	0	0.59	0.59	0.50	0	20	32%
13	Enclose paper machine hood [b, c]	86.5	7.44	1.56	1.59	7.93	0	25	28%
14	Air system optimization [b, c]	86.5	0	0.20	0.20	1.68	0.07	15	30%

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)	Capital cost (US$/t product)	Change in O&M cost (US$/t product)	Typical life time (year)	Potential adoption rate (%)
15	Waste heat recovery	92.7	0	0.50	0.50	17.6	1.60	20	27%
16	Anaerobic wastewater treatment and methane utilization [b]	92.7	-2.52[e]	0.21	0.20	3.72	0.22	20	36%
17	Sludge recovery and utilization [b]	92.7	0.65	0.28	0.28	1.26	0	20	56%
18	Vacuum system optimization	92.7	5.56	0	0.02	0	0	15	48%
General Measures									
19	Adjustable-speed drives	92.7	10.5	0	0.04	0.95	0	15	40%
20	Energy-efficient lighting	92.7	14	0	0.05	1.20	0.01	10	40%
21	Steam traps maintenance	92.7	0	1.79	1.79	1.24	0.06	15	27%
22	Condensate return	92.7	0	0.21	0.21	1.18	0	15	18%
23	Real-time energy management system [d]	92.7	0	0.40	0.40	4.41	0	20	43%

[a] Appendix A contains brief descriptions of these energy-efficiency measures. More detailed information can be found in Martin et al. (2000), EC (2001) and Kramer et al. (2009).

[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.

5. Results and Discussion

Using the methodology described in Section 3 and the information in Table 2, we constructed the FCSC and ECSC to estimate the cost-effective and total technical potential for fuel- and electricity-efficiency improvements, respectively, in China's pulp and paper industry. In reality, this potential would be realized over a period of time in the future, but our analysis results show only the total potential in 2010. In addition, we estimated the CO_2 emissions reduction potential from implementing these efficiency measures based on the energy savings and associated CO_2 emission factors. Of the 23 energy-efficiency measures that were applicable to China's pulp and paper industry, 18 of them are fuel-saving measures that are included in FCSC, and five are electricity-saving measures, which we used to derive the ECSC.

Table 2 shows the total production capacity of each pulping and papermaking step. The 2010 production capacity of energy-efficiency measures for the pulping process is in most cases based on the relevant pulping method. For chemical recovery measures such as falling film black liquor evaporation, black liquor concentration, and lime kiln modifications, the production capacity is based on kraft pulping because these three measures are applied only in kraft pulp mills. We estimate that 96 percent of the pulp mills in China are kraft mills, based on the pulping methods of medium and large pulp companies in the country.

There are some technologies save both electricity and fuel, and some increase electricity consumption as a result of saving fuel. These measures include: heat recovery in thermomechanical pulp (TMP) mills, updating press section to shoe press, enclosing the paper machine hood, incorporating anaerobic wastewater treatment and methane utilization, incorporating sludge recovery and utilization, and installing a real-time energy management system. When a technology's fuel savings account for the larger portion of total primary energy savings, we include this technology only in the FCSC while not ECSC.

5.1 Fuel Conservation Supply Curve for China's Pulp and Paper Industry

As mentioned above, we constructed the FCSC using 18 energy-efficiency measures. Figure 11 shows that 12 of these 18 measures fall below the average fuel price line for the pulp and paper industry in 2010 (4.8 US$/GJ). For these measures, the CCF is less than the average fuel price. In other words, the cost of investing in these 12 measures to save 1 GJ of energy is less than purchasing the same amount of fuel at the given fuel price. The other six measures (numbers 13-18 in Table 3) have CCFs 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.

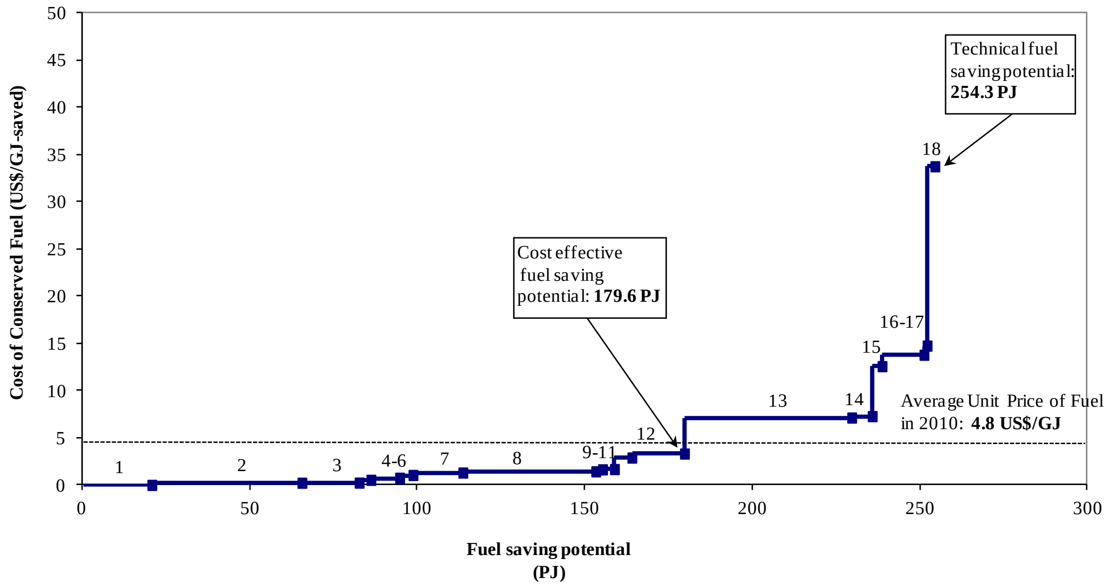

Figure 11. FCSC for China's pulp and paper industry

Table 3 presents the fuel-efficiency measures applicable to China's pulp and paper industry, ranked by CCF. The table also shows the fuel savings and CO_2 emissions reductions from each measure. Installing stationary siphons, maintaining/upgrading steam traps, and installing turbulent bars are the top three most cost-effective measures. Furthermore, steam traps maintenance saves the most fuel of all of the energy-efficiency measures. However, the energy savings of the product change measures highly depends on the plant-specific situation and the efficiency of the current facilities.

The cost-effective fuel-efficiency improvement potential for China's pulp and paper industry in 2010 is 179.6 PJ, representing approximately 26.8 percent of the industry's total fuel use in 2010. The total technical fuel-savings potential is 254.3 PJ, equal to approximately 38.0 percent of the pulp and paper industry's total fuel consumption in China in 2010 (Table 4). The CO_2 emissions reduction associated with the cost-effective savings potential is 16.9 Mt CO_2, and the total CO_2 emissions reduction associated with the technical fuel-savings potential is 24.2 Mt CO_2. As Table 4 shows, the cost-effective and technical potentials for CO_2 emissions reductions are equal to 17.1 percent and 24.4 percent, respectively, of the total CO_2 emissions from China's pulp and paper industry in 2010.

Table 3. Fuel-efficiency measures for China's 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

Table 4. Fuel savings and CO_2 mitigations for 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	179.6	254.3	16.9	24.2
Share of China's pulp and paper industry in 2010	26.8%	38.0%	17.1%	24.4%

5.2 Electricity Conservation Supply Curve for China's Pulp and Paper Industry

Five energy-efficiency measures are included in the ECSC. Figure 12 and Table 5 show that all five electricity-efficiency measures fall under the average electricity price line for the pulp and paper industry in 2010 (91.3 US$/MWh). Therefore, for these measures, the CCE is less than the average unit price of electricity. In other words, these measures can be considered cost effective because the cost of investing in them to save 1 MWh of energy is less than purchasing the same amount of electricity at the given electricity price.

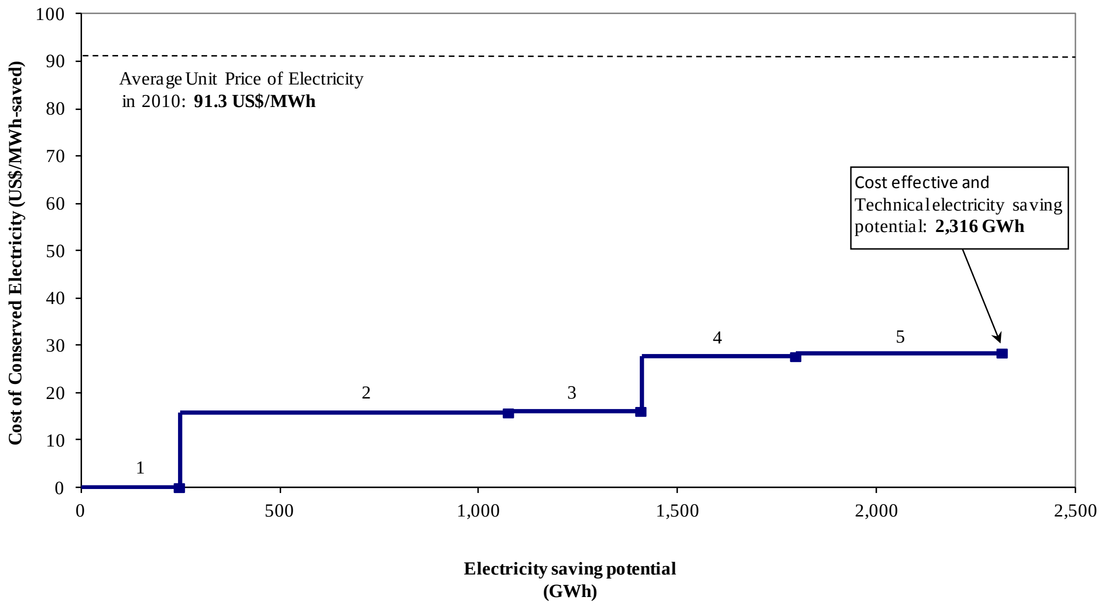

Figure 12. ECSC for China's pulp and paper industry

Table 5 shows all of the electricity-efficiency measures applicable to China's pulp and paper industry, ranked by CCE, as well as the electricity savings and CO_2 emissions reductions achieved by applying each measure. Among all of the electricity-efficiency measures, optimizing the vacuum system, installing high-efficiency double-disc refiners, and improving refiners performance are the top three cost-effective energy-efficiency measures.

Table 5. Electricity-efficiency measures for China's pulp and paper industry by CCE

CCE Rank	Energy-Efficiency Technology/Measure	Electricity savings (GWh)	CCE (US$/MWh saved)	CO_2 mitigation (Mt CO_2)
1	Vacuum system optimization	247	0.00	0.2
2	High-efficiency double-disc refiners	827	15.79	0.6
3	Refiner improvements	333	16.11	0.3
4	Adjustable-speed drives	389	27.68	0.3
5	Energy-efficient lighting	519	28.44	0.4

The total electricity-efficiency improvement potential for China's pulp and paper industry in 2010 is 2,316 GWh or approximately 4.3 percent of the industry's total electricity use in 2010. Especially interesting is that all of the electricity-efficiency improvement potential is cost effective (Figure 12). The CO_2 emissions reduction associated with the total electricity savings potential is 1.8 Mt CO_2. As Table 6 shows, the cost-effective and technical potential for CO_2 emissions reduction represents approximately 1.8 percent of the industry's total CO_2 emissions in 2010.

Table 6. Electricity savings and CO_2 mitigations for 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	1.8	1.8
Share of China's pulp and paper industry in 2010	4.3%	4.3%	1.8%	1.8%

5.3 Total Energy-Savings Potential for China's Pulp and Paper Industry

Final energy-savings potential

Table 7 shows the total final energy-savings potential and the total CO_2 emissions reduction potential for China's pulp and paper industry from all of the applicable electricity and fuel-saving measures presented above. The cost-effective and technical final energy-savings potentials are equal to 22 percent and 30 percent, respectively, of the final energy consumption of the industry in 2010. Total technical CO_2 reduction potential in the Chinese pulp and paper industry associated with the studied energy efficiency measures is equal to 26.0 Mt CO_2 which is equal to around 26 percent of the total CO_2 emissions of this industry in 2010. Of the total technical final energy-savings potential, 73 percent is cost effective, but these measures have not been adopted by the industry for financial, technical, and other reasons. These reasons are very important to be investigated, understood, and addressed, and could be a good topic for future studies.

Table 7. Final energy-savings and CO_2 mitigation potential for China's pulp and paper industry

	Final energy-savings potential (PJ)		**CO_2 mitigation potential (Mt CO_2)**	
	Cost-effective	**Technical**	**Cost-effective**	**Technical**
Savings potential for 2010	187.9	262.7	18.7	26.0
Share of China's pulp and paper industry in 2010	22%	30%	19%	26%
Share of global pulp and paper industry in 2007[a]	3%	4%	5%	6%

[a] The most recent available data on world pulp and paper final energy use are for 2007 (IEA 2010).

We also compared the final energy-savings potential to the total final energy use in the world pulp and paper industry in 2007. The world pulp and paper industry consumed 6.87 exajoules (EJ) of final energy and emitted about 400 Mt CO_2 in that year (IEA 2010). From Table 7, we can see that the cost-effective and total technical final energy-savings potential in China's pulp and paper industry are equal to 3 percent and 4 percent, respectively, of world pulp and paper industry final energy consumption. The CO_2 mitigation potentials associated with the cost-effective and total final energy-savings potential are equal to approximately 5 percent and 6 percent, respectively, of CO_2 emissions from the global pulp and paper industry in 2007. One of the reasons that China's share of world CO_2 emissions reduction is greater than China's share of world final energy-savings potential is that China's pulp and paper industry depends heavily on fossil fuel.

The IEA (2010) estimates that the global technical potential for final energy savings in the pulp and paper sector is 1.47 EJ, and the associated CO_2 emissions reduction potential is 80 Mt (IEA 2010). Based on this, China's pulp and paper industry could contribute 18 percent of the global final energy-savings potential and 32 percent of the global CO_2 emissions reduction potential.

Primary energy-savings potential

We used a conversion factor of 2.9 to convert the electricity-savings potentials to primary energy for the year 2010 in China. This takes into account the average efficiency of power generation as well as transmission and distribution losses (6.53 percent) in that year. Table 8 shows the total primary energy-savings and CO_2 emissions reduction potentials from all applicable electricity and fuel-saving measures presented in Sections 5.1 and 5.2. The cost-effective and technical primary energy-savings potentials are 203.8 PJ and 278.5 PJ, respectively, representing 17 percent and 23 percent of the total primary energy use in China's pulp and paper industry in 2010.

Table 8. Primary energy-savings and CO_2 mitigation potential for China's pulp and paper industry

	Primary energy-savings potential (PJ)		CO_2 mitigation potential (Mt CO_2)	
	Cost-effective	**Technical**	**Cost-effective**	**Technical**
Savings potential for 2010	203.8	278.5	18.7	26.0
Share of China's pulp and paper in 2010	17%	23%	19%	26%

5.4 Sensitivity Analysis

We performed sensitivity analysis to assess the influence of the following five parameters on the energy-efficiency potentials and cost-effectiveness results: adoption rate, discount rate, electricity and fuel prices, investment costs, and energy savings from the energy-efficiency measures. These analyses are described in the following subsections.

Adoption rate sensitivity analysis

Cost-effective and technical energy savings are directly related to the adoption rate of each measure in the next few years. A reduced adoption rate reduces total energy savings and CO_2 mitigation, and an increased adoption rate increases savings and CO_2 mitigation. We tested four cases: a 10-percent and a 20-percent decrease in actual adoption rate and a 10-percent and 20-percent increase in adoption rate in the future. We applied these changes in adoption rate to each energy-efficiency measure in the base year to assess the effect on the final results (see Table 9).

Table 9 shows how the cost-effective energy savings and their associated CO_2 emissions reductions change as the adoption rate varies while the other parameters (discount rate, energy prices, investment costs, and energy savings from the measures) are held constant. For fuel-saving measures, the cost-effective energy-savings potential changes from 143.7 PJ to 215.5 PJ when the adoption rate increases from -20% to +20%. The associated cost-effective CO_2 reduction potential changes accordingly. However, the CCF does not change when the adoption rate changes. The cost-effective electricity savings increase from 1,853 GWh to 2,779 GWh when the adoption rate changes from -20% to +20%. It can be seen that the adoption rate of each energy-efficiency measure has a great impact on the total energy-saving and CO_2 reduction potentials. Thus, the results of the base case analysis should be used with caution.

Table 9. Sensitivity analysis for cost-effective fuel- and electricity-savings potentials and CO_2 emissions reductions in China's pulp and paper industry with different adoption rates

Adoption rate (%)	Fuel			Electricity		
	Cost-effective savings (PJ)	Cost-effective CO_2 mitigation (Mt CO_2)	Cumulative CCF* (US$/GJ saved)	Cost-effective saving (GWh)	Cost-effective CO_2 mitigation (Mt CO_2)	Cumulative CCE* (US$/GWh saved)
-20%	143.7	13.6	104.77	1,853	1.4	88.02
-10%	161.6	15.2	104.77	2,084	1.6	88.02
AD**	179.6	16.9	104.77	2,316	1.8	88.02
+10%	197.6	18.6	104.77	2,548	2.0	88.02
+20%	215.5	20.3	104.77	2,779	2.1	88.02

* Cumulative CCF (the sum of CCFs of all 18 applicable fuel-saving measures) and CCE (the sum of CCEs for all five applicable electricity-saving measures) are presented as indicators to show that the change in adoption rate will affect the cost effective energy savings and CO_2 mitigation except the CCF and CCE.

** AD is the base-case scenario used in the main analysis presented in this report.

Discount rate sensitivity analysis

In this analysis, the CCE is directly related to the discount rate. Reduction of the discount rate will reduce the CCE, which might or might not increase the cost-effective energy savings potential, depending on the energy price. We performed a sensitivity analysis using discount rates of 5, 15, 25, 30, and 40 percent to assess the effect of changing the discount rate on the CCE and cost-effective energy savings (see Table 10).

Table 10 shows how changes in the discount rate can affect the cost effectiveness of the energy savings potentials and associated CO_2 emissions reductions, with other parameters (adoption rate, electricity and fuel prices, investment costs, and energy savings from each measure) held constant. From Table 10, we can see that reducing the discount rate from 30 percent to 5 percent will increase the cost-effective fuel-savings potential from 179.6 PJ to 238.6 PJ. While the cost-effective electricity-savings potential (which is 2,316 GWh) does not change with the discount rate varies in the studied range. The reason is that the total electricity savings in the ECSC are already extremely cost effective, so changes in the discount rate between 5- and 30-percent do not influence its cost effectiveness.

The cost effectiveness of the savings might not change with variation in the discount rate because energy prices also play a role in determining the cost effectiveness (as is the case for cost-effective electricity savings when the discount rate varies from 40 percent to 5 percent). The cumulative CCF and CCE will decrease with a decline in the discount rate, regardless of the cost effectiveness. The total technical energy-savings potentials do not change with a decline in the discount rate, but CCFs and CCEs lower than those we analyzed could affect these potentials.

Table 10. Sensitivity analysis for the cost-effective fuel- and electricity-savings potentials and CO_2 emissions reductions in China's pulp and paper industry with different discount rates

	Fuel			Electricity		
Discount rate (%)	**Cost-effective savings (PJ)**	**Cost-effective CO_2 mitigation (Mt CO_2)**	**Cumulative CCF* (US$/GJ saved)**	**Cost-effective saving (GWh)**	**Cost-effective CO_2 mitigation (Mt CO_2)**	**Cumulative CCE* (US$/GWh saved)**
5%	238.6	22.7	39.04	2,316	1.8	35.05
15%	235.6	22.4	62.84	2,316	1.8	54.06
25%	179.6	16.9	90.45	2,316	1.8	76.27
30%**	179.6	16.9	104.77	2,316	1.8	88.02
40%	179.6	16.9	133.78	2,316	1.8	112.24

* Cumulative CCF (the sum of CCFs of all 18 applicable fuel-saving measures) and CCE (the sum of CCEs for all five applicable electricity-saving measures) are presented as indicators to show that although a change in discount rate might not result in a change in cost-effective savings and CO_2 emissions reduction, the change in discount rate will change the CCF and CCE in general.

** 30 percent of the discount rate is the base-case scenario used in the main analysis presented in this report.

Energy price sensitivity analysis

Energy price can directly influence the cost effectiveness of energy-savings 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-percent increases in energy prices as well as a 10-percent decrease in energy prices (we considered multiple potential increases but only one decrease because energy prices are more likely to increase than to decrease). Since coal prices vary in different regions of China, this sensitivity analysis is especially important for FCSC.

Table 11 shows how the cost-effective energy savings and their associated CO_2 emissions reductions change with the changes in energy prices while the other parameters (adoption rate, discount rate, investment costs of measures, and energy savings from measures) are held constant. For fuel-saving measures, the cost-effective energy-savings potentials do not change with a 30-percent reduction in fuel price. This is because a change of fuel price in this range does not change the positions of the CCFs 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.

An increase in electricity price does not change the cost-effective electricity-savings potential. Similarly, an up to 70-percent reduction in the average electricity price does not change the cost-effective electricity-savings potential because a change in the average electricity price in this range does not change the positions of the CCEs of the measures compared to the electricity price line. That is, no measures will move up to the average electricity price line as a result of this price change. The total technical energy-savings and CO_2 mitigation potentials do not change with variation in energy prices.

Table 11. Sensitivity analysis for the cost-effective fuel- and electricity-savings potentials and CO_2 emissions reductions in China's pulp and paper industry with different energy prices

Energy price	Fuel			Electricity		
	Fuel price (US$/GJ)	Cost-effective savings (PJ)	Cost-effective CO_2 mitigation (Mt CO_2)	Electricity price (US$/MWh)	Cost-effective saving (GWh)	Cost-effective CO_2 mitigation (Mt CO_2)
-10%	4.3	179.6	16.9	82.1	2,316	1.8
Energy price*	4.8	179.6	16.9	91.3	2,316	1.8
+10%	5.3	179.6	16.9	100.4	2,316	1.8
+20%	5.8	179.6	16.9	109.5	2,316	1.8
+30%	6.2	179.6	16.9	118.6	2,316	1.8

* The base-case energy prices are those used in the main analysis presented in this report.

Investment costs/energy-savings sensitivity analysis

Variations in the investment costs and energy savings assumption for each energy-efficiency measure will also change the results. A change in either the investment costs or the energy savings of the measures will directly change the CCE (Equation 4). If the change in the investment costs or/and the energy savings is large enough to change the position of the CCE of any energy-efficiency measure relative to the energy price line in the CSC (for example, to bring it below the line if it was above the energy line before the change, or vice versa), then it will change the cost-effective energy-savings potential. Furthermore, a change in the energy savings of any measure will change the total amount of energy-savings potential regardless of the measure's cost effectiveness.

Therefore, we performed sensitivity analysis for changes in investment costs and energy savings for each measure (shown in Table 12 and 13, respectively) to assess the impact of these changes on the results. We analyzed four cases: a 10-percent and 20-percent increase in investment costs or energy savings and a 10-percent and 20-percent decrease.

As note above, in reality, the energy-savings potentials and investment costs of each energy-efficiency measure and technology may vary and will depend on various factors such as raw materials (hardwood, softwood, non-wood, recycled paper), the technology provider, production capacity, size of installations, final product quality, and time of the analysis. Thus, we performed sensitivity analyses to assess the effect of changes in investment costs and energy savings of each measure on the final results.

Equation 4 shows that the CCE is directly related to the investment costs and has an inverse relation to the energy savings of the measures. However, the cost-effective energy-savings potential changes only if a change in investment costs and/or energy savings is large enough to change the position of the CCE of any energy-efficiency measure relative to the energy price line in the CSC (e.g., to bring a measure's CCE below the line if it was above the line before the change or vice versa). In addition, the change in energy savings of any measure changes the total energy-savings potential regardless of the measure's cost effectiveness.

Tables 12 and 13 show how changes in the investment costs and energy savings of the measures can affect the cost-effective energy-savings potentials and their associated CO_2 emissions reduction potentials, respectively, while the other parameters are held constant.

Table 12 shows that the cost-effective fuel- and electricity-savings potential and associated CO_2 reductions do not change when the investment costs of the energy-efficiency technologies change by +/-20 percent. This is because the variation in the investment cost does not change the position of the CCFs and CCEs relative to the energy price line in the CSC. Table 12 also shows that although the cost-effective energy-savings potential does not change when the investment cost varies in the above range, the cumulative CCE declines with a decrease in investment cost of the technologies. That is to say that the energy-savings potential can be achieved with lower costs if the investment cost of the technologies decreases. The total technical energy-savings and CO_2 mitigation potentials do not change when investment costs vary.

Table 12. Sensitivity analysis for the cost-effective fuel- and electricity-savings potentials and CO_2 emissions reductions in China's pulp and paper industry with different investment costs of measures

Investment Cost (%)	Fuel			Electricity		
	Cost-effective savings (PJ)	Cost-effective CO_2 mitigation (Mt CO_2)	Cumulative CCF* (US$/GJ saved)	Cost-effective saving (GWh)	Cost-effective CO_2 mitigation (Mt CO_2)	Cumulative CCE* (US$/GWh saved)
-20%	179.6	16.9	83.82	2,316	1.8	70.42
-10%	179.6	16.9	94.30	2,316	1.8	79.22
IC**	179.6	16.9	104.77	2,316	1.8	88.02
+10%	179.6	16.9	115.25	2,316	1.8	96.82
+20%	179.6	16.9	125.73	2,316	1.8	105.63

* Cumulative CCF (the sum of the CCFs of all 18 applicable fuel-saving measures) and CCE (the sum of the CCEs for all five applicable electricity-saving measures) are presented as indicators to show that although the change in investment costs may not result in a change in cost-effective savings and CO_2 emissions reduction, it will change the CCF and CCE in general.

** The base-case investment costs used in the main analysis presented in this report.

Table 13. Sensitivity analysis for the cost-effective fuel- and electricity-savings potentials and CO_2 emissions reductions in China's pulp and paper industry with different energy savings of measures

Energy Saving (%)	Fuel				Electricity			
	Cost-effective savings (PJ)	Cost-effective CO_2 mitigation (Mt CO_2)	Cumulative CCF* (US$/GJ saved)	Total fuel savings (PJ)**	Cost-effective saving (GWh)	Cost-effective CO_2 mitigation (Mt CO_2)	Cumulative CCE* (US$/GWh saved)	Total electricity savings (GWh)**
-20%	144.2	13.6	130.44	204.5	1,853	1.4	110.03	1,853
-10%	161.9	15.3	116.19	229.4	2,084	1.6	97.80	2,084
ES**	179.6	16.9	104.77	253.8	2,316	1.8	88.02	2,316
+10%	197.3	18.6	95.41	279.3	2,548	2.0	80.02	2,548
+20%	215.0	20.3	87.59	304.2	2,779	2.1	73.35	2,779

* Cumulative CCF (the sum of the CCFs of all 18 applicable fuel-saving measures) and CCE (the sum of the CCEs of all give applicable electricity-saving measures) are presented as indicators to show that although a change in energy savings may not result in a change in cost-effective savings and CO_2 emissions reduction, it will change the CCF and CCE in general.

** The base-case energy savings used in the main analysis presented in this report.

Table 13 shows how the cost-effective fuel-savings potential increases from 144.2 PJ to 215.0 PJ and the cost-effective electricity-savings potential increases from 1,853 GWh to 2.779 GWh as a result of a change in energy savings from the technologies from -20 percent to +20 percent. That is, even greater energy savings can be achieved than indicated by the CSC analysis, depending on the current efficiency of a plant and the degree of efficiency that a specific technology can attain. Furthermore, the cumulative CCF and CCE decrease in accordance with the increase in energy savings of each technology. The total technical energy- (electricity and fuel) savings potentials also increase as the energy savings of each measure increase (see Table 13).

6. Conclusions

This report uses bottom-up energy CSCs to estimate the potential for 23 technologies and measures to improve the energy-efficiency and reduce the CO_2 emissions of China's pulp and paper industry. Pulp and paper production is one of the most energy-intensive industries in China, with high associated CO_2 emissions. In 2010, the industry's energy intensity 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 CO_2 emissions were 99 Mt.

The cost-effective fuel-efficiency improvement potential for the industry is estimated to be 179.6 PJ, and the total technical fuel-savings potential is 254.3 PJ, which are equal, respectively, to 26.8 percent and 38.0 percent of total fuel consumption by the industry in 2010. The CO_2 emissions reduction potentials associated with the cost-effective and technical fuel savings are 16.9 Mt CO_2 and 24.2 Mt CO_2, respectively, equal to 17.1 percent and 24.4 percent, respectively, of total CO_2 emissions from China's pulp and paper industry in 2010. The electricity-efficiency potential is 2,316 GWh, which is equal to 4.3 percent of the industry's total electricity use in 2010. All of the electricity-efficiency potential is found to be cost effective. The CO_2 emissions reduction potential associated with the total electricity savings is 1.8 $MtCO_2$. The cost-effective and technical primary energy savings potentials for China's pulp and paper industry represent 17 percent and 23 percent, respectively, of total primary energy consumption by the industry in 2010.

We performed sensitivity analyses to determine the influence of the following parameters on the results of our analysis: adoption rate, discount rate, energy prices, investment costs, and energy savings for each measure. The results show that the variations of adoption rate or energy savings of each energy-efficiency measure have a significant influence on the cost-effective energy- and electricity-savings potential as well as the technical energy-savings potential. The cost-effective energy savings or CO_2 reductions potential does not change with variations in energy prices or investment costs of measures in the studied range. The sensitivity analysis results for discount rate show that the cost-effective fuel savings do not change until the discount rate is lowered to 15 percent. Furthermore, the cost-effective electricity savings do not change with changes in the discount rate within the specified range.

Some energy-efficiency measures provide productivity and environmental benefits in addition to energy savings, but it is difficult or impossible to quantify those benefits. Including quantified estimates of other benefits could decrease the CCE and therefore increase the number of efficiency measures that would prove cost effective. Quantifying these non-energy benefits could be the subject of further research.

The model used in this study should be viewed as a screening tool to assist policy makers in assessing the savings potential of energy-efficiency measures in support of designing appropriate sector-specific energy-efficiency policies. The fuel CSC shows that maintaining/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 saving. Three promising electricity-savings technologies based on cost-effectiveness and high energy saving criteria are employing high-efficiency double-disc refiners, installation of variable frequency drives and energy-efficient lighting. In reality, energy-savings potentials and the cost of energy-efficiency measures and technologies may vary depending on various conditions. For the country-level analysis as presented in this report, a certain level of generalization and assumptions are required. However, for the plant-level analysis for investment purposes, more detailed and plant-specific data and analysis are needed than is possible for the country-level analysis. Energy-efficiency policies and programs are also needed to realize or exceed cost-effective potentials.

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References

China Paper Association (CPA). 2001-2011. *Annual Report of China Paper Industry*. Beijing.

China Paper Association (CPA). 2011. *Annual Report of China Paper Industry*. Beijing.

China Technical Association of Paper Industry (CTAPI). 2011. *Almanac of China Paper Industry*. Beijing: China Light Industry Press.

European Commission (EC). 2001. *Integrated Pollution Prevention and Control (IPPC) Reference Documents on Best Available Techniques in the Pulp and Paper Industry*. Brussels.

U.S. Energy Information Administration (EIA). 2011. *International Energy Outlook 2011*.

China Energy Research Institute (ERI). 2011. *Analysis and Evaluation of Key Industrial Energy-Efficient and Emission Reduction Technologies*.

Food and Agricultural Organization of the United Nations (FAO). 2011. *FAO Yearbook of Forest Products 2009*. Rome.

Food and Agricultural Organization of the United Nations (FAO). 2012. *ForesSTAT - Forest products production, import and export statistics*. Retrieved on 5 January, 2012. Available at: http://faostat.fao.org/site/630/Forestry.aspx.

Focus on Energy (FOE). 2005. *Pulp and Paper Energy Best Practice Guidebook*. Madison, Wisconsin.

Hasanbeigi, A., C. Menke, and L. Price. 2010a. "The CO_2 abatement cost curve for the Thailand cement industry". *Journal of Cleaner Production* 18 (15): 1509-1518.

Hasanbeigi, A., C. Menke, and A. Therdyothin. 2011. "Technical and cost assessment of energy efficiency improvement and greenhouse gas emission reduction potentials in Thai cement industry". *Energy Efficiency* 4 (1): 93-113.

Hasanbeigi, A., W. Morrow, E. Masanet, J. Sathaye, and T. Xu. 2012a. *Assessment of Energy Efficiency Improvement and CO_2 Emission Reduction Potentials in the Cement Industry in China*. Berkeley, CA: Lawrence Berkeley National Laboratory, LBNL-5536E.

Hasanbeigi, A., W. Morrow, J. Sathaye, E. Masanet, and T. Xu. 2012b. *Assessment of Energy Efficiency Improvement and CO_2 Emission Reduction Potentials in the Iron and Steel Industry in China*. Berkeley, CA: Lawrence Berkeley National Laboratory, LBNL-5535E.

Hasanbeigi, A., L. Price, H. Lu, and L. Wang. 2010b. "Analysis of energy-efficiency opportunities for the cement industry in Shandong Province, China: A case study of 16 cement plants". *Energy* 35 (8): 3461-3473.

Hill, K. C. 2006. "Five Rules for Energy Efficiency to Improve Dryer Section Operations". *Pulp & Paper* 80 (9): 52-57.

International Energy Agency (IEA). 2007. *Tracking Industrial Energy Efficiency and CO_2 Emissions - In support of the G8 Plan of Action*. Paris, France.

International Energy Agency (IEA). 2009. *Energy Technology Transitions for Industry - Strategies for the Next Industrial Revolution*. Paris, France.

International Energy Agency (IEA). 2010. *Energy Technology Perspectives - Scenarios and Strategies to 2050*. Paris, France.

International Energy Agency (IEA). 2011. *Energy Transition for Industry: India and the Global Context*. Paris, France.

Intergovernmental Panel on Climate Change (IPCC). 2006. *2006 IPCC Guidelines for National Greenhouse Gas Inventories, Vol.2 Energy*.

Karlsson, M. 2000. Papermaking Part 2, Drying. In *Papermaking Science and Technology*, edited by J. Gullichsen and H. Paulapuro. Helsinki, Finland: Fapet Oy.

Kinstrey, R. B., and D. White. 2006. *Pulp and Paper Industry Energy Bandwidth Study*. Atlanta, Georgia: Report for the American Institute of Chemical Engineers (AIChE). Prepared by: Jacobs Engineering, Greenville, South Carolina & Institute of Paper Science and Technology (IPST) at Georgia Institute of Technology.

Kong, L., L. Price, A. Hasanbeigi, H. Liu, and J. Li. 2012. "Potential for Reducing Paper Mill Energy Use and Carbon Dioxide Emissions through Plant-wide Energy Audits: A Case Study in China". *Applied Energy* 102: 1334-1342.

Kramer, K. J., E. Masanet, T. Xu, and E. Worrell. 2009. *Energy Efficiency Improvement and Cost Saving Opportunities for the Pulp and Paper Industry, An ENERGY STAR Guide for Energy and Plant Managers*. Berkeley, California: Lawrence Berkeley National Laboratory, LBNL-2268E.

Lang, I. 2009. "Effect of the Dryer Fabric on Energy Consumption in the Drying Section". *Pulp & Paper Canada* 110 (5): 33-37.

Li, Z. 2006. "Current Energy Efficiency in the Pulp & Paper Industry of China". Paper presented at the IEA-WBCSD Workshop on Energy Efficient Technologies and CO_2 Reduction Potentials in the Pulp and Paper Industry, Paris, France.

Lung, R. B., A. McKane, R. Leach, and D. Marsh. 2005. "Ancillary Savings and Production Benefits in the Evaluation of Industrial Energy Efficiency Measures". Paper presented at the 2005 ACEEE Summer Study on Energy Efficiency in Industry.

Maltais, D. 1993. "Heat recovery on a paper machine hood". *Pulp and Paper Canada* 94 (12): 113-117.

Martin, N., N. Anglani, D. Einstein, M. Khrushch, E. Worrell, and L. Price. 2000. *Opportunities to Improve Energy Efficiency and Reduce Greenhouse Gas Emissions in the U.S. Pulp* *and Paper Industry*. Berkeley, California: Lawrence Berkeley National Laboratory, LBNL-46141.

Meier, A. K. 1982. *Supply Curves of Conserved Energy*. PhD Thesis, University of California, Lawrence Berkeley Laboratory.

National Bureau of Statistics (NBS). 2009. *China Energy Statistical Yearbook 2008.* Beijing: China Statistics Press.

National Bureau of Statistics (NBS). 2009-2011. *China Energy Statistical Yearbook 2008-2010.* Beijing: China Statistics Press.

National Bureau of Statistics (NBS). 2011a. *China Energy Statistical Yearbook 2010.* Beijing: China Statistics Press.

National Bureau of Statistics (NBS). 2011b. *China Statistical Yearbook 2011*. Beijing: China Statistics Press.

National Development and Reform Commission (NDRC). 2007. *China Paper Industry Development Policy*. Retrieved on 10 May, 2010. Available at: http://www.eng.yn.gov.cn/image20010518/9179.pdf.

National Development and Reform Commission (NDRC). 2011a. *China Paper Industry Development Plan in the 12th Five Year Plan Period*. Retrieved on 5 January, 2012. Available at: http://www.ndrc.gov.cn/zcfb/zcfbtz/2011tz/t20120109_455383.htm.

National Development and Reform Commission (NDRC). 2011b. *Industrial Energy Efficiency Plan for the 12th Five Year Plan Period*. Retrieved on 5 January, 2012. Available at: http://www.miit.gov.cn/n11293472/n11293832/n12843926/n13917012/14476058.html.

New Energy and Industrial Technology Development Organization (NEDO). 2008. *Japanese Technologies for Energy Savings/GHG Emissions Reduction (2008 Revised Edition)*.

Pettersson, F., and J. Söderman. 2007. "Design of robust heat recovery systems in paper machines". *Chemical Engineering and Processing* 46 (10): 910-917.

Pulkowski, J. H., and G. L. Wedel. 1988. "The effect of spoiler bars on dryer heat transfer". *Pulp & Paper Canada* 89 (8): 61-66.

Reese, D. 2005. "Low-Cost Dryer Upgrade Opportunities Offer Efficiency Gains, Energy Savings". *Pulp & Paper* 79 (3): 54.

Sathaye, J., T. Xu, and C. Galitsky. 2010. *Bottom-up Representation of Industrial Energy Efficiency Technologies in Integrated Assessment Models for the Cement Sector*. Berkeley, CA: Lawrence Berkeley National Laboratory. LBNL-4395E.

State Electricity Regulatory Commission (SERC). 2010. *2010 Power Enterprises Energy Savings and Emissions Reduction Bulletin*. Retrieved on 20 December, 2011. Available at: http://www.serc.gov.cn/zwgk/jggg/201110/t20111026_15470.htm.

State Electricity Regulatory Commission (SERC). 2011a. *2010 Power Generation Business Briefing of China*. Retrieved on 20 December, 2011. Available at: http://www.serc.gov.cn/zwgk/jggg/201109/t20110901_15293.htm.

State Electricity Regulatory Commission (SERC). 2011b. *Electricity Price Monitoring and Supervision Report 2010*. Retrieved on 20 December, 2011. Available at: http://www.serc.gov.cn/zwgk/jggg/201009/t20100913_13544.htm.

Stoica, A., M. Sandberg, and O. Holby. 2009. "Energy use and recovery strategies within wastewater treatment and sludge handling at pulp and paper mills". *Bioresource Technology* 100 (14): 3497-3505.

Szabó, L., A. Soria, J. Forsström, J. T. Keränen, and E. Hytönen. 2009. "A world model of the pulp and paper industry: Demand, energy consumption and emission scenarios to 2030". *Environmental Science & Policy* 12 (3): 257-269.

Thompson, G., J. Swain, M. Kay, and C. F. Forster. 2001. "The treatment of pulp and paper mill effluent: A review". *Bioresource Technology* 77 (3): 275-286.

Vickerman, K. D. 1995. *Papermaking: Then and Now. A History of Hand Papermaking from Its Beginning, Plus a Process for Using Natural Fibers To Make Paper*. Educational Resources Information Center.

Worrell, E., L. Bernstein, J. Roy, L. Price, and J. Harnisch. 2009. "Industrial energy efficiency and climate change mitigation". *Energy Efficiency* 2 (2): 109-123.

Worrell, E., J. A. Laitner, M. Ruth, and H. Finman. 2003. "Productivity benefits of industrial energy efficiency measures". *Energy* 28 (11): 1081-1098.

Worrell, E., N. Martin, and L. Price. 2000. "Potentials for energy efficiency improvement in the US cement industry". *Energy* 25 (12): 1189-1214.

Worrell, E., L. Price, and N. Martin. 2001. "Energy efficiency and carbon dioxide emissions reduction opportunities in the US iron and steel sector". *Energy* 26 (5): 513-536.

Xu, T., J. Sathaye, and C. Galitsky. 2010. *Development of Bottom-up Representation of Industrial Energy Efficiency Technologies in Integrated Assessment Models for the Iron and Steel Sector*. Berkeley, CA: Lawrence Berkeley National Laboratory. LBNL-4314E.

Appendix A. Description of Energy-Efficiency Technologies/Measures

Chemical Pulping

EE-1: Batch digester modifications

During the batch cooking process, steam is produced when the hot pulp and cooking liquor are reduced to atmospheric pressure. The thermal energy in this steam can be used throughout the mill, reducing the need for other heating energy sources. In addition, many measures can reduce the energy use of batch digesters, such as indirect heating, cold-blow system, and blow-heat recovery. Indirect heating involves in drawing cooking liquor from the digesters and pumping it through an external heat exchanger, then returning to the digesters at two separate locations (Martin *et al.* 2000). Cold-blow systems displace hot spent cooking liquor from the digester contents (chips, cooking liquor, air, etc.) using brownstock washer filtrate. Heat can be recovered from the spent liquor for heating subsequent cooks, which reduces cooking steam consumption. Blow-heat recovery uses the heat produced from cooking liquor in other facility applications, such as chip steaming, process water heating, or black liquor evaporation (Kramer *et al.* 2009).

EE-2: Continuous digester modifications

Continuous digester modifications focus on reducing the amount of material that must be heated and increasing the level of heat recovery. In a continuous digester, spent pulping liquor is withdrawn at the extraction screens and then flashed to atmospheric pressure. The flash vapor can be used in other processes, such as chip pre-steaming or black liquor evaporation. Continuous digester performance can also be enhanced using advanced control systems to regulate various parameters and thus improve process operation. This includes minimizing the liquor-to-wood ratio and ensuring the efficiency of waste heat recycling. Energy efficiency is improved as a result of reduced demand for steam and thus for fuel in the chemical pulping process (Martin *et al.* 2000).

Chemical Recovery

EE-3: Falling film black liquor evaporation

A tube-type falling-film evaporator effect operates almost exactly the same way as a more traditional rising-film effect except that the black liquor flow is reversed. The falling-film effect is more resistant to fouling because the liquor is flowing faster and the bubbles flow in the opposite direction of the liquor. This resistance to fouling allows the evaporator to produce black liquor with considerably higher solids content (up to 70 percent solids rather than the traditional 50 percent), thus eliminating the need for a final concentrator (Kramer *et al.* 2009).

EE-4: Black liquor concentration

Minimizing the amount of water to be evaporated by increasing the dry solids content of black liquor fired in the recovery boiler improves boiler thermal efficiency. The solids concentration of black liquor can be enhanced by installing a solids concentrator between multiple-effect evaporator and the recovery boiler. Black liquor concentration is designed to increase the solids content of black liquor prior to combustion while minimizing scaling and fouling in the recovery boiler. Although additional energy is required for transferring and heating the black liquor, the energy gained from combusting high-solids liquor more than offsets the steam and electricity demand of the concentrator (EC 2001).

EE-5: Lime kiln modifications

The lime kiln process converts lime mud ($CaCO_3$) to lime (CaO) and CO_2 where high temperature is required for calcination. Large amounts of heat exit the lime kiln with the lime product and flue gases. Opportunities to improve the energy efficiency of lime kilns include oxygen enrichment, high-efficiency filters and refractory bricks, and capture of waste heat for preheating incoming lime and combustion air. Oxygen enrichment is an established technology for increasing combustion efficiency and has been adopted in various forms by a number of industries with high-temperature combustion processes. High-efficiency filters are used to reduce the water content in materials fed into the kiln, which reduces the energy needed for evaporation. High-efficiency refractory bricks can be installed to decrease radiation heat loss. The implementation of these measures has additional benefits, including improving the recovery rate of lime from green liquor. Electrostatic precipitators can also replace wet scrubbers in lime kilns, which saves energy and water (Kramer *et al.* 2009).

Mechanical Pulping

EE-6: Refiner improvements

Several improvements within the refining process of a pulp mill can reduce electricity consumption in mechanical pulping. Refiner improvements are important for the electricity reduction potential of various measures. Electricity consumption can be reduced by using a refiner control system to minimize variations in the freeness. Using conical refiners instead of the commonly used disk refiners is a promising modification that reduces electricity demand by decreasing the pulping consistency (Kramer *et al.* 2009).

EE-7: Heat Recovery in Thermomechanical pulp mill

The refiners in TMP mills use large amounts of electrical energy, which is converted to heat and steam through friction. A large amount of low-pressure steam is produced as the byproduct of

TMP. This steam is often contaminated, but heat recovery equipment can reclaim most of the energy from it, for use in other mill processes (EC 2001). This secondary heat can be used to replace primary heat in the paper machine dryer, in black liquor evaporation, and in water or stock heating. The pressure of the steam may need to be boosted by a heat pump for some applications, such as the paper machine dryers. TMP heat recovery is applicable in any mill that uses pressurized refining and currently does not use heat recovery (Kramer *et al.* 2009).

Bleaching

EE-8: Chlorine dioxide preheating

As the pulp and paper industry moves to chlorine-free bleaching technology, the use of ClO_2 to bleach pulp will increase in pulp bleaching process, which will in turn increase steam demand in pulp bleaching. The ClO_2 solution is normally chilled to maximize its concentration. Preheating of the chilled ClO_2 solution before it enters the mixer can reduce live steam use in pulp bleaching. Chilled ClO_2 can be heated using secondary sources (e.g., alkaline-stage effluent) by installing heat exchangers in the ClO_2 feed circuit (Kramer *et al.* 2009).

Papermaking

EE-9: High-efficiency double-disc refiners

Using high-efficiency double-disc refiners for the fiber beating or refining process instead of traditional conical or cylindrical refiners can increase refining energy efficiency. A double-disc refiner uses two flat discs that rotate in opposite directions, creating a refining zone between them. An advanced control system keeps the disc clearance constant for specific operating conditions and loads. Many commercialized high-efficiency double-disc refiners are available on the market worldwide. According to ERI (2011), some double-disc refiners manufactured in China already meet international advanced performance standards. A Shandong (China) paper mill with paper production of 300 kt/year installed double-disc refiners and achieved annual energy savings of approximately 5.1 GWh. Costs saving were about US$266,000/year (1.80 million RMB/year), for an estimated payback period of 0.6 years (ERI 2011).

EE-10: Shoe press

Most of the water in the papermaking process is removed in the wire and press sections of a paper machine; only about one percent of the original water content is removed in the dryer section. However, the dryer section uses the largest amount of energy in the papermaking process. Therefore, maximizing the performance of the press section is critical to minimizing energy consumption. It is estimated that 3 to 8 percent of dryer steam can be reduced for every one-percent improvement in the solids content of web exiting the press section (Kong *et al.* 2012).

Normally, pressing occurs between two felt liners between two rotating cylinders. Shoe presses use a large concave shoe instead of one of the conventional rotating cylinders; this extends dwell time, thus improving mechanical dewatering compared to that of conventional roll presses (Kramer *et al.* 2009). The web solids content leaving a shoe press can be as much as 50 to 55 percent, which improves overall energy efficiency even though a shoe press consumes more electricity than a conventional press does (EC 2001).

EE-11: Stationary siphons

Many dryers in existing paper machines are equipped with rotary siphons. Replacing rotary siphons with stationary siphons in dryers that discharge directly to condensers can improve paper drying efficiency. Rotary siphons are fixed in the dryer and rotate with the dryer; stationary siphons are held in a fixed position, and the dryer rotates around the siphons. Stationary siphons are designed for a blow-through steam flow of 8 to 12 percent of total steam consumed in the dryer whereas rotary siphons may require 20 to 25 percent blow-through steam to remove condensate adequately (Hill 2006; Lang 2009). Stationary siphons reduce the amount of condensate in the dryers, which improves thermal efficiency and reduces the required differential pressure. Stationary siphons generally could improve energy efficiency by 5 to 10 percent (Kinstrey and White 2006).

EE-12: Turbulent bars

Turbulent bars could increase heat-transfer efficiency and improve cross-machine temperature profiles by creating turbulence in the condensate layer when the dryer is operating above rimming speed. Turbulence bars break the laminar condensate layer to create a turbulent condition. The effect of turbulent bars on drying efficiency varies according to the machine speed. The heat-transfer coefficient can be improved by 40 to 50 percent using turbulent bars in paper machines with the speed of 1,000-1,400 meter/minute (Pulkowski and Wedel 1988; Reese 2005).

EE-13: Enclose paper machine hood

The water evaporated during paper drying is captured and removed from the dryer by a hood air system. There are three types of paper machine hoods: open, semi-open, and closed. Open hoods are not used today, but semi-open hoods are still in use on some narrow paper machines. Modern paper machines are usually equipped with closed hoods, which are more energy efficient than other designs (Karlsson 2000). A closed hood uses only one-third as much air as an open hood to remove the same amount of moisture. Enclosing the machine hood reduces dryer steam consumption. Electricity can be saved if fan speeds can be reduced because of lower exhaust flow volumes. Exact savings will depend on the heat-recovery method and extent of utilization. An estimated 15- to 20-percent reduction in steam can be achieved by replacing a semi-open hood with a closed hood. This, in turn, means a savings of about 40 to 50 percent of the electricity used by air-circulation fans. A closed hood reduces heat losses and allows recovery of more waste heat than is possible with a semi-open hood (Kong *et al.* 2012).

EE-14: Air system optimization

The importance of the air system in paper drying is often ignored during operation of the dryer section of a paper machine. During the drying process, water is evaporated from the paper or paperboard, and moist air is exhausted through the machine hood. The exhaust stream from the paper machine hood is often used in place of fresh steam to heat different process streams, such as supply air, process water, and circulation water. Drying performance can also be improved by optimizing the air system through adjusting supply-air temperature, exhaust air humidity, and supply and exhaust air rates. Exhaust humidity control results in efficient drying performance and thus can reduce dryer thermal energy consumption as well as fan electricity consumption because the need for ventilation is reduced. Implementing hood exhaust moisture controls will also minimize the heat losses from the paper drying process (Kong *et al.* 2012).

EE-15: Waste heat recovery

There are several opportunities exist to recover thermal energy from steam and waste heat in the paper drying process (Martin *et al.* 2000; EC 2001). A large amount of the thermal energy used in the drying process ends up in the exhaust air, so a heat-recovery system is vital to the overall energy economy of the papermaking process. For a modern paper machine with an efficient heat recovery system, more than 60 percent of the exhaust heat from the dryer section can be recovered (Maltais 1993; Pettersson and Söderman 2007). However, some paper machines in China are not equipped with heat recovery systems. Recovering the waste heat from these paper machines could dramatically decrease their energy consumption. An estimated 114.34 TJ of thermal energy can be saved by installing a heat-recovery system on a case paper machine. This is one of the most cost-effective efficiency measures, with a simple payback period of only 0.7 years (Kong *et al.* 2012).

EE-16: Anaerobic wastewater treatment and methane utilization

Aeration in biological wastewater treatment often consumes more than 50 percent of the electricity used in the wastewater treatment plant. The alternative is using anaerobic treatment methods that require no oxygen and produce methane (EC 2001). Anaerobic biological wastewater treatment produces 10 times less sludge than aerobic wastewater treatment. The process is slower and more sensitive to disturbances compared to conventional aerobic biological wastewater treatment (Stoica *et al.* 2009). Anaerobic wastewater treatment has many potential advantages over aerobic treatment including requiring fewer chemicals, producing less sludge, and producing energy in the form of methane (Thompson *et al.* 2001). Paper mill effluent contains abundant organic materials, so large amounts of methane gas can be produced if the effluent is treated under anaerobic conditions. The methane can be collected and burned in place of fossil fuel to generate electricity, either in a conventional combined heat and power system or in a new biogas-based electricity generation system (Kong *et al.* 2012).

EE-17: Sludge recovery and utilization

Sludge is a byproduct of a mill's wastewater treatment process. Traditionally, paper mill sludge has been disposed of at landfills. If the sludge were recovered and reused as fuel for the mill's steam-generating boilers, much of the landfill cost could be reduced. Paper mill sludge consists mainly of fines and fillers from the papermaking process. The caloric value of the dry solids can reach 11.5MJ/kg. The primary investment for this measure would be the cost of sludge dehydration equipment. Mechanical dewatering is the most energy-efficient way to remove large quantities of water, thereby increasing the heating value and decreasing the mass of sludge. Thermal dewatering is also used in some large mills. Sludge recovery and utilization reduces the fossil fuel used in boilers, thus mitigating the environmental impacts of obtaining the fuel as well as the emissions from burning it (Kong *et al.* 2012).

EE-18: Vacuum system optimization

A vacuum system is used to remove water from the wet-web and to help the runnability of the web. The vacuum system uses approximately 10 to 15 percent of the total electrical energy used by a paper machine. However, inefficiencies within vacuum systems increase the electrical and/or steam energy required for water removal. Adjustments that could save energy could be changes in furnish, chemistry, headbox consistency, retention, and forming and press fabrics. Vacuum system optimization can be achieved through system modifications, operational changes, and even removal of some vacuum pumps (Kramer *et al.* 2009).

General Measures

EE-19: Adjustable-speed drives

Fans, pumps, and motors are used throughout the pulping and papermaking process. Converting motors to high energy-efficiency drives would save electricity. Adjustable-speed drives are an excellent option because they allow operators to fine-tune processes while reducing electricity use and equipment maintenance costs. Adjustable-speed drives better match speed to load requirements for motor operations and therefore ensure that motor energy use is optimized to a given application. Motors that could be optimized with adjustable-speed drives include stock, liquor, filtrate, and paper machine pumps in pulp and paper mills; kiln and dryer fans in wood product facilities; boiler air fans; and any other pumps or fans with variable flows (Kramer *et al.* 2009).

EE-20: Energy-efficient lighting

Facility lighting (including lighting in manufacturing areas, offices, laboratory spaces, and warehouses) accounts for approximately 4 percent of the total electricity used by the U.S. pulp and paper industry. Although the energy used for lighting at pulp and paper mills represents a small portion of the overall energy usage, efficiency improvements in lighting systems can be easy changes with rapid payback periods. Thus, lighting efficiency improvements are often an attractive area for many pulp and paper mills. Lighting efficiency measures include turning off lights in unoccupied areas, replacing inefficient lights, and installing automated lighting controls (Kramer *et al.* 2009).

EE-21: Steam traps maintenance

Steam traps can be optimized with various techniques such as proper maintenance, monitoring and by improvement of the current equipment use. Regular systematic inspection, testing, and repair of steam traps should also be established to reduce steam losses. In addition, installing modern thermostatic-element steam traps can reduce energy consumption and losses. Additional benefits of these traps are that they improve system reliability, improve system discharge when temperature rises to saturated steam levels, and improve purge of non-condensable gases with each opening, and reduce steam warm-up time period (Kramer *et al.* 2009).

EE-22: Condensate return

The condensate from paper dryers can be recovered and reused as boiler feed water. Typically, fresh feed water must be treated to remove solids that might accumulate in the boiler; returning condensate to a boiler can substantially reduce the amount of steam and of purchased chemical required for this treatment. Increased steam condensate recovery should be possible in all paper mills. In most cases, partial recovery can be achieved without need additional investment (EC 2001).

EE-23: Real-time energy-management systems

Installing real-time energy management system to comprehensively measure, monitor, analyze, and optimize the energy system of the entire pulping and papermaking line will reduce energy use and losses from the manufacturing process. Production units that could benefit from energy management systems include boilers, evaporators, brownstock washers, lime kilns, paper machines, and wastewater treatment units. The energy management system can be tied into the current distributed control system as well as the operator control system to allow operators access to trend charts. The energy management system should allow for on-line reporting and accounting for energy usage in the unit, including steam, condensate return, fuel consumption, and other important process variables specific to each unit.